Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Evaluation of Quality Stability of Film Laminated Panels under Varying Process Conditions

Master's Final Degree Project

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Kaunas, 2026

Kaunas University of Technology
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Industrial Engineering and Management (6211EX018)

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Task of the Master's Final Degree Project

Given to the student – Ula Valantinaitė

1. Title of the Project

Evaluation of Quality Stability of Film Laminated Panels under Varying Process Conditions

(In English)

Plėvele dengtų plokščių gamybos proceso kokybės stabilumo vertinimas, esant kintančioms technologinėms sąlygoms

(In Lithuanian)

2. Aim and Tasks of the Project

Aim: to evaluate the stability of quality of film laminated panels in the manufacturing of flat–pack furniture
Tasks:

1. to analyse the principles of film lamination and the influence of environmental and process parameters on adhesive bond formation and product quality stability;
2. to identify the critical process parameters affecting the quality of film laminated panels;
3. to calculate main quality indicators, determine their dependence on parameter fluctuations and evaluate the influence of different parameters on product quality;
4. to perform laboratory evaluation of film adhesion and thermal stability under different conditions;
5. to determine optimal process parameter ranges and develop practical recommendations for improving process stability and reducing production defects.

3. Main Requirements and Conditions

The project must evaluate the quality stability of film laminated furniture panels under varying process conditions. The research assesses the influence of adhesive amount, adhesive distribution uniformity, adhesive and calander temperature, line speed, pressure, film type. Adhesion and stability have to be evaluated using laboratory relevant methods including ISO 2409:2020 cross - cut adhesion test and thermal ageing conditions based on ISO 9142. The expected result is to determine optimal process parameters that reduce defects.

4. Additional Requirements for the Project, Report and its Annexes

Non applicable

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Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: furniture manufacturing; film laminated panels; lamination; adhesion stability; delamination; EVA adhesives; Hot melt adhesives; line speed; adhesive amount; thermal stability; defect rate.

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Summary

This master’s thesis evaluates the quality stability of the production process for film-faced panels by analysing various technological parameters. The research is relevant to the production of ready-to-assemble furniture, where MDF and MDP panels are coated with decorative film, and the quality of the final product depends on stable adhesion between the panel, adhesive, and film. The main problem analysed is the delamination of black decorative film from the board, which occurs not only immediately after the lamination process but also during subsequent production processes, storage, and at the customer’s site. The theoretical part of the study analysed the principles of film lamination, the properties of MDF and MDP panels, the influence of environmental conditions, and the main mechanisms of adhesion formation. It was determined that lamination quality depends on surface wetting, physical interactions, mechanical adhesive bonding, and the compatibility of technological parameters; therefore, it can be concluded that the lamination process functions as a multifactorial system in which quality depends on environmental and technological parameters. The practical section examined the main parameters affecting the process: adhesive quantity, uniformity of adhesive distribution, adhesive and calander temperature, line speed, pressure conditions, film type, and the adhesive system used. The research methodology includes the analysis of production data, the calculation of quality indicators, the comparison of technological parameters, and the laboratory evaluation of adhesive stability. Film adhesion is evaluated using methods that closely reflect real-world conditions, including the ISO 2409:2020 cross-cut adhesion test and thermal aging conditions in accordance with the principles of ISO 9142. The study also examines how defect reduction can impact production efficiency, material consumption, and the environmental assessment of the process. The study underscores the importance of integrated process control, where quality stability is ensured not only by regulating individual parameters but by managing their interactions throughout the entire lamination process.

Valantinaitė Ula. Plėvele dengtų plokščių gamybos proceso kokybės stabilumo vertinimas, esant kintančioms technologinėms sąlygoms. Magistro baigiamasis projektas, vadovė prof. dr. Rūta Rimašauskienė; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: baldų gamyba; plėvele dengtos plokštės; laminavimo procesas; sukibimo stabilumas; delaminacija; EVA klijai; Hot melt klijai; linijos greitis; klijų kiekis; terminis stabilumas; defektų lygis.

Kaunas, 2026. 80 p.

Santrauka

Šiame magistro projekte vertinamas plėvele dengtų plokščių gamybos proceso kokybės stabilumas vertinant įvairius technologinius parametrus. Tyrimas aktualus surenkamųjų baldų gamyboje, kur naudojamos MDF ir MDP plokštės yra dengiamos dekoratyvine plėvele, o galutinio gaminio kokybė priklauso nuo stabilaus sukibimo tarp plokštės, klijų bei plėvelės. Pagrindinė analizuojama problema juodos dekoratyvinės plėvelės atsisluoksniavimas nuo plokštės, kuris pasireiškia ne tik iš karto po laminavimo proceso, bet ir tolimesniuose gamybos procesuose, sandėliavimo metu, bei pas klientą. Teorinėje Darbo dalyje buvo išanalizuoti plėvelės laminavimo principai, MDF ir MDP plokščių savybės, aplinkos sąlygų poveikis bei pagrindiniai sukibimo formavimosi mechanizmai. Nustatyta, kad laminavimo kokybė priklauso nuo paviršiaus sudrėkinimo, fizikinių sąveikų, mechaninio klijų įsitvirtinimo ir technologinių parametrų suderinamumo, todėl galima teigti, kad laminavimo procesas veikia kaip daugiafaktorė sistema kurioje kokybė priklauso nuo aplinkos bei technologinių parametrų. Praktinėje dalyje buvo išnagrinėti pagrindiniai procesą veikiantys parametrai: klijų kiekis, klijų pasiskirstymo tolygumas, klijų bei kalendrų temperatūra, linijos greitis, prispaudimo sąlygos, plėvelės tipas ir naudojama klijų sistema. Tyrimo metodologija apima gamybinių duomenų analizę, kokybės rodiklių skaičiavimą, technologinių parametrų palyginimą ir laboratorinį sukibimo stabilumo vertinimą. Plėvelės sukibimas vertinamas taikant praktikai artimus metodus, įskaitant ISO 2409:2020 kryžminio pjūvio sukibimo testą ir terminio sendinimo sąlygas pagal ISO 9142 principus. Darbe taip pat nagrinėjama kaip defektų mažinimas gali paveikti gamybos efektyvumą, medžiagų suvartojimą ir aplinkosauginį proceso vertinimą. Tyrimas leidžia pagrįsti integruotos proceso kontrolės svarbą, kai kokybės stabilumas užtikrinamas ne vien reguliuojant atskirus parametrus, bet valdant jų tarpusavio sąveiką visame laminavimo procese.

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List of Abbreviations and Terms

Abbreviations:

RTA – ready to assemble;
MDF – medium density fibber board;
MDP – medium density particle board;
TDS – technical data sheet;
RH – relative humidity;
MC – moisture content;
UV – ultraviolet;
EVA – ethylene-vinyl acetate;
PUR – polyurethane reactive;
DR – defect rate;
FPY – first – pass yield;
RR – rework rate;
SR – scrapped rate;
CV – variation coefficient;
FR – non – conformity rate;
PR – rate of compliance;
CI – cost index.

Introduction

The stability of the manufacturing process for film laminated panels is a critical issue in production engineering in ready to assemble furniture manufacturing. As the lamination of these panels directly determine the aesthetic quality, functional reliability and production efficiency of the final furniture component. Medium density fiberboard and MDP based components used in the production of ready to assemble furniture are typically manufactured in large quantities, therefore even a minor fluctuation in technological parameters can lead to significant amount of defective parts, additional reprocessing costs, material losses and customer complaints. The quality of film lamination depends on several interrelated factors. The most important of these are the amount of adhesive, the uniformity of adhesive distribution, the temperature of the adhesive and the calander, the line sped, pressure conditions, properties of the film and the ambient temperature and relative humidity. These parameters help to determine the adhesive viscosity, surface wetting, mechanical interlocking of the adhesive and the film, the stability of the final bond and contact time between film, adhesive and the panel. Since, MDF and MDP boards are sensitive to moisture, and the film and adhesive systems are used to react to temperature changes the laminated product must be considered as a multilayered system in which the properties of each element directly influence the overall quality stability. In practice, one of the most significant quality issues is the delamination of the film from the board surface. This defect can occur immediately after lamination, during subsequent production stages, during storage or even in the customers environment. This problem indicates that visual inspections alone after production are insufficient as initial adhesion does not always guarantee long – term resistance to mechanical, thermal or environmental influences. For this reason, the evaluation of the lamination process quality must include not only defect counting but also an analysis of bond stability, thermal resistance and the influence of process parameters. The relevance of this project stems from the need to ensure more stable production of film laminated panels, reduce the number of overall defects, rework, scrap and unnecessary material consumption. Quality fluctuations in mass production result not only in direct economic loses but also in increases strain on production system, as well as additional consumption of energy and labour. Therefore, controlling technological parameters becomes an essential condition for ensuring stable product surface adhesion, a lower defect rate and more reliable performance of the final product under real life use conditions.

Aim: to evaluate the stability of quality of film laminated panels in the manufacture of flat–pack furniture by analysing the influence of varying environmental and process parameters on defect rate and the quality of film adhesion.

Tasks:

1. to analyse the principles of film lamination and the influence of environmental and process parameters on adhesive bond formation and product quality stability;
2. to identify the critical process parameters affecting the quality of film laminated panels;
3. to calculate main quality indicators, determine their dependence on parameter fluctuations and evaluate the influence of different parameters on product quality;
4. to perform laboratory evaluation of film adhesion and thermal stability under different conditions;
5. to determine optimal process parameter ranges and develop practical recommendations for improving process stability and reducing production defects.

Hypothesis: changing environmental and process parameters and conditions can significantly increase the variation of quality of film laminated panels in flat–pack furniture manufacturing, and control of these parameters helps to ensure a more stable level of quality and fewer defects.

1. Quality Stability of Film Laminated Panels for Flat–pack Furniture

The consistency of quality of film laminated panels is one of the most important factors in the mass production of flat–pack furniture. The flat–pack furniture segment has remained a significant and growing part of the furniture industry in recent years, as this production model allows for more efficient organization of mass production, reduces transportation and storage costs and offers consumers a functional, easy to assemble product. The production of this type of furniture is based on the use standardised flat–pack components, so the quality of the final product directly depends on the dimensional accuracy of individual parts, surface quality and the repeatability of the manufacturing process. As production volumes increase, even a minor quality fluctuation can result in significant number of defects, additional rework, material waste and customer complaints. For this reason, the quality stability of film laminated panels becomes a key factor linking material properties, surface finishing technology and the reliability of the final furniture component.

1.1. Flat–pack Furniture Manufacturing

Flat–pack furniture, which is most often referred as ready – to – assemble (RTA), is defined as a furniture system in which the final product reaches a customer disassembled into separate structural components, packaged in flat packages and are assembled at the final place of use, as shown in Fig.1 [1]. This furniture packaging model has transformed the logistics and manufacturing paradigms of the furniture industry, because it allowed the separation of production, logistics and assembly functions, thereby optimizing each of them. The RTA model became economically attractive because it enabled a substantial reduction in transportation volumes, optimisation of storage, increased supply chain efficiency and the ability to centralise large scale production, which is particularly relevant in globalized supply chain. Based on United Nations Economic Commission for Europe 2020 Forest Products Annual Market Review data, the flat–pack furniture industry segment accounts for a significant share of the European furniture market and is one of the fastest growing sectors with its expansion directly linked to advances in flat–pack furniture manufacturing [2, 3].



Fig. 1. Ready to Assemble Furniture

The RTA furniture system is based on a modular structure in which structural elements are designed in a way, that could be easily standardized and compatible with a wide range of automated manufacturing systems. It means that in a design stage not only ergonomics and aesthetics are considered but also manufacturing optimisation. Structural decisions are often oriented at minimal

variety of details, which in the end helps to minimize the complexity of manufacturing and costs of inventory management. Looking from an economical point of view, flat–pack model creates conditions for economies of scale, as large production volumes allow fixed costs and investments in automation to be distributed across a broader product base [4]. But at the same time, this model requires extremely high stability of different processes, as the cost of defects in mass production can increase exponentially, due to the nature of this way of manufacturing, even 5 minutes of faulty operation can lead to hundreds of defected pieces, as production is often counted in tens or hundreds of thousands of units, and even small deviations from set measurements can lead to problems at assembly or loss of structural integrity [5].. Logistics optimisation also has a direct impact on product price, as transportation and storage costs account for a significant portion of the final price. The RTA furniture system allows for maximum utilization of transport capacity, as flat packs take up less space than assembled furniture. This is particularly important in international trade, where transport costs and carbon dioxide emissions are becoming an increasingly important competitive factor [6]. The final quality of RTA furniture is determined by not one but by several interrelated stages, starting with selection the of raw materials and ending with storage and logistics conditions. Firstly, the physical and mechanical properties of the panels determine the structural reliability and create the conditions for a successful production process. Secondly, the parameters of the film lamination process such as temperature, pressure, line speed and adhesive dosage must be controlled within narrow limits to ensure sufficient and uniform adhesion. Thirdly, storage and transport conditions can act as an additional risk factor if products are exposed to sudden changes in microclimate [5]. The final quality of RTA furniture is a systematic phenomenon, that only occurs when there is stable and controlled interaction between all processes and film laminating technology becomes one of the most sensitive and highest risk stages in this context [1].

1.1.1. Types and Properties of Wood Based Panels

RTA furniture system, as mentioned before, is based on a modular structure, large–scale standardisation and panel material usage in the manufacturing scheme [1]. In this production model, structural solutions are directly linked with the properties of raw used materials, as the pieces are designed considering the mechanical behaviour, workability and surface characteristics of the panel. In other words, the engineering logic of RTA furniture cannot be analysed separately from the production of the panels, which is the main structural element of the furniture. European market data shows that wood-based panels account for the largest share of furniture construction materials, and their consumption remains stable even, when raw materials fluctuate [7]. For this reason, the stability of the panel becomes a key factor in assessing the reliability and service life of the final product.



Fig. 2. Visual Difference Between MDP and MDF [8]

Wood based panels exhibit anisotropic behaviour and sensitivity to moisture changes, so their parameters must be evaluated not only according to nominal standard values, but also according to actual operating conditions [9]. Although the flat–pack concept is often viewed through the point of logistics and marketing its technological core is the wood based panels. This material absorbs loads, ensures the stability of the furniture, forms the basis for surface finishing. Therefore, it's important to understand the base material that is used for RTA furniture. There are two main types of wood based panels that are used in flat–pack furniture: chipboard (MDP) and medium-density fibber board (MDF), as shown in Fig. 2, which differ in both their structural and performance characteristics [10].

MDF is made from fine wood fibers which are bonded with synthetic binders under high pressure and temperature conditions, resulting in a more homogeneous microstructure and a more uniform density distribution through the thickness. Due to this structure of the board, MDF has a better surface smoothness, higher internal cohesion which is particularly important for milling profiled parts and requires a high-quality surface finish [10]. MDP on the other hand, consists of layers of wooden chips in different sizes, with finer surface layers and a coarser inner core, thus resulting in less homogeneous structure, as shown in Table 1. MDP is generally characterised by lower density and lower cost, but its mechanical properties are lower than those of MDF [11]. But MDP usually has a lower cost and density, which reduces the weight of the final piece of furniture and optimizes transportation costs. Recent studies have shown that modern MDP technologies allow for sufficient bonding strength and screw holding capacity in cabinet furniture structures provided that the requirements of EN 312:2020 are met [12]. While MDF remains superior in terms of surface finishing, painting and lamination, the higher density means higher raw material prices and energy requirements in production. Therefore, the choice of material today is based not only on mechanical properties but also on a balance of cost, weight and sustainability.

Table 1. Properties Difference Between MDF and MDP [13]

Parameter	**MDF**	**MDP**
Density (kg/m^3)	680 – 800	600 – 700
Bending strength (MPa, 16 mm)	≥ 23 – 30	≥ 11 – 16
Modulus of elasticity (MPa)	2500 – 3000	1600 – 2400
Internal adhesion (MPa)	0,6 – 0,75	0,35 – 0,5
Swelling after 24 hours (%)	10 – 15	12 – 18
Sensitivity to moisture changes	Medium – high (due to density)	High (due to heterogeneous structure)
Surface smoothness	Very high	Medium
Cost	Higher	Lower

As seen in recent years there has been a trend in the industry to switch from MDF to MDP, especially in the production of horizontal structural elements. This change is based on economic efficiency and a lower carbon footprint, as MDP production often uses a higher proportion of recycled wood, but if MDP does not meet the requirements for density, moisture content or emissions class, there may be an increased risk of surface deformation, delamination or dimensional instability [14]. Such defects are particularly critical in film laminating technology as the adhesion of the film depends on the integrity of the surface and the interaction with the adhesion substrate. The dimensional stability of wood based panels directly relates to environmental humidity, so an insufficiently stabilized panel

can cause stresses in the finish layer and delayed defects during use. The higher density and homogeneous structure of MDF ensure more even glue distribution during the film laminating process and greater adhesion reliability, especially in the case of complex profiles. The board not only forms the structural basis but also defines the limits of quality stability, the structural and physical parameters of the material determine whether the final product will remain mechanically reliable and aesthetically stable through its life cycle [15].

1.2. Decorative Film Lamination Process

Decorative film lamination (including profile wrapping and flat lamination) is a surface finishing technology in which decorative film/film is continuously bonded to linear panels using controlled heat, a layer of adhesive and pressure. This process is used for both linear profiles (1D laminating) and flat or slightly curved parts (2D wrapping), such as furniture fronts, doors, tabletops, cabinet elements or decorative panels, the difference is shown in Fig. 3 [1].



Fig. 3. Difference Between Wrapping and Laminating [16]

This process is chosen because it allows high aesthetic value to be effectively “transferred” to an economical substrate (MDF or MDP) [1], while maintaining serial production with repeatable quality, as shown in Fig. 4. The panel passes through a preparation zone, which consists of profiling, cleaning, preheating, priming (if necessary), then the surface of the film is coated by adhesive via roller or slot nozzle system and a sequence of pressure/guide rollers that force the film to precisely replicate the profile geometry and ensure contact between the panel and the film and forming uniform, visually homogeneous surface. By combining all of these processes together quality is formed directly in the production line rather than post operation. For this reason, lamination is considered a process technology in which the final result is sensitive to the conditions of the panel, the rheology of the adhesive and the mechanical pressure profile [17]. Modern lines use a pre melter type adhesive melting equipment and slot nozzle or roller application, which allow control of the uniformity of the adhesive layer and the process window, especially when working with hot melt adhesives. Industry technology guides describe the lamination process as one of the most versatile because it is

compatible with several adhesive chemistries (EVA, PO, PUR) and a wide range of films (PVC, PP, PET and much more [16]). Because this technology is based on hot melt adhesive technology, it allows high speeds and in line production without long drying times, which is critical for mass furniture production. Film lamination production lines can produce 15 – 40 m/min, while film wrapping lines often work in 8 – 25 m/min range, and the line speeds are directly related to finished piece quality, defect rate and the stability of the process [1].

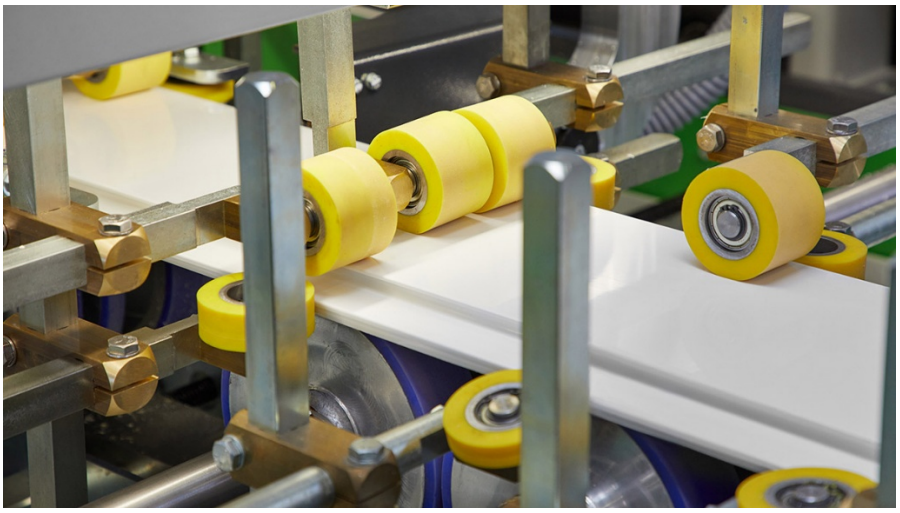


Fig. 4. Film Lamination Line [18]

The choice of this process in furniture manufacturing is based on the ability to combine productivity, economic efficiency and aesthetics by being accessible for a variety of film finishes and profiles. The process technology is quite simple: it is based on the interaction of physical adhesion between the adhesive, film and the panel. First the panels have to be stabilized, the surface must be clean, free of dust and the moisture content must generally be within the range of 6 – 10 % [6]. The adhesive is heated to its working temperature, every type of glue used uses different working temperature intervals. For example, in the case of hot melt adhesives, initial adhesion is formed when the adhesive cools and solidifies in the pressure zone, followed by a second stage – chemical cross linking, which involves greater resistance to heat and moisture [17]. After the application of adhesive, the film is positioned and pressed onto the panel using a pressure roller or pressing system. The whole process is sensitive to changes in temperature, line speed, adhesive quantity so the parameters have to be controlled within narrow limits. Industrial technical documents indicate that even small fluctuations in temperature or pressure can affect film and adhesion uniformity, as shown in Fig. 5. Thus, the principle of operation is based not only on the properties of the adhesive, film and the panel but also on precise control of the process conditions [1]. Critical film wrapping parameters are divided into four main groups [15]:

- Condition of the panel – moisture content is the important parameter; in some technical data sheets (TDS) it is stated that the moisture content of the board has to be around 8 – 10 %;
- film properties and preparation – thickness, elasticity, surface energy and thermoplastic behaviour of the film are most important because the film must “follow” the profiles radius, edges other surface finishes to prevent bubbles, wrinkles or tensions zones;
- adhesive chemistry and application – temperature of adhesive, adhesive layer weight, open time, line speed are the most important;

- mechanical part of the line and thermal settings – for mechanical part the hardness, geometry and the sequence of pressure rollers are critical, as it is the place where the contact between the panel and the film happens and the end product is formed, improper mechanical parameters can lead to bubbles, wrinkles, lifting, stripes or even delamination.

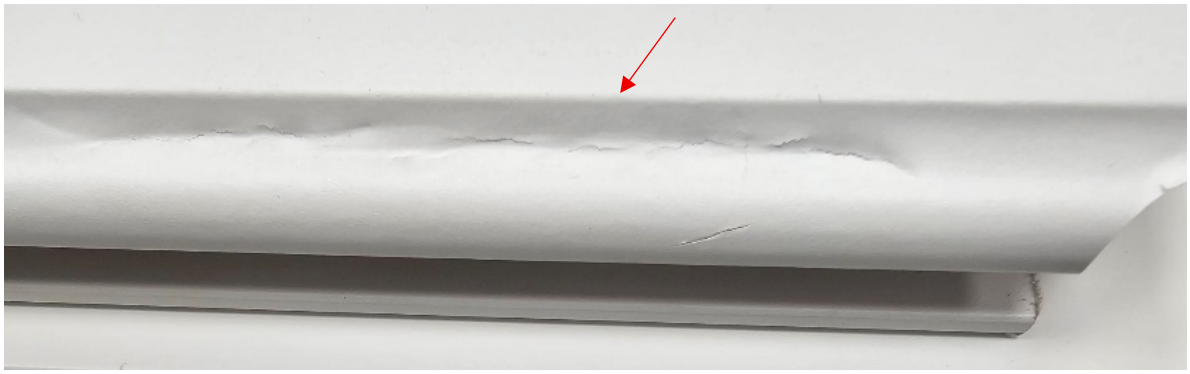


Fig. 5. Improper Parameter Configuration Result

1.3. Influence of Environmental Conditions on Quality Stability

Environmental parameters – temperature, relative humidity (RH) and the associated moisture content (MC) of wood based materials – are the key factors which determine the stability of the decorative film lamination process and the quality of the end product. These parameters work in an interrelated "panel – adhesive – film" systems, where each component has a different tolerance to heat and moisture. Both, MDF and MDP, are hygroscopic materials, who constantly seek an equilibrium with the relative humidity of the environment, so the MC and dimensions vary due to changes in RH [10]. At the same time, temperature has a significant impact on the mechanical properties of the paned, the rheology of the adhesive and the thermomechanical behaviour of the film. Different thermal expansion coefficients between the wood panel and the thermoplastic film mean that temperature changes generate internal stresses in the adhesive seal. When using hot melt adhesives, the humidity in the environment directly affects the curing process, so changes in RH not only change the stability of the process but also the final bond strength and how long does it take to fully form [12]. Scientific research confirms that the mechanical properties and internal adhesion of wood panels decrease with increasing humidity [19]. The practical implication for film lamination is such: if the panel enters the manufacturing process at a non – equilibrium moisture content, it continues to exchange the moisture with the environment after lamination, and the dimensional change generates shear and peel stresses in the adhesive joint. Such stresses are particularly important at edges, areas with a small radius and places where the adhesive layer is thinner due to geometry of the panel or uneven application, which concludes that climatic fluctuations have a direct impact on structural and adhesive reliability. For these reasons, environmental parameters must be considered as a systematic factor which determines quality, rather than just background production conditions – control of these parameters become a prerequisite for ensuring long – term stability of laminated furniture during production and use.

Temperature regulates the rheology of thermoplastic hot melt adhesives: when the temperature increases viscosity of the glue decreases, surface absorbency improves, but the effective open time window shortens and the adhesive absorption into porous MDF or MDP structure increases. But if we look at it the other way around when the temperature decreases, surface absorbency decreases, viscosity increases and not full contact between the panel and the film forms, which can lead to delamination. RH for reactive hot melts is a critical factor, because the final curing happens through

a reaction with the moisture. Experimental research shows, that as RH (for example 65 – 85 %) and temperature increase, the kinetics of moisture curing of hot melts accelerate. Thus, under different climatic conditions, the time it takes for the adhesive joint to reach its final strength and resistance changes [20]. In a similar way RH affects the film: polypropylene (PP) films, as thermoplastic materials, has higher linear thermal expansion coefficient than wood composites, so temperature fluctuations can cause different deformations between the film and panel which generates shear stresses in the adhesive layer [21]. Paper impregnated films, have a cellulose base, are hydroscopic and react to changes in RH, which together with the changes in the panel, create an additional stress component in the system [19]. Therefore, temperature and RH fluctuations simultaneously change the viscosity and curing speed of the hot melt adhesives, the deformation response of the film and the stress balance of the final bond. Thus, unstable environmental conditions can lead to bubbles, wrinkles or delayed delamination even with nominally correct technological settings. Critical environmental parameter intervals are shown in Appendix 1.

1.4. Process Parameter Impact on Quality

In the film lamination/wrapping process final quality is determined not only by properties of materials, environmental parameters, but also by how precisely the entire technological parameter system is controlled, that is the reason why the final quality depends on the right balance between technological, environmental and material parameters and properties. Temperature of the adhesive determines its viscosity, viscosity determines the uniformity of application and the depth of glue penetration, which in turn affects the amount of pressure and contact time required to form a reliable bond [22]. Similarly, line speed is not just an indicator of productivity: as speed increases, the actual available time for the adhesive to wet the substrate and film decreases, so the same temperature or the same amount of adhesive no longer ensures the same level of adhesion. Scientific literature emphasizes that the quality of lamination is a function of three main factors: heat, pressure and time, all of these factors together determine the formation of the adhesive layer and the effectiveness of adhesion [22]. In this heat – pressure – time relationship it is really important to control within a narrow range to ensure the best quality. If these parameters are not balanced together, even high-quality materials cannot ensure a consistent result, which manifests as surface defects or overall reduced bond strength. Uncontrolled process variation directly increases the likelihood of defects, drives up costs and reduces product quality consistency, while quality improvement is practically inseparable from process control and parameter management. This means that in the lamination process quality must be understood not as a matter of final inspection but as a direct function of parameter stability [23]. For this very reason, it makes sense to evaluate the impact of process parameters on final quality as the interaction between two interrelated groups of parameters. The first group includes mechanical and production parameters that determine the actual contact between the film and the bord: line speed, contact time, pressure mode, stability of workpiece movement and overall process repeatability. The second group includes adhesive application and thermal parameters – adhesive temperature, viscosity, application stability, heat transfer between the adhesive, board and the film, and surface condition during application process [23]. These two main groups cannot be analysed separately due to interconnectivity of these parameters, for example, a higher line speed automatically changes the required adhesive temperature, contact time and pressure requirement, while a change in adhesive viscosity affects how effective the same pressure is. Therefore, in this chapter, the process parameters are analysed as a unified system, from which the following

subsections are logically derived: mechanical and production parameters and adhesive application and thermal parameters [24].

1.4.1. Mechanical and Operational Parameters

Mechanical and operational parameters in film wrapping technology are among the critical parameters that determine the formation of actual contact between the film, adhesive and the substrate and therefore directly affect the bond strength and surface quality of finished product. One of the three most important parameters is the contact pressure, which in industrial wrapping lines typically range from 0,2 to 0,6 MPa, depending on the geometry of the workpiece and equipment used. When pressure is below 0,2 MPa, an incomplete contact often occurs between the film and the substrate and micro gaps still remain, which reduces the effectiveness of van der Waals interactions and results in weak adhesion, when pressure exceeds ~ 0,6 MPa it can cause the adhesive layer to be squeezed out of the contact zone or even the deformation of the film surface [25]. Optimal range often is considered 0,3 – 0,5 MPa, because this range often ensures a sufficient removal of air pockets and help to even out the distribution of the adhesive, thus preventing the adhesive layer from being squeezed out or the film form deforming. The contact time between the film, pressure roller and the substrate directly depend on the length of the contact zone in the line and the line speed, this contact time typically ranges from 0,5 to 3 seconds and must be sufficient for the adhesive to form an initial adhesion prior to its thermoplastic stabilization [26].

Line speed is another important parameter and typically range from 10 to 40 m/min and directly determine the contact time and the amount of thermal energy each piece receives. Based on scientific articles and industrial research the optimal line speed is 15 – 25 m/min, to ensure stable adhesion in EVA adhesive systems. This range helps to achieve a balance between sufficient contact time approximately 1 – 2 seconds, depending on the length of the pressure zone and process efficiency [26]. As speed increases, the time during which adhesive is applied, the contact time between the film and substrate decreases proportionally, as shown in Fig. 6, therefore without compensating for other parameters, bond strength decreases and the likelihood of defect occurrence increases. Contact time in lamination process can be calculated by using this formula:

$$t = \frac{60L}{v}, \tag{1}$$

where: t is contact time, s; L is effective contact zone length, m; v is line speed, m/min.

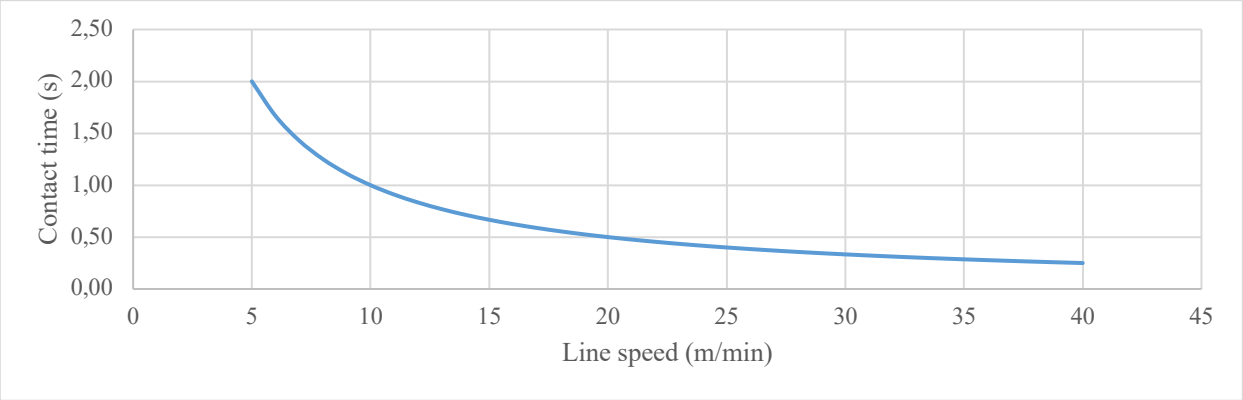


Fig. 6. Relationship Between Line Speed and Contact Time

This real-life example shows how each parameter is dependent on others and if one part of the relationship fails, others have to compensate for it [27]. Studies show that reducing contact time below a critical threshold can significantly reduce adhesive strength, even if the properties of the adhesive and material remain unchanged [28].

Another important factor in mechanical parameters is the length of the pressure zone, which is directly linked to the contact time of the workpiece. In typical laminating lines the pressure zone ranges from 0,5 to 1,5 m; therefore, at a speed of 20 m/min the contact time between film and the substrate approximately would be 1,5 – 4,5 seconds. This range is considered to be the most optimal for most EVA adhesive systems, at it allows for sufficient initial adhesion to form before the adhesive sets. The length of the substrate itself does not directly affect the bond strength; however, substrates that are longer than 2 meters are more sensitive to temperature and mechanical fluctuations, as greater length increases the likelihood of deformation and stress accumulation. In addition, longer workpieces require more stable transportation and more uniform pressure distribution, as even minor fluctuations can cause local adhesion defects. In this same group mechanical contact uniformity is also a critical factor. The pressure roller system must ensure an even distribution of pressure across the entire width of panel, as even the 10 – 20 % difference in pressure can cause uneven adhesion and localized defects [25]. Critical mechanical and operational parameters are shown in Appendix 2.

1.4.2. Adhesive Application and Thermal Parameters

Equally important as mechanical parameters are application and thermal parameters of the adhesive as these parameters determine whether sufficient adhesion will form between the film and the board. For EVA hot melt adhesives, the balance between temperature and viscosity is crucial: the adhesive must heat sufficiently to flow effectively and wet the surface, but not so much that it loses process stability or penetrates too deeply into porous substrate. EVA type hot melt adhesives exhibit thermoplastic behaviour, so their performance depends directly on temperature, which is typically maintained within the range of 160 – 200 °C, with the optimal working range usually being 170 – 190 °C. Within this range the adhesive's viscosity decreases to ~ 10, 000 – 50,000 mPa·s, ensuring sufficient flow and surface wetting; at temperatures that are below 160 °C, viscosity may exceed 60,000 mPa·s, which significantly limits wetting and reduces the contact area. Meanwhile, at temperatures that exceed ~ 200 °C, the risk of thermal degradation of adhesive increases and its mechanical properties may deteriorate, and the likelihood of excessive absorption into the porous MDF or MDP substrate also increases [29]. It is important to note that thermal parameters affect not only the adhesive but also the decorative film, especially if a paper film with UV varnish is used. The surface layer or different types of films are sensitive to temperature, as UV – cured varnish is thermally stable only within a limited range. In practice, it has been found that surface degradation of UV varnishes can start at surface temperatures >120 – 140 °C, depending on the varnish formulation and exposure time. This means that while the adhesives can be used at higher temperatures (170 – 190 °C), the film surface must not be exposed to these temperatures directly. Due to heat transfer mechanisms (conduction and to some extent convection), the actual film temperature is typically ~ 20 – 60 °C lower than the adhesive temperature, depending on the line speed, contact time and the thermal conductivity of the materials [30]. Thus, when adhesive temperature reaches 180 °C, the film surface typically heats up to ~80 – 120 °C, which is considered a safe range for most UV varnishes.

The optimal range for film during lamination is typically 60 – 100 °C, as this range ensures sufficient flexibility of the film and good contact with the adhesive layer, thereby preventing surface damage. If temperature exceeds ~ 120 °C, the varnish may begin to soften, causing changes in gloss, microcracks or even localized "burning" of the surface, which is considered a critical quality defect. Meanwhile, too low a film temperature (<50 – 60 °C) reduces films ability to adapt to the substrate's microgeometry, increases internal stresses and may impar adhesion [31]. For this reason, some technologies use preheating of the film to ~ 30 – 50 °C to stabilize the process. These temperature differences between adhesive and the film indicate emphasizes the importance of finding the right balance between all of the parameters that impact the final quality of the final piece.

Amount of adhesive and consistency of the dosage are critical factors determining the uniformity of adhesion. Amount of EVA adhesive applied in lamination processes typically range from 60 to 120 g/m^2, with the optimal range in most cases being 80 – 100 g/m^2, depending on the film type and surface structure [34]. A lower amount (<60 g/m^2) may result in insufficient contact area and reduce adhesive strength, while a higher amount (> 120 g/m^2) may cause excessive penetration into a substrate and reduce the effective adhesive layer thickness. Dosing accuracy should be maintained within ± 5%, as uneven adhesive distribution can create local areas of weak bonding, which later manifests as delamination or edge lifting [35].

Open time and setting time parameters also have a significant impact on quality, open time range for EVA adhesives is typically 5 – 20 seconds, depending on the formulation and working temperature; however the effective contact time during the lamination process is usually much shorter, 1 – 3 seconds, so it is essential to ensure that adhesive still remains sufficiently tacky until the moment of pressing [35, 36]. If open time window is too short due to low temperature or longer transportation time, the adhesive begins to set before the contact with the substrate, thus resulting in poor adhesion. On the other hand, an excessively long open time window can reduce process stability and increase the risk of film displacement. Critical ranges of thermal and adhesion parameters are shown in Appendix 3 [34, 36].

1.5. Adhesive Bond Formation Mechanisms

The formation of adhesion bonds during the decorative film lamination process is the result of complex physical and chemical reactions between three main components: the substrate (MDF or MDP board), the adhesive and the film. This process is not just an instantaneous sticking of the film but a multistage reaction that involves surface energy, adhesive rheology, diffusion, mechanical interlocking and chemical bonding [37]. The strength of this adhesive layer in this type of furniture is critical as this adhesive joint ensures not only the aesthetic integrity of the surface but also long-term resistance to environmental influences and mechanical loads. Scientific literature emphasizes that adhesion is interdisciplinary phenomenon in which several different mechanisms work together simultaneously, and the final quality of the adhesive bond depends on their combination. The formation of adhesive layer during lamination process begins with the formation of an adhesive layer and its interaction with the substrate and the film – this process is governed by surface energy, the rheological properties and molecular interactions [38, 39].

The first critical stage is wetting of the substrate, during this process the melted adhesive spreads across the substrate and fills all of micro irregularities. Wetting efficiency is characterised by the contact angle (symbol θ_C) – the smaller the angle, the better the wetting and the larger the effective

contact area between the adhesive and the surface, visual representation of this process is shown in Fig. 7. This process is described by Young – Dupré equation, which relates the surface energies between the three phases (solid, liquid, gas) [27, 37]. Young equation defines the relationship between the contact angle (θ) and surface energies, while Dupré's work of adhesion describes the energy required to separate two phases. Mathematically, the work of adhesion can be expressed as:

$$\gamma_{LG}(1 + cos\theta_C) = \Delta W_{SLG}, \quad (2)$$

where: ΔW_{SLG} is the solid – liquid adhesion energy per unit area when in the medium gas / vapor phase; γ_{LG} is the surface tension of the liquid; θ_C is the contact angle of the liquid on the solid.

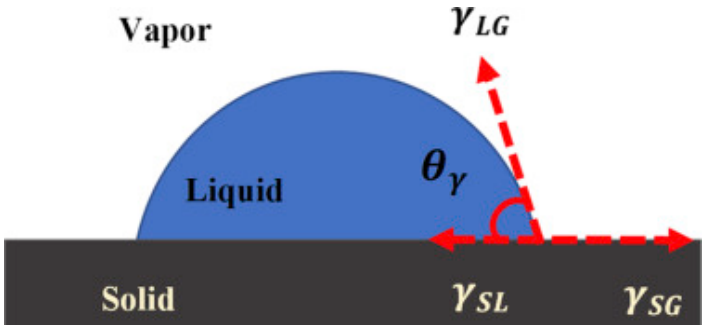


Fig. 7. Visual Explanation of Young - Dupré Equation [40]

In practical terms, the higher the surface energy of the substrate and the lower the surface tension of the adhesive, the better the wetting and the greater the bonding potential. If the surface tension of the adhesive is lower than the surface energy of the substrate, the adhesive can spread spontaneously and form a stable contact. In the case of MDF and MDP, the capillary penetration additionally occurs due to the porous structure, which depends on the difference between the adhesive's viscosity and surface energy [39]. If the contact angle is small, close to 0º, the adhesive spreads out as much as possible and forms a large effective contact area, which is a necessary condition for further adhesion mechanisms. If wetting does not occur, even strong chemical or physical interactions cannot fully take place due to the limited contact area. Therefore, the Young – Dupré model serves as a fundamental basis for explaining why surface preparation and energy compatibility are critical in the lamination process. At this stage an initial adhesive layer is formed, which determines the effectiveness of subsequent bonding mechanisms, as seen in Fig. 8.

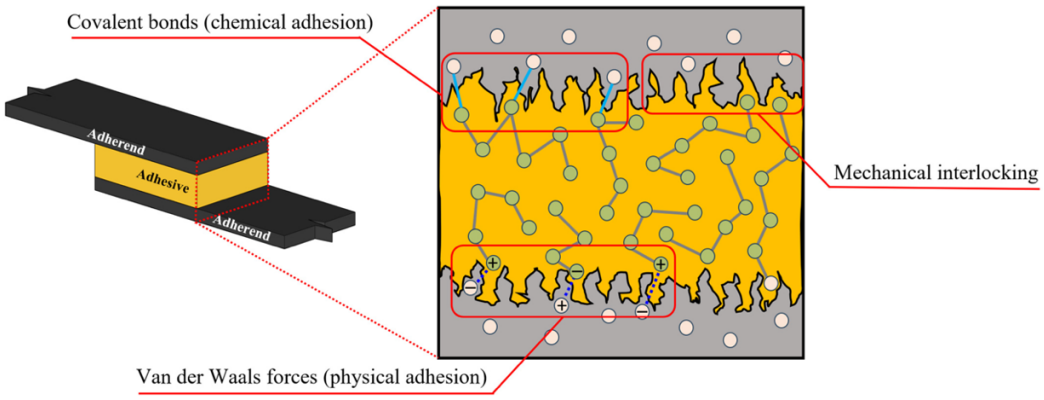


Fig. 8. Adhesion Mechanisms [41]

The second stage involves physical bonding between the three main components; this second stage is governed by van der Waals interaction. Van der Waals interactions are weak intermolecular forces, which are caused by momentary fluctuations in the distribution of electrons within atoms and molecules. Although molecules are generally neutral, electrons within them are constantly moving leading to a slight, temporary charge imbalance: one part of the molecule becomes slightly positive, the other slightly negative [37]. These temporary dipoles can induce similar changes in neighbouring molecules, thus resulting in a weak attractive force between them (London dispersion forces), in addition there are permanent dipole – dipole interactions between polar molecules and induced dipoles. The energy of each individual interaction is relatively small about 0,1 – 10 kJ/mol, but their sum over a large contact area can generate a significant adhesive strength. The strength of these forces depends heavily on the distance" while they are effective on the nanometer scale (~0,3 – 0,5 nm), they are not effective in the larger distances, which is why the contact between the adhesive and the surface is essential for good adhesion [39]. This is the reason why wetting of the substrate is critical, the larger the effective contact area, the more van der Waals interactions can form. If the surface is not sufficiently wetted or is uneven at the micro scale, the contact area decreases and with it, the overall physical adhesion. This mechanism is dominant in the case of thermoplastic adhesives, ethylene vinyl acetate (EVA), and low surface energy films where chemical reactivity is limited.

The third mechanism is mechanical interlocking, which is particularly important in porous structures such as MDF and MDP. At this stage, the adhesive penetrates the micro- and mesoporous structures of the board surface and upon curing creates a physical "anchoring" effect. From a mechanical perspective this can be interpreted as a microscopic "lock – and – key" principle, where the adhesives' polymeric structure fills the substrates' irregularities, thereby increasing resistance to shear and peel loads [38]. If there were no mechanical interlocking, the adhesive joint would rely solely on van der Waals or chemical interactions, which may be insufficient in rough and low energy surfaces. In practice, this would mean that even with good wetting of the surface, the joint would be more sensitive to mechanical stress and would delaminate more easily. However, this mechanism is optimal only at a certain level of penetration: too little penetration does not create sufficient mechanical locking, while too much reduces the thickness of the adhesive layer in the contact zone and weakens the overall adhesion. The depth of penetration depends on the adhesive viscosity, temperature and the density and porosity of the substrate.

The fourth and the most complex bonding mechanism is chemical bonding, this mechanism is show in Fig. 9, which forms through covalent or strong polar bonds between the adhesive and the surface molecules. In the case of polyurethane reactive (PUR) adhesives, the primary mechanism is the reaction between the isocyanate groups (-NCO-) and the hydroxyl groups (-OH) that are both found in wood components and in ambient moisture [22]. During this reaction, urethane bonds (-NH-CO-O-) are formed, they are covalent and characterised by high bond strength, ~200 – 400 kJ/mol, which is significantly greater than van der Waals interactions. During the curing of PUR adhesives, a three – dimensional crosslinked polymer network forms, which imparts thermosetting properties to bond – resistance to temperature, moisture and chemical exposure. Covalent bonds are particularly important for long- term bond stability, as they are not that easily broken under mechanical or thermal stress, but their formation depends on environmental conditions, particularly humidity, which initiates the reaction. Meanwhile, EVA adhesives are thermoplastic, and their adhesion is primarily based on physical interactions. In EVA polymers there are vinyl acetate segments with carboxyl ester groups (-COO-), which interact with carboxyl groups on the substrate via dipole interactions or hydrogen

bonds. For example, hydroxyl groups that are present in wood – based panels can form hydrogen bonds with EVA ester groups, which enhance adhesion, although they are not covalent bonds [22]. The energy of these interactions is lower, ~10 – 40 kJ/mol, than covalent bonds but they still contribute significantly to the overall bond strength, especially if good surface contact is ensured. The main difference between PUR and EVA systems is that EVA adhesives do not form a three – dimensional network structure, so the adhesion remains dependent on temperature – as temperature rises, the adhesive layer softens, which can reduce its load-bearing capacity [43]. PUR adhesives form a stable network after the curing that retains its mechanical properties even at higher temperatures. As a result, EVA adhesive glue systems are more sensitive to long – term environmental effects, particularly temperature cycles, which can cause the adhesive joints to loosen and lead to delayed delamination.

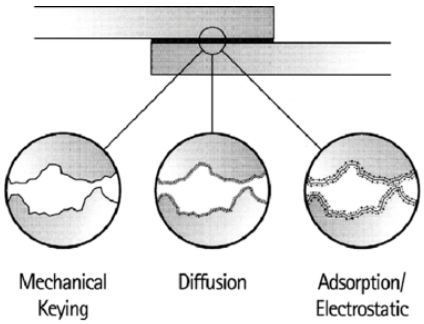


Fig. 9. Chemical Adhesion Mechanism [42]

When evaluating the adhesion between the panel and the film the significance of the chemical mechanism also depends on the type of film used. PP films are low in surface energy and have limited chemical reactivity, so chemical adhesion with EVA adhesives is weak and physical interactions and mechanical interlocking play the primary role. In cases like this, surface activation methods are used to increase surface energy and improve adhesion. On the other hand, paper (cellulose) films contain hydroxyl groups, which allow them to form stronger polymeric interactions with EVA and even participate in chemical reactions with PUR adhesives, thus resulting in better adhesion and greater stability. This would explain why paper films often exhibit more stable adhesion than low surface energy plastics, provided the process is properly controlled [44].

1.6. Chapter Summary

The first chapter analyses the importance of film laminated panels in the production of ready to assemble furniture and the key factors determining the consistency of the final products quality. It examines the structure of MDF and MDP panels, their physical and mechanical properties, surface characteristics and sensitivity to ambient humidity are discussed, as these factors directly affect adhesive distribution, bond strength and the long-term stability of the laminated surface. It also examines the decorative film lamination process, in which quality is determined by interrelated environmental, material and technological parameters such as temperature, relative humidity, adhesive amount, line speed, pressure and contact time [16, 43] The chapter emphasizes that adhesion of the film is due to physical and chemical interactions between film, adhesive and the panel. therefore, the quality stability of film coated panels must be evaluated as a complex process in which fluctuations in individual parameters can lead to surface defects, edge delamination or long-term loss of adhesion.

2. Quality Stability of Film Laminated Panels: Theoretical Analysis and Research Methodology

The inconsistency in the quality of film laminated panels should be viewed not merely as an isolated manufacturing defect but as the result between the technological parameters and the adhesion mechanisms. To assess the quality stability of film laminated panels, it is not sufficient to simply describe the lamination process. Therefore, it is necessary to determine how individual process factors influence defect formation and the reliability of adhesion. Lamination defects, such as: film delamination, air gaps, surface irregularities are rarely the result of a single isolated factor and this is the reason why their causes must be linked to the operation of the entire process system. In a production environment, the quality of adhesion is determined not only by the properties of materials but also how consistently the conditions under which the bond between the panel, adhesive and film forms are controlled. For this reason, further analysis requires a clear methodological framework that allows for the identification of critical parameters, the substantiation of their influence on defect formation and the selection of appropriate quality assessment methods.

2.1. Quality Instability Problem in Film Lamination Process

First chapter presents a comprehensive literature review that examines the mechanisms of bond formation which occurs during the decorative film lamination process, including wetting, physical interactions and mechanical interlocking. But a purely theoretical description of these mechanisms does not explain the real-life quality instability problems that happen under real production processes. Therefore, in this chapter these processes are analysed from an engineering perspective, to help identify the relationship between specific defects and process parameters. In this way, adhesion theory becomes not only a descriptive but also a diagnostic tool for the interpretation of quality fluctuations.

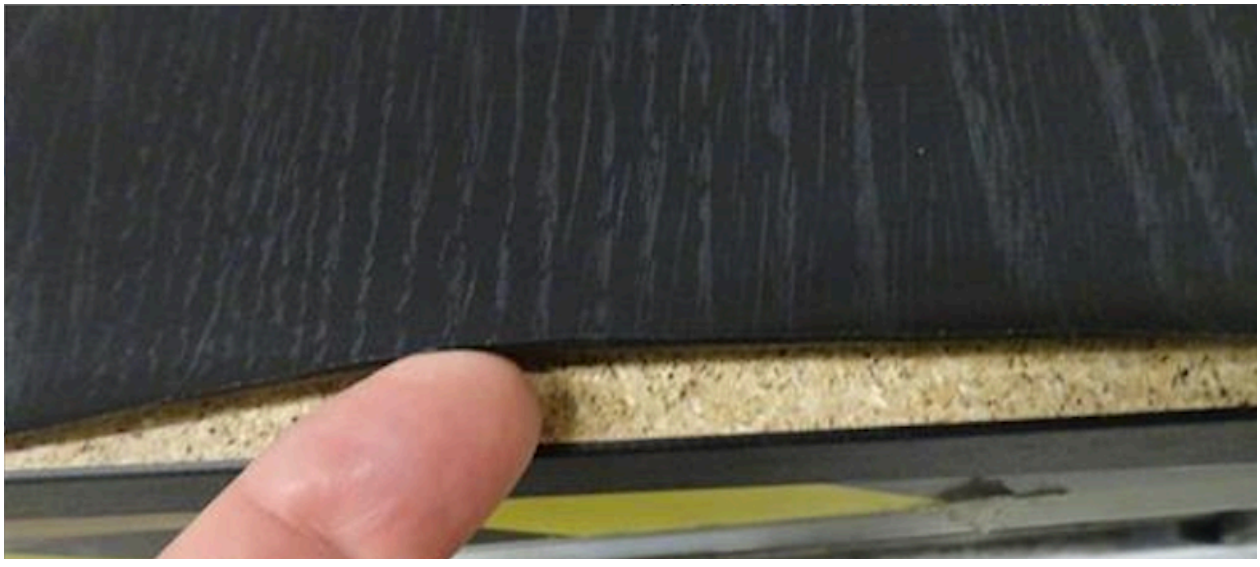


Fig. 10. Edge Delamination

Decorative film lamination process in the manufacturing of RTA furniture is multifactorial technological system, where final quality is determined in short period of time but is influenced by several interrelated physical and rheological factors. Because this process is a multifactorial system quality variability cannot always be attributed to a single isolated factor but must be analysed as a multi parameter system. That is the reason why it is harder to find the root cause of the main occurring

defects and requires a systematic approach to process analysis. Defects are most often observed in practice are: edge delamination, complete surface delamination, formation of air gaps and localized surface defects, as shown in Fig. 10, 11. These defects indicate that adhesion formation is unstable and sensitive process, that react even to minor parameter fluctuations. It is important to understand that the timing of defect formation is not uniform: some defects can be identified immediately after lamination, while others appear in later operations or even in storage, this helps to indicate that this affects not just adhesive deficiencies in initial adhesion but also structural instability of the joint.

Based on theoretical perspective, the formation of adhesion during the lamination process is based on three main mechanisms: surface wetting, physical (which include van der Waals forces) interactions and mechanical interlocking. As talked in the first chapter, wetting defines the adhesive's ability to spread across the surface and establish molecular contact, which is essential for the realization of van der Waals interactions. EVA adhesive systems do not form covalent bonds, so these physical interactions become the primary source of adhesion, so their effectiveness directly depends on the process conditions [22]. Mechanical interlocking completes this process, but the effectiveness also depends on the rheology and the structure of the substrate.



Fig. 11. Complete Surface Delamination

However, in practice, these mechanisms not always function ideally, as they are limited by process and environmental factors. For example, insufficient wetting due to excessive adhesive viscosity or too short contact time can result in inadequate molecular contact, which directly reduces the bond strength. Likewise, excessive penetration of the adhesive into the substrate can reduce the effective surface layer of the adhesive, which limits the strength of physical interactions. These observations indicate that bond quality is a function not just of material properties but also of process parameters [40]. Different defects can be interpreted as the result of disruptions in different adhesion stages, edge delamination is most often associated with insufficient contact time or uneven pressure distribution, whereas air gaps indicate incomplete wetting or uneven adhesive distribution. Surface defects are mostly related to the presence of dust and flake of the panel and indicate cases where bonding mechanisms generally do not occur locally due to a lack of physical contact [35]. Meanwhile,

complete surface delamination is most often the result of systematic process imbalance related to improperly selected thermal or rheological parameters. Equally important factor is the long-term stability of the adhesive bond, which is limited in EVA adhesive systems due to their thermoplastic nature. Temperature fluctuations, the relaxation of internal stresses and differences in material properties can lead to bond degradation even when the initial bond strength is sufficient [41].

In conclusion, it can be stated that the instability of the lamination process is a complex problem arising from insufficiently controlled adhesion mechanisms. This problem is directly linked to impact of process parameters on adhesive rheology, wetting, contact time and heat transfer. Therefore, a theoretical justification of this problem is necessary to identify critical parameters and develop a sound research methodology that allows for the assessment of their impact on the final product quality.

2.2. Identification of Critical Quality Parameters

Based on theoretical principles and the latest scientific research, the stability of the lamination process depends on parameters that control adhesive rheology, heat transfer and the formation of the contact surface. As mentioned in literature before, the lamination processes are highly sensitive to even small fluctuations in process parameters, as adhesion forms over a short period of time and is strongly dependent on kinetic factors [42].

Parameters that affect the lamination quality are divided into environmental and process groups, but their influence is not equivalent. Environmental parameters such as temperature and relative humidity affect the properties of the panels, including moisture content of the board, dimensional stability and surface energy. In recent studies there have been an indication that changes in moisture content of wood composites can significantly affect their mechanical properties and interaction with adhesives [43]. But, when these parameters are kept stable, their influence becomes secondary compared to process parameters, which directly determines the conditions for bond formation. Process parameters are the primary source of quality variation in the lamination process, as they directly affect the properties of adhesive and its interaction with the panel. The importance of these parameters is based on the fact that they shape the adhesive viscosity, wetting efficiency and contact time – the three main factors in bond formation. Literature analysis show that the performance of hot melt adhesives is highly sensitive to temperature, as changes in viscosity can be exponential [37], which directly affects their ability to wet the surface [44]. Adhesive temperature is one of the most important factors, as it controls the adhesives rheology and its ability to spread over the substrate. If the temperature is too low, the adhesive remains too viscous thus preventing the formation of a sufficient contact area. On the other hand, excessively high temperatures can cause adhesive degradation, reduce its mechanical strength. Also, temperature affects heat transfer to film and panel, which can lead to additional surface defects or internal stresses [45]. Line speed is another parameter that directly defines the kinetics of the lamination process. As speed increases, the contact time between the panel and film decreases, thereby reducing the possibility of fully realizing the wetting and adhesion mechanisms. Studies show that contact time is a critical factor in lamination process, as insufficient time prevents the formation of a stable bond, even if the adhesive properties are optimal [46]. This means that line speed must be evaluated not only as an indicator of productivity but also as a parameter which helps to determine quality. The amount of adhesive applied determines the thickness of adhesive layer and the depth to which it penetrates the panel. Recent studies have showed that the thickness of the adhesive layer has a direct impact on bond strength, as too thin of a layer cannot ensure efficient contact, while a layer

too thick can lead to inefficient heat transfer, indentations and uneven bonding [46]. This helps to indicate that the amount of glue must be optimized in relation to other parameters, like line speed and temperature. And lastly, surface cleanliness is another important factor which has direct impact on the aesthetic quality of the manufactured piece. Studies show that surface contamination can significantly reduce bond strength due to reduces effective contact area and disrupted molecular interactions [47].

2.3. Theoretical Analysis of Process Parameter Influence

The influence of process parameters on quality is described through a model of energy transfer and material interaction. The temperature of adhesive determines the rheological state, which defines adhesive's ability to spread out and form a molecular contact with the panel surface. That is why adhesive temperature is one of the most critical parameters that directly influence mechanisms of bond formation through changes in adhesive's rheological properties. EVA adhesives are characterised by strong temperature dependence of viscosity, which can be described by an Arrhenius equation, where viscosity decreases exponentially as temperature increases:

$$\eta = \eta_0 \cdot e^{\frac{E_a}{RT}}, \tag{3}$$

where: η is viscosity, Pa·s; η_0 is material constant; E_a is activation energy, J/mol; R is gas constant, 8,314 J/mol·K; T is temperature, K.

This equation shows that when temperature increases the viscosity exponentially decreases, so the adhesive becomes sticky and can more effectively spread through the surface. But too high of a temperature can lower adhesives molecular mass and reduce mechanical properties. The optimal temperature range for EVA adhesives is 160 -200 °C, this temperature interval allows the adhesive to achieve a viscosity of ~5000 – 20000 mPas·, that allows it to effectively fill the microstructure of the panel, whereas lower temperatures, higher viscosity limits the wetting and at higher temperatures, the risk of adhesive degradation and uncontrolled penetration increases [48]. Too low temperatures limit the contact surface, and the adhesive cannot spread properly through the surface, while also not forming the required surface area, thus resulting in weak van der Waals interactions and poor adhesion. On the other hand, when temperature is higher than 200 °C thermo – oxidative degradation begins, thus reducing the length of the molecular chain and the strength of the adhesive bond. Wetting process can also be described quantitatively through contact angle, which has to be lower than 90º, to get effective wetting process. If wetting is not sufficient, a discrete contact forms between the surfaces, which is directly linked to the risk of delamination. Therefore, temperature fluctuations determine not just instantaneous adhesion changes but also long-term instability of the connection.

Furthermore, line speed introduces a time dimension into the process, which is critical for the realization of adhesion mechanisms, it also introduces contact time, which is important for adhesive mechanism implementation. Contact time can be calculated through formula No. 1, as shown in previous chapter. When line speed is higher than 30 m/min, contact time decreases below a critical threshold (~ 0,5s), where the adhesive does not have enough time to spread out and form sufficient contact. This results in incomplete bonding between the panel and the film, which manifests as delamination at the edges or air gaps. Furthermore, a short contact time limits the formation of mechanical interlocking, as the adhesive does not have enough time to penetrate the panels microstructure. When the line speed is too low (<10 m/min), the opposite effect occurs, excessive

adhesive penetration can happen, which would reduce the surface adhesion. That is why, the line speed must be optimized in conjunction with the adhesive temperature to ensure sufficient time for the bonding mechanisms to take effect.

Amount of adhesive applied determines the thickness of adhesive layer, which directly defines mechanical interlocking, formation of the contact area between film and the panel. Typical amount of glue in lamination process ranges from 20 to 40 g/m^3, which corresponds to layer thickness of about 50 – 150 µm, depending on the density of the adhesive. Amount lower than 20 g/m^3, produces pieces with incomplete surface coverage, thus resulting in delamination and dry spots. On the other hand, when adhesive amount is higher than 40 g/m^3, the adhesive penetrates too deeply into the panels porous structure, reducing the effective surface adhesive layer. Mechanical bonding in this context depends on the adhesives ability to fill micro irregularities of the panel and form an "anchor" type structure upon curing. If the layer is too thin, this mechanism is not fully realized and if it is too thick, the adhesive loses stiffness and its load transfer efficiency decreases. Also, uneven adhesive distribution can lead to local stress concentration points, thus the amount of adhesive must be evaluated not just quantitatively but also as a stability parameter.

The properties of the film also play a crucial role in the final quality of adhesion, particularly regarding that they can be sensitive to temperature and mechanical deformation. Thicker films, > 100 µm, exhibit greater stiffness and lower ability to conform to surface irregularities, thus requiring a thicker adhesive layer and a longer contact time. Also, this type of films generates higher internal stresses due to differences in thermal expansion between film and the adhesive, the typical coefficient of thermal expansion for polymers is ~ 50 – 150 · 10^{-6} K^{-1}. If these internal stresses exceed bond strength, delamination occurs through all the surface. This creates a situation where the bond between adhesive and the film becomes the weakest link in the system. Therefore, it is important to coordinate film selection with process parameters to ensure a stable final bond.

2.4. Theoretical Justification of Solutions

Based on the identified critical parameters and their influence on the formation of adhesion mechanisms, the theoretical solution to the problem in this work is based on the principle of process stabilisation, which prioritises the coordination of individual parameters rather than their individual adjustment. This approach allows for a transition from fragmented process control to a systematic one, in which quality stability is understood as the result of repeatable and controllable conditions rather than solely to material properties [49]. The scientific literature analysed emphasises that a reliable adhesive bond is achieved not by maximising individual parameters, but by ensuring a stable process window in which all bonding mechanisms can be fully realized.

The first approach involves defining the process window in terms of adhesive temperature. In this context, temperature is not a variable that needs to be increased or decreased, but rather a limit range, within which the adhesive maintains optimal rheological parameters. Stabilised temperature range allows for the elimination of fluctuations in adhesive viscosity, which are one of the main causes of adhesion variation. It is important to note that UV – coated or paper films, have limited heat resistance, so excessive temperatures can cause surface degradation [50]. Therefore, it is important that the theoretical solution is based on a compromise between sufficient adhesive activation and protection of the film against thermal damage. Such a balance ensures both good adhesion and high surface quality. In recent studies, it has been shown that hot melt adhesive systems have a narrow

processing window, so temperature stability is a critical factor for ensuring consistent bond quality through all of the manufacturing process [37]. Thus, temperature control acts as the primary “anchor” for process stability.

The second solution is based on coordinating the line speed with the dynamics of the adhesive’s state. Unlike in section 2.2., where speed is analysed as an influencing factor, in this context it is treated more as a control mechanism. Line speed has to be selected not just for a maximum throughput but also based on the condition that the adhesive has sufficient time to form adequate contact time before it sets. This means that speed becomes a dependent parameter that has to be coordinated with temperature and adhesive properties, since adhesive bond formation is a kinetic process, it requires sufficient time for the adhesive to spread, wet the surface and form physical interactions that directly impact the adhesive bond quality. Therefore, ensuring contact time is essential for the formation of a stable bond and its absence is one of the main causes of delamination and the theoretical solution is not to optimize the speed but to also synchronize it with the duration of the adhesive’s activity [51].

The third solution is to stabilize the amount of adhesive that is applied, focusing on reducing variation rather than changing the absolute value. In this context, the amount of adhesive acts as an indicator of process stability: fluctuations in it directly translate to irregularities in the contact layer. The thickness of adhesive layer has to be sufficient to ensure continuous contact between the film and the panel but not so excessive as to cause excessive penetration into the substrate or lead to imprints in further manufacturing processes. It is indicated that even with an appropriate average adhesive amount, variation can lead to local adhesion defects. Therefore, the theoretical solution is to ensure not only the appropriate amount but also its reproducibility, which reduces the likelihood of surface defects and local delamination.

An important aspect is the interaction between these parameters. The process cannot be stabilized by isolating just a single parameter. For example, increasing temperature can compensate for excessive speed, but at the same time it destabilizes the adhesive structure or can affect the film surface. For these reasons, the theoretical solution is based on integrated parameter control, in which each parameter has to be analysed as a part of a system. This logic aligns with a modern engineering approach to process optimisation, where priority is given to system stability rather than just an improvement of individual indicators.

In conclusion, it can be stated that the theoretical solution to the problem in this work is based on three principles: the definition of the process window, parameter synchronization and variation reduction. Adhesive temperature, line speed and adhesive amount are three main parameters that have to be controlled as an interrelated system, rather than as independent variables. This approach ensures that bonding mechanisms are implemented consistently, in every production cycle, thereby reducing the likelihood of defects and ensuring uniform quality of the final product.

2.5. Experimental Design

The experimental design of this study is based on an assessment of influence of process parameters on the quality stability of laminated panels, with the aim of identifying relationships between process conditions and final defects. The study was organized to eliminate as many extraneous variables as possible, with the primary focus on controlled process parameters. The test samples used in experiments were cut from the same laminated piece, thus ensuring uniform substrate structure, density and moisture content. Standardized test pieces, measuring 150 x 150 mm, were prepared to

ensure their suitability for thermal testing equipment and the repeatability of the tests. This approach reduces the influence of material variation and increases the reliability of results.

In this research, the following process parameters were selected as the main variables: adhesive temperature, line speed and adhesive application amount. These parameters were systematically varied to assess their influence on bond strength and defect formation. Meanwhile, environmental conditions, temperature (~ 22 °C) and relative humidity (~ 60 %), were kept stable and treated as constant parameters. Two different adhesive application rates were used, 25 g/m^2 and 35g/m^2, to evaluate the effect of adhesive layer thickness on adhesion quality and defect formation. Tests were also conducted using two different decorative films that differed in their technical properties (thickness, surface coating, structure), which allowed for an assessment of the influence of material factors on the process. This experimental design allows for a direct correlation between process parameters and quality indicators and the identification of causal relationships. The evaluated results include both quantitative and qualitative indicators: bond strength, surface integrity, defect topology. This ensures a comprehensive quality assessment that encompasses both the mechanical strength if the joint and the visual quality of the product.

2.5.1. Evaluation Methods

This study applies semi – quantitative and qualitative methods to evaluate adhesion quality, allowing for the assessment of both the adhesion bond strength and the presence of surface defects. Due to equipment limitations, classical instrumental tests (standardized peel test according to ASTM D903 [53]) were not used in this study, therefore, methods were consistent with industrial practice and capable of reliably identifying differences in adhesion between samples were selected. The primary method for adhesion evaluation was the crosscut adhesion test, standardized according to ISO 2409:2020 [54], Paints and varnishes – Cross cut test, as seen in Fig. 12.

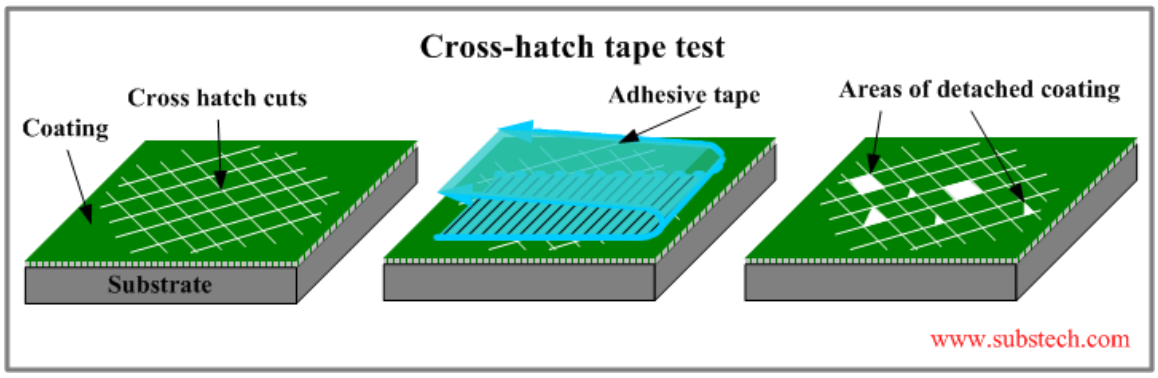


Fig. 12. Cross - Hatch Tape Test [55]

In this method, crosscuts are made on the laminated surface, after which the degree of coating delamination is identified and evaluated according to a defined classification system. This method is widely used to evaluate the adhesion of thin coatings and laminated surfaces, as it allows of weak adhesion zones and the assessment of coating integrity.

Additionally, visual and functional adhesion assessments were performed, which allow for evaluating the films resistance to local delamination and identifying areas of weakened adhesion. Although this method is not strictly standardized, it is widely used in industry as a rapid quality control tool and allows for the effective differentiation of samples based on adhesion quality. Visual inspection was

used to identify surface defects such as air gaps, edge delamination and surface irregularities. Even though this method is not standardized it is important from the customers perspective because the quality of the final product is directly related to the surface appearance.

2.5.2. Thermal Stability Testing

To evaluate adhesion stability at elevated temperatures, an accelerated aging test was performed using a laboratory oven. The standardized samples were exposed to a gradually increasing temperature range: 50 °C, 60 °C and 70 °C, for one hour at each cycle. After these three cycles, the samples were additionally held at 60 °C for 24 hours to assess the long-term effect of thermal loading on adhesion. This multistage method allows not only for identification of critical temperature at which defects begin to form, but also for the assessment of bond stability during prolonged exposure. This method is based on the principles of accelerated aging defined in ISO 9142, Adhesives – Guide to selection of standard laboratory aging conditions [56]. Such tests allow for the evaluation of the adhesive's resistance to temperature effects and the identification of critical conditions under which delamination or other defects may occur. Elevated temperature affects the adhesive in several ways that can influence final quality: it reduces viscosity, promotes the relaxation of internal stresses and may cause softening or partial structural destabilization of the adhesive. This is particularly important, since EVA adhesives are thermoplastic, their mechanical properties are dependent on temperature, therefore, thermal testing is essential to evaluate the stability of the bond under real operating conditions [47].

In addition, thermal stress affects not just the adhesive but the entire laminated system, including the film and the panel. Due to different coefficients of thermal expansion between the film, adhesive and the panel, internal stresses can develop, which is particularly evident at edges or in areas of weaker adhesion. Such stresses can initiate delamination even after the initial adhesion is sufficient. Therefore, thermal test allows to evaluate not just the adhesive properties but also the entire system as a whole and how it is resistance to thermomechanical effects.

After thermal testing, the specimens were evaluated using visual and adhesion tests to identify any defects that could have developed, such as film delamination, formation of air gaps or edge delamination. In this way, this method allows for identification of not only immediate defects but also temperature induced delayed defect that may manifest under real life using conditions.

2.6. Analysis Approach and Approach Logic

This study is based on the analytical logic of establishing a causal relationship between process parameters, the formation of adhesion and the occurrence of final defects. The main analytical model in this work is shown in Fig. 13. This allows systematic identification of which parameters help to determine quality fluctuations and enables a shift from the superficial identification of defects to an analysis of their origin and the formulation of well-founded solutions.

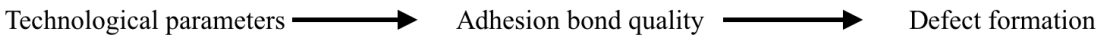


Fig. 13. Analytical Model

In this analysis, each parameter that is studied (adhesive amount, adhesive system and film type) is evaluated based on the influence on the conditions for bond formation, rather than directly on the final result. This means that the primary focus of the research is on intermediate indicators, such as bond integrity, surface contact and defect distribution. This analytical framework makes it easier to distinguish whether a defect is a direct consequence of a parameter or arises from the interaction of multiple factors.

The results obtained are analysed by comparing different combinations of parameters and evaluating their impact on bond stability. Each sample is evaluated according to the same criteria to ensure comparability of results. The analysis employs a comparative model that allows to identify trends, such as whether higher adhesive amount reduces the likelihood of defects, or whether a higher line speed increases the risk of delamination. For result interpretation, it is important to define what results are good and bad, so a good result is considered to be a sample in which the bond is continuous, there is no visible signs of delamination, and the surface remains aesthetically high quality immediately after production and after additional testing. Meanwhile, a bad result is defined as any adhesion defect that results in delamination, air gaps, surface irregularities or dust induced defects. Particular attention is paid to the evaluation of quality stability over time. Stability in this research is defined as the ability to maintain adhesion quality not only after lamination but also after a certain period or additional exposure. Therefore, the analysis clearly distinguishes between immediate results and results after storage and thermal testing. Such a comparison allows for the identification of parameter combinations that ensure not only initial adhesion but also the long-term stability.

An important aspect of the analysis is the evaluation of the interactions between the parameters. Since this process is multidimensional, the impact of individual parameters can vary depending on the values of other parameters. That is why, the analysis aims not only to establish a direct relationship but also to identify the best combinations of parameters that lead to the best and worst results. This approach helps to formulate practical recommendations that are focused on process stabilization.

2.7. Chapter Summary

Chapter 2 addresses the issue of quality inconsistency in film laminated panels and establishes a research methodology that allows for the evaluation of the relationship between lamination defects and technological, material and environmental parameters. In this chapter, quality instability is assessed not as the occurrence of individual defects, but as the result of a multifactorial system in which film delamination, air gaps, surface irregularities and edge delamination cannot be explained solely as isolated defects as their formation depends on the interaction of adhesion mechanisms, rheological properties of the adhesive, contact time, surface preparation and thermal effects. This chapter also outlines a research methodology based on the analysis of production data and laboratory evaluation of adhesion stability. Key critical parameters were identified that have the greatest impact and will be analysed in laboratory testing. Research methodology involves the use of evaluation methods that are close to industrial practice including ISO 2409:2020 cross – cut adhesion test, thermal stability tests accordance with ISO 9142 principles and the assessment of aging effects under controlled environmental conditions. This methodological framework allows for the evaluation not only of the immediate lamination quality after production but also of defects that may manifest later and could be related to internal stresses, thermal effects or insufficient long-term adhesion stability. Overall, the second chapter provides theoretical and methodological foundation for further practical analysis.

3. Project Analysis and Results

Chapter 3 presents a practical assessment of the quality stability of film laminated panels based on actual production data and laboratory testing. As mentioned before, film delamination problem is not related to a single specific parameter, it has to be analysed as a whole system of together interacting technological parameters. The analysis of production data allows for an assessment of how defects are distributed according to part types, adhesive systems, the stage of detection and fluctuations in process parameters. At this stage, it is important to determine not only the overall defect rate but also to distinguish between momentary surface quality defects and potential long term adhesion instability. The practical analysis is supplemented by laboratory adhesion and thermal stability tests, which allow for the influence of different films, adhesive systems and adhesive amounts on the laminated surface's resistance to delamination.

3.1. Experimental Object and Definition of Quality Problem

Experimental part of this study focuses on the quality stability of the lamination process for film laminated components. First important step in manufacturing of RTA furniture is laminating the MDP or MDF panels to the determined size. Films of different colours and technical properties are used in production, but practical production observations have showed that the problem of quality stability is not equal for all films. No systematic adhesion problems were identified for parts that were laminated with white film under normal production conditions, but one of used black films exhibit an increased risk of delamination. The analysed defect occurs at various stages of the product flow: immediately after lamination, during subsequent processes, during storage and after the product reaches the customer. The most critical cases are when the film peels off at customers home, as in such cases the product may have passed internal quality control but failed to withstand transportation, storage or usage conditions. This indicates that it is not sufficient to determine only the current number of defects in production, but it is necessary to evaluate the stability of adhesion over time and resistance to additional stresses. Since, in the analysed case, white film produced under similar conditions does not cause systematic delamination problems, it can be assumed that the defect is related not only to the technological process itself but also to the compatibility of the specific black film with the adhesive system and the range of production parameters. This assumption is further tested by analysing quality indicators and their dependence on process parameters.

Firstly, MDP or MDF board is loaded onto the conveyor and transported to the first step of the line - formatting and profiling. In this step the shape of the board is created, it can be a straight, curved or have a 3D edge. After profiling the board is cleaned and transported to the heating and glue application stage where the board is heated and adhesive is applied through a slot nozzle, process technology for EVA adhesive is shown in Fig. 14. All stages shown in Fig. 14 are critical because EVA adhesives are a thermoplastic system whose properties are highly temperature dependent. Therefore, adhesive temperature is considered in this work to be one of the key process parameters determining quality stability.



Fig. 14. Process Technology for EVA Adhesives

After application of adhesive the foil is pressed on to the surface with the help of calander or roller press system. At this stage, initial contact is established between the film, adhesive and the panel, the adequacy of the contact time and pressing conditions determine whether the adhesive has a sufficient time to wet the surface, fill micro geometric irregularities and form sufficient mechanical interlock. After the pieces are laminated, they are transported to the separation and cutting, where they are cut in the needed size. After cutting there is an automated quality control system, which helps to sort out defective pieces and the process finishes with stacking of the details.

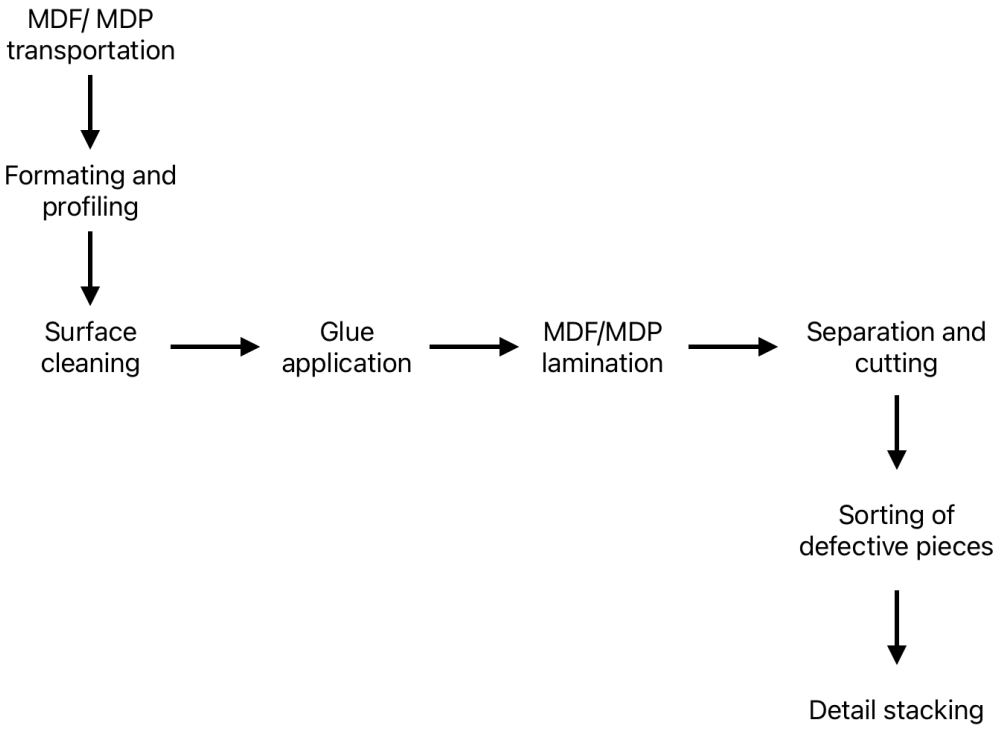


Fig. 15. Process Scheme of Analysed Lamination Line

The lamination process diagram shown in Fig. 15 allows us to identify main technological stages and the flow of materials and energy through the production line. However, this structural representation of the process does not reveal how individual technological parameters interact with each other and how this determines the final product quality. Since the lamination process is a multidimensional process and quality of the final piece is based on the interaction of interrelated parameters, a sequential analysis of the process stages alone is not sufficient to identify the causes of quality variation. For this reason, it is necessary to move from a linear representation of the process to a more systematic approach, in which the process is analysed as a system of interrelated parameters. In this research the primary defect examined is the delamination of the black film from the laminated surface. The defect is classified as critical when the film separates from the entire or nearly the entire surface area. Such delamination differs from local surface defects because it indicates not just one time contamination or isolated mechanical damage but a possible systematic failure of the adhesion mechanism. If the film delaminates across the entire surface area, it is likely that the bond strength was insufficient through the entire adhesive - film interface. For further analysis, it is important to distinguish between immediate and delayed defects: immediate defect is noticeable immediately after lamination or during quality control, while a delayed defect manifests itself in later stages of production, during storage or while customer is already using the product. Delayed film delamination is particularly important in the context of this work, as it indicates that initial adhesion may be

sufficient in the short term but insufficient to ensure long – term stability. For this reason, in Fig. 16 diagram of parameter interactions is provided, illustrating the interrelationships between key technological, material, and environmental parameters and their combined effect on lamination quality.

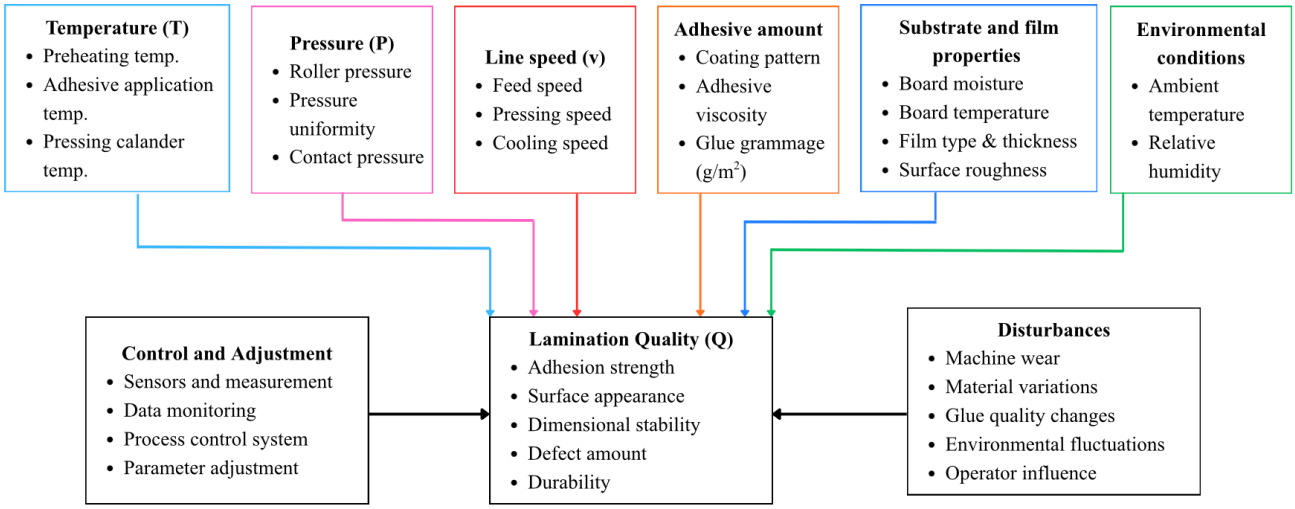


Fig. 16. Parameter Interaction

For this reason, Chapter 3 goes on to evaluate not only the percentage of defective units, but also a broader system of quality indicators. Such evaluation allows to determine not only how many defects occur, but also what types of defects are dominant, at which stage they occur and how they are related to fluctuations in process parameters. White film will be considered a reference case, as it does not cause systematic adhesion problems in production. Meanwhile, the problematic black film is selected as the main object of analysis, as its use specifically reveals the limits of process stability. If different films, produced under similar conditions, result in different defect risks, this indicates that quality stability depends not only on general line parameters but also on the specific properties of the film and its compatibility with the EVA adhesive system.

In production, process parameters are typically controlled through established process intervals, equipment control systems, periodic checks by the operator or quality control personnel. Parameters such as line speed, adhesive temperature, calander temperature, pressure and adhesive quantity are set according to the technical data sheet based on the adhesive, equipment and film parameters, and these parameters are monitored to ensure they do not exceed permissible limits during production process. If a parameter deviates from the set range, the process is adjusted by changing the equipment setting.

3.2. Main Quality Indicators

In order to quantitively asses the stability of the lamination quality of black decorative film, this subsection defines the key quality indicators used for further analysis of production results. Since the main problem in real life production is the delamination of the black film from the surface of the part, all defect data in this study is evaluated only for the black film. As mentioned before, no systematic peeling problems were identified in the production of the white film pieces; therefore, it is not

included in the defect calculations as the primary subject of evaluation at this stage. Main quality indicators will be analysed using a logic provided in Fig. 17.

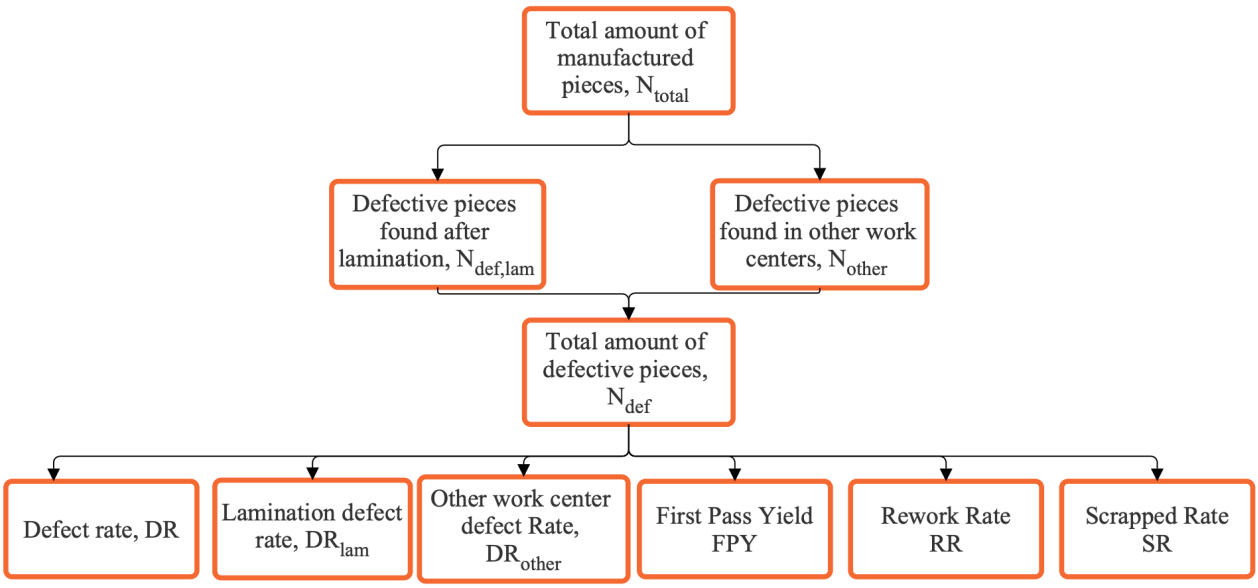


Fig. 17. Flowchart of the Calculation Logic for Key Quality Indicators

During the analysed period, two adhesive systems were used in production – EVA and Hot melt adhesives. Since the initial production data show similar quality results between the adhesive systems, they are evaluated as comparable technological alternatives at this stage. In the subsequent analysis, the adhesive system is used as one of the process factors to determine whether the defect rate depends more on the type of adhesive or on the overall stability of the process parameters. Primary data for calculations are shown in Appendix 4.

The nominal amount of adhesive determined for test pieces is:

$$A_{nom} = 35\ g/m^2 \tag{4}$$

Where: A_{nom} is nominal determined adhesive amount, g/m^2.

Under real life production conditions, adhesive application is not entirely consistent, therefore a permissible tolerance range for adhesive quantity is applied in production:

$$A_{max} = A_{nom} - 2{,}5 \tag{5}$$

$$A_{max} = A_{nom} + 2{,}5 \tag{6}$$

Where: A_{min} is minimum permissible adhesive amount, g/m^2; A_{max} is maximum permissible adhesive amount, g/m^2; A_{nom} is nominal determined adhesive amount, g/m^2.

The general condition for the permissible adhesive amount range is expressed as follows:

$$A_{min} \leqq A_i \leqq A_{max} \tag{7}$$

Where: A_i is the actual amount of adhesive measured in a specific batch or at a specific measurement point, g/m^2.

This criterion is used to determine whether a specific production batch falls within the specified range for adhesive content. If the actual adhesive content is below the lower limit, an insufficient adhesive layer may form, reducing the contact area between the film, adhesive and the pane, thereby increasing the risk of delamination. If actual adhesive context exceeds the upper limit, the likelihood of excessive adhesive penetration into the substrate, adhesive excess or surface defects may increase. Therefore, in this work, not only the average adhesive content is important, but also its deviation from the specified value. Table 2 presents the data received from the company, which was used as the basis for further calculations.

Table 2. Analysed Detail Data

Detail type	Adhesive type	Total manufactured amount, pcs	Defective units, after lamination, pcs	Defective units, in other work centers, pcs
X_1	EVA	13691	27	264
	Hot melt	4586	59	198
	Hot melt	3271	11	59
	Hot melt	6983	17	104
X_2	EVA	14574	42	167
	Hot melt	8150	24	168
	Hot melt	4131	11	87
	Hot melt	7637	26	119
X_3	EVA	18372	94	416
	Hot melt	7496	22	124
	Hot melt	4270	43	207
	Hot melt	7298	25	87

Total number of defective pieces is calculated by adding the defects detected after lamination to the defects detected at other work centers:

$$N_{def} = N_{def,lam} + N_{def,other} \quad (8)$$

Where: N_{def} is total amount of defective pieces, pcs; $N_{def,lam}$ is amount of defective pieces found after lamination, pcs; $N_{def,other}$ is amount of defective pieces found in other work centers, pcs.

3.2.1. Defect Rate Indicators

This classification is important because delamination can be found not just after lamination process but also in other manufacturing processes. If a significant proportion of defects are found in other work centers, this indicates that the problem is related not only to immediate quality of the lamination but also to the long-term stability of the bond and while finding the defected pieces after lamination is important, it is more important to ensure that long-term stability of the laminated piece. That is the reason why it is important to understand and find where the majority of the defected pieces can be found.

The primary quality indicator is the defect rate. It shows what percentage of the manufactured parts were classified as defective:

$$DR = \frac{N_{defect}}{N_{total}} \cdot 100\% \quad (9)$$

Where: DR is defect rate, %; N_{defect} is defective detail amount, pcs; N_{total} is total manufactured pieces, pcs.

$$DR_1 = \frac{264 + 27}{13691} \cdot 100 = 2{,}13\ \%$$

All calculations were done with the data from the first row in Table 3.

The same calculations are done with each produced piece, and further calculations are shown in Table 3. Defect rate allows for determining the overall defect rate for a specific part type, production batch or adhesive system. This indicator is the primary initial indicator for assessing process quality. However, it alone is insufficient for a comprehensive review of process stability, as a similar defect percentage may conceal a different defect structure or a different stage of defect occurrence.

Defect level after lamination reflects current quality of the lamination process. If the calculated indicator is high, defects become visible immediately after lamination. In such cases, the problem may be related to the adhesive application, surface preparation, pressure, temperature settings or line speed. DR_{lam} is calculated:

$$DR_{lam} = \frac{N_{defect,lam}}{N_{total}} \cdot 100\% \quad (10)$$

Where: DR_{lam} is lamination defect rate, %; $N_{def,lam}$ is defective detail amount after lamination, pcs; N_{total} is total manufactured pieces, pcs.

$$DR_{\text{lam}} = \frac{264}{13691} \cdot 100 = 1{,}93\ \%$$

The same calculations are done with each produced piece, and further calculations are shown in Table 3.

Lamination defects, which are found in other work centers defect rate:

$$DR_{other} = \frac{N_{def,other}}{N_{total}} \cdot 100\% \quad (11)$$

Where: DR_{other} is defect rate of other work centers, %; $N_{def,other}$ is defective detail amount found in other work centers, pcs; N_{total} is total manufactured pieces, pcs.

$$DR_{other} = \frac{27}{13691} \cdot 100\% = 0{,}20\ \%$$

The same calculations are done with each produced piece, and further calculations are shown in Table 3. Visual representations of where the defect was found is shown in Fig. 18.

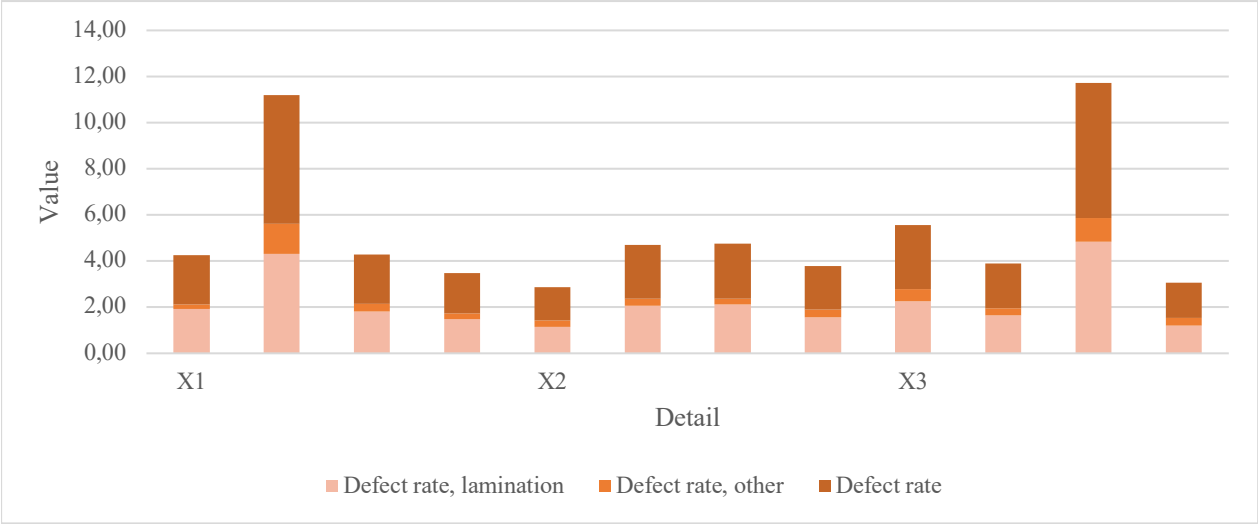


Fig. 18. Defect Rate by Details

The most important interpretation – is that DR_{other} does not mean that the defect was caused by another operation or in another work center. This indicator means that a lamination defect was identified in other work center. This indicator is important for analysis of delayed defects if DR_{other} accounts for a significant portion of the total defects it can be concluded that the initial bond strength may be sufficient for short term stability but insufficient for long – term durability. In such case, the problem may be related to the internal stresses, the properties of the thermoplastic or hot melt adhesive, the stiffness of the film, temperature fluctuations of insufficient compatibility between adhesive and the film.

Table 3. Distribution of Defects by Detection Stage

Detail type	Adhesive type	Defect rate lamination DR_{lam}, %	Defect rate other DR_{other}, %	Defect rate DR, %
X_1	EVA	1,93	0,20	2,13
	Hot melt	**4,32**	1,29	**5,60**
	Hot melt	1,80	0,34	2,14
	Hot melt	1,49	0,24	1,73
X_2	EVA	2,20	0,45	1,43
	Hot melt	2,06	0,29	2,36
	Hot melt	2,11	0,27	2,37
	Hot melt	1,56	0,34	1,90
X_3	EVA	**2,26**	0,51	**2,78**
	Hot melt	1,65	0,29	1,95
	Hot melt	**4,85**	1,01	**5,85**
	Hot melt	1,19	0,34	1,53

3.2.2. First Pass Yield. Rework and Scrap Rate Indicators

The first pass yield (FPY) rate indicates the percentage of production that is manufactured correctly on the first attempt, without requiring additional corrections or being scrapped:

$$FPY = \frac{N_{good}}{N_{total}} \cdot 100\% \quad (12)$$

Where: FPY is first pass yield, %; N_{good} is good detail amount, pcs; N_{total} is total produced amount, pcs.

$$FPY = \frac{13400}{13691} \cdot 100\% = 97{,}87\ \%$$

The same calculations are done with each produced piece, and further calculations are shown in Table 4.

FPY metric is important for assessing process stability because it indicates the processes' ability to produce acceptable parts without additional adjustments and right from the first time. In the start of the production cycle is normal to get a few defected details and almost all of the time they are calculated in the price. This happens because not every production line can start from the first try, also equipment adjustment happens trying to reach the highest needed quality. The higher the FPY, the more stable process. If the FPY decreases, the likelihood of defects, rework or scrap increases.

When some of the defective parts can be repaired the rework rate (RR) is calculated as follows:

$$Rework\ rate = \frac{N_{rework}}{N_{total}} \cdot 100\% \quad (13)$$

Where: Rework rate is how many details can be reworked, %; N_{rework} is reworked detail amount, pcs; N_{total} is total produced amount, pcs.

$$Rework\ rate = \frac{158}{13691} \cdot 100\% = 1{,}15\ \%$$

The same calculations are done with each produced piece, and further calculations are shown in Table 4.

The rework rate allows us to assess the impact of defects on production efficiency. Even if a part is not scrapped, repairing it requires additional labour and resources and can disrupt the production flow. Lamination defected details usually are reworked by using heat to try to adhere the delaminated foil back on to the board. If the adhesion is in full contact after the rework the detail can be brought back to the production cycle and then shipped off to customers. But when a defective part can no longer be repaired it is written off. The scrap rate (SR) is calculated as follows:

$$Scrap\ rate = \frac{N_{scrap}}{N_{total}} \cdot 100\% \quad (14)$$

Where: SR is scrap rate, %; N_{scrap} is scrapped detail amount, pcs; N_{total} is total produced amount, pcs. The scrap rate is an important factor in analysing critical defects.

$$Scrap\ rate = \frac{133}{13691} \cdot 100\% = 0{,}97\ \%$$

Full surface delamination is generally considered a critical defect, as the part loses its aesthetic quality and often can no longer be used for its intended purpose. Scrap rate also includes details with defects that are not okay for the customer, as edge delamination because if the surface is used regularly the foil can delaminate easily from the edges and that would lead to customer complaints. The same calculations are done with each produced piece, and further calculations are shown in Table 4.

Table 4. Calculated Main Parameters

Detail type	Adhesive type	FPY, %	RR, %	SR, %
X_1	EVA	97,87	1,15	0,97
	Hot melt	94,40	1,66	3,95
	Hot melt	97,86	0,58	1,56
	Hot melt	98,27	0,74	0,99
X_2	EVA	98,57	0,60	0,84
	Hot melt	97,64	1,41	0,94
	Hot melt	97,63	1,31	1,07
	Hot melt	98,10	0,89	1,01
X_3	EVA	97,22	0,25	2,53
	Hot melt	98,05	0,85	1,09
	Hot melt	94,15	0,98	4,87
	Hot melt	98,47	0,19	1,34

3.2.3. Calculation of Statistical Indicators

In this study, the arithmetic mean, standard deviation, and coefficient of variation are calculated not based on the number of raw, defective, reworked, or good parts, but rather based on the calculated quality indicators expressed as percentages. This approach is used because the production volume of different production lines is not uniform. A larger batch may naturally contain more defective units, but its defect percentage may be lower than that of a smaller batch. To compare process metrics across different parts, adhesive systems, and production batches, the arithmetic mean is calculated:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{15}$$

Where: $\bar{x}$ is the arithmetic mean of the indicator under analysis; n is analysed means number; i is the serial number of a specific observation.

The arithmetic mean indicates the overall level of the indicator but does not reveal the stability of the process. Two or two adhesive systems can have a similar defect rate, but in one system defects may be distributed evenly, while other may fluctuate heavily through batches. That is why it is important to calculate standard deviation:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{16}$$

Where: s is standard deviation; x_i is the value of a specific batch or detail; $\bar{x}$ is the arithmetic mean of the indicator under analysis; n is analysed means number; i is the serial number of a specific observation.

Standard deviation shows how much individual values vary from the arithmetic mean. A lower standard deviation indicates a more stable process, while a higher one indicates greater process

variation. This metric is important in cases where the average defect rate is similar across different parts or adhesive systems.

To assess the relative variability of the process, the coefficient of variation is calculated:

$$CV = \frac{s}{\bar{x}} \cdot 100\% \quad (17)$$

Where; CV is variation coefficient, %; s is standard deviation; $\bar{x}$ is arithmetic mean of the indicator under analysis.

The coefficient of variation allows for a comparison of the variability of different indicators or different components even when their mean values differ. This indicator is particularly useful in this study because the raw data show that the average defect rate for different parts and different adhesive systems is similar. In such a case, it is not only the average value that matters, but also the stability of the process.

Since the sizes of the batches under analysis vary, a weighted indicator is additionally calculated for the overall production result. Weighted indicators provide a more accurate picture of the overall level of production quality, as they consider the varying sizes of batches. The weighted defect rate is calculated as follows:

$$DR_{weighted} = \frac{\sum N_{def}}{\sum N_{total}} \cdot 100\ \% \quad (18)$$

Where: $DR_{weighted}$ is weighted defect level, %; N_{def} is all of the defected pieces, pcs; N_{total} is all manufactured pieces.

All calculated statistical indicators are shown in Table 5, 6 and 7.

Tables 3 and 4 shows that the overall defect rate is not evenly distributed across the different combinations of parts and process parameters, indicating a significant influence in both material selection and process related factors on production quality. The obtained results demonstrate that the interaction between adhesive type and manufacturing conditions has a direct impact on the stability and consistency of the production process. The lowest overall defect rate was found for detail X_2 with EVA combination reaching only 1,43 %, which could indicate a comparatively stable and well controlled production configuration. While the highest defect rates were recorded in hot melt adhesive combinations, particularly for part X_1 and X_3, where the total defect rates increased to 5,6 % and 5,85 % respectively. This could suggest that certain hot melt adhesive applications could be more sensitive to process variations and operational inconsistencies. But higher defect rates were also identified in some EVA based configurations, for example detail X_3 with EVA adhesive showed a relatively high total defect rate of 2,78%, compared with considerably lower value obtained for detail X_2 with the same adhesive system. It is important to note that some hot melt combinations demonstrated comparatively low defect level, such as detail X_3 with total defect rate of 1,53 % and detail X_1 with 1,73 %. This proves that the quality stability depends not on a single parameter, but on the interaction of several factors. The statistical parameters for the overall quality indicators are presented in Table 5. The arithmetic mean represents the average value of the indicator across all experimental observations, while the standard deviation indicates the spread of the measured values and the variation coefficient reflects the relative variability of the process. In addition, the coefficient of variation was used to assess the relative stability of different adhesive-detail combinations and to

evaluate the consistency of manufacturing performance under varying manufacturing conditions. Lower coefficient of variation values indicate more stable and predictable process behavior, whereas higher values suggest increased variability and reduced process control.

Table 5. Standard Indicator Calculation Based on Detail Type

	Average mean $\bar{x}$	**Standard deviation s, %**	**Variation coefficient CV, %**	**Weighted value**
Defect rate lamination DR_{lam}, %	2,20	1,17	53,32	1,99
Defect rate other DR_{other}, %	0,45	0,34	75,27	0,40
Defect rate DR, %	2,65	1,49	56,17	2,39
First Pass Yield FPY, %	97,35	1,49	1,53	97,61
Rework RR, %	0,89	0,45	50,67	0,79
Scrapped SR, %	1,76	1,33	75,50	1,60

Based on Table 5, the overall weighted defect rate is 2,39 % while, the weighted first pass yield is 97,61 %. This means that most black laminated parts are produced correctly on the first attempt. The highest coefficient of variation was found for SR indicator – 75,50 % and DR_{other} – 75,27 %. This indicates that the scrap rate and the level of lamination defects detected at other work centers vary the most across individual production lines. This result is significant because some lamination defects do not become apparent immediately after lamination, but only later. Such defects may be related to insufficient long – term adhesion stability of the film. The variation coefficient for the overall DR is 56,17 % so the process cannot be considered fully stable. The average defect percentage describes the overall quality level but does not reveal which part types or adhesive system combinations are the most sensitive, an additional comparison of results by adhesive system and part type is performed. A comparison of adhesive systems is presented in Table 6.

Table 6. Comparison of Adhesive Systems

Adhesive Type	**EVA**	**Hot Melt**
No. of observations	3	9
Weighted DR_{lam}, %	1,82	2,14
Weighted DR_{other}, %	0,35	0,44
Weighted DR, %	2,17	2,58
Weighted FPY, %	97,83	97,42
Weighted RR, %	0,62	0,94
Weighted SR, %	1,54	1,65

Based on the Table 6, the overall defect rate for EVA adhesive system is 2,17 %, while Hot melt adhesive system is 2,58%. Based on this indicator, the EVA system shows a better overall result. In this case EVA has lower defect rate after lamination, in other work centers and also higher FPY rate was observed. However, this difference cannot be interpreted as conclusive proof that the adhesive

system is the primary cause of defects. The sample size for the EVA data is smaller than just three observations, while for the Hot Melt system it was nine observations. Also, for Hot Melt system showed inconsistent results across production: in some cases, the defect rate was lower while in others it was higher. This helps us to indicate that adhesive systems interact with other technological parameters to create the highest quality.

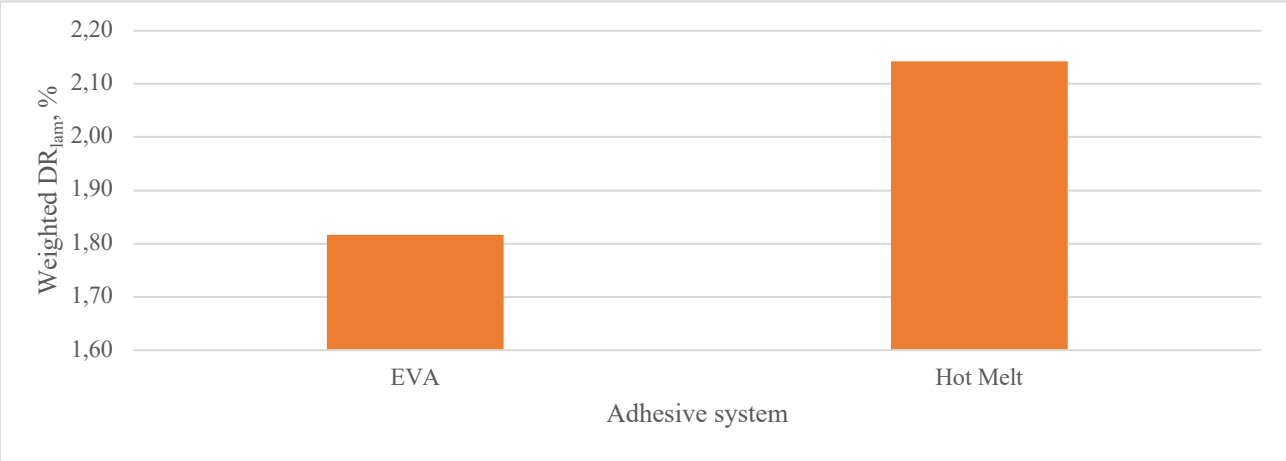


Fig. 19. Weighted DR_{lam} Comparison by Adhesive System

When comparing the stage at which the defects appear, it is evident that the DR_{lam} and DR_{other} is lower for EVA than for Hot melt adhesive system, as seen in Fig. 19, but DR_{other} is very similar to Hot Melt adhesive system. This could suggest that some defects in both adhesive systems may not be detected immediately after lamination but later at other work centers. However, due to the smaller number of observations for EVA this interpretation should be treated with caution.

A comparison of quality indicators by part type is presented in Table 7.

Table 7. Comparison of Quality Indicators by Part Type

Detail Type	**X_1**	**X_2**	**X_3**
No. of observations	4	4	4
Weighted DR_{lam}, %	2,38	1,72	2,49
Weighted DR_{other},%	0,52	0,30	0,54
Weighted DR, %	2,90	2,02	3,03
Weighted FPY, %	97,10	97,98	96,97

Based on Table 7, the most stable result was seen in X_2 pieces. The overall weighted DR for these parts is 1,87 % and the FPY is 98,13 %. For X_1 parts the overall weighted DR increases to 2,59 % and for X_3 parts to 2,72 %. This indicates that the part type influences the stability of the lamination process quality. X_3 parts exhibit the highest overall defect rate and the highest scrap rate. For X_3, SR reaches 2,28%, which is a higher value than for X_1 and X_2 parts. This suggests that X_3 parts are more susceptible to critical defects or that defects in these parts more often results in scrap than rework. This interpretation has to be verified through an analysis of technological parameters and laboratory testing. The X_2 parts show the best weighted FPY and the lowest overall defect rate. This suggests that the X_2 parts were manufactured under more stable conditions during the analysed period and process settings were more suitable to black film adhesion.

The structure of defect detection stages is presented in Table 8.

Table 8. Defect Detection Stage

Defect detection state	Amount of defected details	% from all wrapped details	% from manufactured amount
After wrapping	2000	83,30	1,99
Other work centers	401	16,70	0,40
Overall:	2401	100,00	2,39

According to Table 8, most lamination defects – 83,30 % are determined immediately after lamination. This helps to indicate that most defects form or become visible during the initial stage of the process. However, 16,70 % of defects are detected only at a subsequent work center. This proportion is significant because it shows that not all lamination defects are identified immediately after lamination. Some defects become apparent later, as the part moves through subsequent production stages, undergoes additional handling, comes into contact with equipment or is affected by short-term storage. The weighted DR after lamination after lamination is 1,99 %, while the rate of lamination defects detected at other work centers is 0,40 %. This means that the primary inspection point remains immediately after lamination; however, this inspection alone is insufficient as some defects are detected later. This result justifies the need to evaluate the stability of film adhesion not just after immediate lamination process but also in subsequent production stages.

In summary, it can be stated that the quality indicators calculated in Section 3.2 allows for a quantitative assessment of the quality level of the black film lamination process. The overall weighted defect rate is 2,39 % and the weighted FPY is 97,61 %. Although most defects are detected immediately after lamination, a significant portion of them is identified only at subsequent work centers. These results shot that most of the output is produced correctly the first time, but the process is still subject to fluctuations in quality. The greatest relative variation was observed in the scrap rate and the level of laminating defects detected at other work centers. This indicates that although the overall defect level is not very high, the consequences of defects can be significant in further production lines. The DR_{other} indicator is particularly important, as it reflects later-detected lamination defects that are be related to delayed film adhesion instability. A comparison of adhesive systems showed that the EVA system performs slightly better than the Hot Melt system based on weighted indicators. However, due to the varying number of observations and inconsistent results across individual production lines, the adhesive system cannot be considered the sole cause of quality differences. An analysis of part types showed that X_2 parts exhibit the most stable overall results, while X_3 parts exhibit the highest overall defect and scrap rates. This suggests that the part type and the associated production conditions influence the stability of film adhesion.

3.3. Quality Indicator Dependence on Parameter Fluctuation

This section analyses how the quality indicators of black film lamination vary depending on the main process parameters: adhesive system, actual adhesive amount, adhesive distribution between the top and bottom surfaces of the parts, adhesive temperature, calander temperature, line speed and pressure setting. The analysis was performed using the quality indicators defined and calculated in section 3.2: defect rate after lamination and in other work centers (DR_{lam} and DR_{other}), the total defect level DR, first pass yield FPY, the rework rate (RR), and the scrap rate (SR). It is important to note that defects

recorded at other work centers are not interpreted in this study as defects resulting from drilling, cutting or other subsequent operations. The analysis includes only those defects that are related to the lamination process but were detected later, after the part had already moved on to the next stage of production. Therefore, the DR_{other} indicator in this study does not reflect defects that are caused by another work center, but rather lamination defects identified at a later stage.

The purpose of the analysis is to determine not only which parameter has the strongest correlation with the defect rate, but also whether the process parameters remain sufficiently stable to ensure consistent lamination quality. Since the lamination process is multifactorial, the influence of individual parameters are assessed as a trend rather than a clear causal relationship. Such assessment is necessary because the same defect level can result from different combinations of parameters.

3.3.1. Preparation of Technical Parameters for Analysis

Since the amount of adhesive is recorded separately on both top and bottom sides of the part, it is necessary to calculate the average value that represents the actual amount of adhesive for a specific batch. This approach allows the adhesive distribution across the entire part surface to be evaluated more accurately. The average actual adhesive amount for a specific production run is calculated as follows:

$$A_{avg,i} = \frac{A_{top,i}+A_{bottom,i}}{2} \quad (19)$$

Where: $A_{avg,i}$ is the average actual amount of adhesive used in a specific production run, g/m^2; $A_{top,i}$ is the amount of adhesive physically measured on the top side of the part, g/m^2; $A_{bottom,i}$ is the amount of adhesive physically measured on the top of side of the part, g/m^2.

The average actual amount of adhesive provides a single metric for assessing the overall adhesive application level in a specific production run. This parameter enables a simplified but a reliable assessment of the adhesive coating process. The calculated average is used to determine how closely the actual adhesive amount corresponds to the nominal adhesive quantity defined in the technological specifications and process requirements.

To assess the stability of the adhesive content, the deviation of the actual adhesive content from the nominal value is calculated:

$$\Delta A_i = A_i - A_{nom} \quad (20)$$

Where: ΔA_i is deviation of the actual adhesive quantity from the nominal value, g/m^2; A_i is the actual amount of adhesive in a specific batch or at a specific measurement point, g/m^2; A_{nom} is specified nominal amount of adhesive, g/m^2.

The calculated deviation parameter makes it possible to evaluate whether the adhesive application operates within the desired technological limits. If $\Delta A_i < 0$ the actual adhesive quantity is lower than the nominal value which could indicate insufficient adhesive application. Such condition may lead to incomplete bonding, reduced adhesion strength or local delamination. If $\Delta A_i > 0$ the actual adhesive quantity is higher than the nominal value, which could result in excessive material consumption, uneven adhesive distribution, surface imperfections or undesirable changes in the physical properties of the laminated structure. The magnitude of the deviation is also important for evaluating process repeatability and equipment performance. Smaller deviations indicate a more stable and accurately

controlled process, while larger deviations may reveal inconsistencies that are related to process parameters, temperature fluctuations or adhesive viscosity. That is why the relative deviation in the amount of adhesive is calculated as follows:

$$\Delta A_{rel,i} = \frac{A_i - A_{nom}}{A_{nom}} \cdot 100\% \quad (21)$$

Where: $\Delta A_{rel,i}$ is relative deviation of the actual adhesive quantity from the nominal value, %; A_i is the actual amount of adhesive in a specific batch or at a specific measurement point, g/m^2; A_{nom} is specified nominal amount of adhesive, g/m^2.

These indicators make it possible to determine whether the actual amount of adhesive is close to the specified value and whether it falls within the permissible technical range. The deviation in adhesive content is directly linked to the stability of the bond, as too little adhesive can result in insufficient surface coverage, while too much can lead to an uneven layer, excessive absorption or surface defects. Since the amount of adhesive is recorded on both top and bottom sides of the part, the average actual amount of adhesive for a specific batch is calculated as follows:

$$A_{rel,i} = \frac{A_{avg,i}}{A_{nom}} \cdot 100\% \quad (22)$$

Where: $A_{rel,i}$ is the actual adhesive content, expressed as a percentage of the nominal value, %; $A_{avg,i}$ is the average actual amount of adhesive, g/m^2; A_{nom} is specified nominal amount of adhesive, g/m^2.

This metric provides a single figure that summarizes the actual amount of adhesive in a specific batch, so it can be used to compare different types of parts, adhesive systems, production batches. If $A_{rel,i}$ = 100% actual adhesive amount corresponds to the nominal value, if $A_{rel,i}$ < 100% than it's lower than the nominal value, and if $A_{rel,i}$ > 100% than the actual adhesive amount is higher than the nominal value. To assess the uniformity of adhesive coverage the difference between the top and bottom surfaces of the part is calculated:

$$\Delta A_{side,i} = \left| A_{top,i} - A_{bottom,i} \right| \quad (23)$$

Where: $\Delta A_{side,i}$ is the difference in the amount of adhesive between the top and bottom surfaces of the part, g/m^2; $A_{top,i}$ is the amount of adhesive measured on the top side of the part, g/m^2; $A_{bottom,i}$ is the amount of adhesive measured on the bottom side of the part, g/m^2.

This indicator shows the uniformity of the adhesive coating, and even if the average adhesive amount meets the specified nominal value, a significant difference between the top and bottom sides may indicate uneven adhesive distribution. An uneven adhesive amount can create local areas of weak adhesion, which may later become the starting points for the film to peel off.

In addition, it is assessed whether the actual average amount of adhesive falls within the specified technical range:

$$K_i = \begin{cases} 1, if\ A_{min} \leq A_{avg,i} \leq A_{max} \\ 0, if\ A_{avg,i} < A_{min} or\ A_{avg,i} > A_{max} \end{cases} \quad (24)$$

Where: K_i is an indicator of whether the amount of adhesive falls within the specified range; $A_{avg,i}$ is the average actual amount of adhesive, g/m^2; A_{min} is the minimum permissible adhesive content, g/m^2; A_{max} is the maximum permissible adhesive content, g/m^2.

If $K_i = 1$, factual adhesive amount is considered to fall withing the specified tolerance range and if $K_i = 0$ the factual amount falls outside the specified tolerance range.

To assess process stability statistical indicators of the main technological parameters are calculated and presented in Table 9.

Table 9. Technological Parameter Stability Assessment

Technological parameters	Minimal value	Maximal value	Average mean $\bar{x}$	Standard deviation s, %	Variation coefficient CV, %
Average adhesive amount A_{avg}, g/m²	30	37,55	34,17	2,52	7,38
Adhesive amount difference $\Delta A_{side,i}$, g/m²	0,1	3,8	1,32	1,00	75,80
Adhesive temperature, °C	134	195	175,33	22,97	13,10
Calander temperature, °C	132	200	181,17	24,05	13,27
Pressure, mm	17,3	17,7	17,56	0,14	0,79
Line speed, m/min	35,07	38,255	37,06	0,95	2,56

Table 9 shows that the actual average adhesive amount ranges from 30,00 to 37,55 g/m². This indicates that in the actual production process, the adhesive amount does not always fall within the specified technological range of 35 ± 2,5 g/m². Some production runs fall below the lower limit, while few results exceed the upper limit. The highest relative variation was observed in the difference in adhesive amount between the top and bottom sides of the part CV – 75,80 %. This indicates that the uniformity of adhesive application is one of the most unstable technological aspects. Although the average adhesive amount may be close to the nominal value, uneven adhesive distribution between the sides of the part may increase the risk of local adhesion instability. This result is significant because fluctuations in the amount of adhesive can affect the formation of the contact layer, the penetration of the adhesive into the substrate and the final adhesion of the film. Table 9 shows that the most stable technological parameter, based on the coefficient of variation, is the pressure value, with CV of 0,79%. It shows that calander pressure setting varied little across the production lines analysed. The line speed also exhibits relatively low variation with a CV of 2,56%. This means that, based on the overall range of variation, the line speed was not one of the most variable process parameters. The coefficients of variation for adhesive and calander temperatures are 13,89 % and 11,91 % respectively, but should be interpreted with some caution, because different adhesive systems operate within different temperature ranges, so the temperature spread in this case indicates not only process variation but also a technological difference between the EVA and Hot melt adhesive systems.

3.3.2. The Relationship Between Technical Parameters and Quality Indicators

Correlation analysis is used to assess how fluctuations in technological parameters relate to quality indicators. The correlation coefficient is calculated using the following formula:

$$x_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad (25)$$

Where: x_{xy} is the correlation coefficient between the technological parameter x and the quality indicator y; x_i is the value of a specific technical parameter; y_i is the value of a specific quality parameter; $\bar{x}$ is arithmetic mean of the indicator under analysis; $\bar{y}$ is the arithmetic mean of the quality indicator; n is the amount of observations

Correlation coefficient can range from -1 to 1. A positive correlation indicates that as the value of the technological parameter increases, the value of the quality indicator also increases. A negative correlation indicates that as the value of the technological parameter increases, the value of the quality indicator decreases. Since the number of observations in this study is limited, the correlation results are interpreted as engineering trends rather than as statistically conclusive causal relationships. Parameter correlations are calculated and showed in Table 10.

Table 10. Correlation Indicator Comparison Between Technological Parameters

Technological parameter	**DR_{lam} correlation**	**DR_{other} correlation**	**DR correlation**	**FPY correlation**	**RR correlation**	**SR correlation**
Average adhesive amount A_{avg}, g/m²	0,10	0,00	0,08	-0,08	0,33	-0,03
Difference in adhesive quantity ΔA_{side}, g/m²	0,38	0,57	0,43	-0,43	0,55	0,29
Adhesive temperature, °C	0,22	0,20	0,22	-0,22	0,30	0,14
Calander temperature, °C	0,24	0,21	0,23	-0,23	0,39	0,13
Pressure, mm	0,05	0,04	0,05	-0,05	-0,21	0,13
Line speed, m/min	0,63	0,54	0,62	-0,62	0,43	0,55

According to Table 10, the strongest correlation with quality indicators was found for line speed. The correlation coefficient between line speed and the overall defect rate is 0,62, while the correlation with DR_{lam} is 0,63. This indicates that in the analysed data, higher line speed is associated with a higher defect rate. A negative correlation with FPY of -0,62 was also found, meaning that as line speed increases, the FPY decreases. The difference in adhesive amount between the top and bottom sides of the part ΔA_{side} also has a significant relationship with quality indicators. Its correlation with the lamination defects detected at other workstations, DR_{other} reaches 0,57 and with the overall defect level DR 0,43. This suggests that uneven adhesive distribution may be associated not only with immediate defects but also with those detected later. The correlation between the average adhesive amount A_{avg} and defect indicators is weak, as seen in Fig. 20.

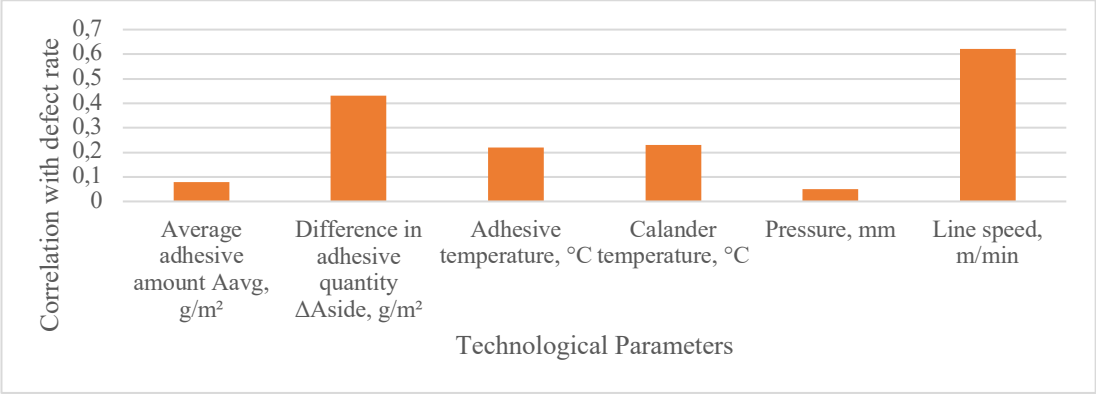


Fig. 20. Correlation of Defect Rate Based on Technological Parameter

This means that the average adhesive amount alone is insufficient to explain fluctuations in the defect level, but this result is methodologically significant: even if the total adhesive amount is close to the nominal value, the quality result may depend on the interaction of adhesive distribution, line speed, temperature and other parameters. The correlation between temperature parameters and defect indicators is weak or moderate. The correlation between adhesive temperature and DR is 0,22, while that between calander temperature and DR is 0,23. These results must be interpreted with caution, as different adhesive systems operate within different temperature ranges. Therefore, the effect of temperature cannot be evaluated in isolation from the adhesive system. The correlation between temperature parameters and defect indicators is moderate. The correlation between adhesive temperature and DR is 0,22, while that of calander temperature is 0,23. These results must be interpreted with caution, as different adhesive systems operate within different temperature ranges. Therefore, the effect of temperature cannot be evaluated in isolation from the adhesive system.

3.3.3. Adhesive Amount Interval Analysis

The nominal adhesive quantity for test pieces is 35 g/m^2 and the permissible tolerance range is ± 2,5 g/m^2. Therefore, the actual average adhesive content is evaluated according to three groups: less than 32,5 g/m^2, from 32,5 to 37,5 g/m^2 and more 37,5 g/m^2.

Table 11. Comparison of Defect Level Based on Adhesive Amount

Average adhesive amount range	**Less than 32,5 g/m^2**	**32,5 - 37,5 g/m^2**	**More than 37,5 g/m^2**
No. of observations	3	8	1
Average DR, %	1,80	3,03	2,13
Weighted DR, %	1,73	2,61	2,13
Weighted FPY, %	98,27	97,39	97,87

Based on Table 11, the lowest weighted overall defect rate was observed in the group where the average adhesive application rate was less than 32 g/m^2. This result can be interpreted as a recommendation to reduce the adhesive application rate below the established lower limit if other technological parameters are within the standard limits. However, this group includes only three observations, so it is not clear if all of the results would be with a low defect rate if more details were analysed. Aso, lower defect rate could have been influenced by other technological parameters, particularly line speed and the uniformity of adhesive distribution. In the 32,5 - 37,5 g/m^2 group, the weighted total defect rate is 2,61 %, but it indicates that simply falling within 35 ± 2,5 g/m^2 range does not account for all quality variations. This result confirms that the amount of adhesive must be evaluated in conjunction with other parameters. It is not only important how much adhesive is applied on average, but also how evenly it is distributed, at what speed the line moves, and what the contact and temperature conditions are. There is only one observation in the group with an interval greater than 37,5 g/m^2, so it cannot be interpreted as a reliable trend. This result can only be used as an isolate case, not as a basis for a technical conclusion.

3.3.4. Analysis of Adhesive Distribution Uniformity

The uniformity of the adhesive coating is assessed based on the difference between the amount of adhesive measured on the top and bottom surfaces of the part.

The results are presented in Table 12.

Table 12. Comparison of Defect Level Based in the Difference in Adhesive Quantity

Difference in adhesive quantity ΔA_{side}, g/m²	**No. of observations**	**Average DR, %**	**Weighted DR, %**	**Weighted DR_{lam}, %**	**Weighted DR_{other}, %**
≤ 1,0 g/m²	7	2,67	2,52	2,11	0,40
More than 1,0 g/m²	5	2,61	2,21	1,82	0,39

Based on Table 12, the overall defect rate is similar between the two groups based on the difference in adhesive content. In the group where ΔA_{side} is ≤ 1,0 g/m² the weighted defect rate is 2,52 %, while in the other group weighted defect rate is slightly lower, at 2,21 %. These results indicate that grouping defects based on the 1,0 g/m² threshold does not reveal a clear trend that a larger difference in adhesive content increases the overall defect rate in all cases. This observation suggests that the relationship between adhesive distribution unevenness and defect formation is more complex than a simple linear dependence. The total defect rate is influenced by multiple technological factors, and as a result local variations in adhesive amount do not always immediately translate into visible defects directly after lamination stage. In some production runs the process may still remain sufficiently stable to compensate for moderate adhesive distribution differences without significantly affecting the immediate quality indicators. However, correlation analysis showed that ΔA_{side} has a moderate positive correlation with the level of lamination defects detected at other work centers, where the correlation coefficient is 0,57. This means that the unevenness of the adhesive distribution may be more significant not for the overall defect level, but for defects that manifest later. From a technological perspective, this result is logically explained by technological parameter and adhesive properties and is consistent with the behaviour of laminated adhesive systems. The obtained results suggest that the uniformity of adhesive distribution should be considered not as a parameter affecting immediate lamination quality but an important predictor of long-term process stability.

3.3.5. Line Speed Analysis

Line speed is one of the most important technological parameters, as it is directly influences to the contact time between the film, the adhesive, and the substrate. The duration of contact time is critical for the development of proper adhesion, as sufficient time is required for the adhesive to wet the surface effectively and form a stable bonding interface. As line speed increases, the part spends less time in the active pressing and contact zone, so the adhesive has less time to wet the surface, fill the microstructure, and form initial adhesion. Also, the adhesive may not fully spread across the surface or achieve the required level of initial adhesion before the part exits the lamination zone. The theoretical analysis presented at previous sections establishes that excessive line speed can increase the risk of incomplete adhesion, air gaps, and film delamination. However, in practical production, line speed does not act in isolation but in conjunction with other parameters: adhesive quantity, adhesive temperature, calander temperature, pressure settings, and part geometry. In this study, the influence of line speed is evaluated based on the speed in meters per minute provided in the production data. In the production runs analyzed, the line speed ranged from 35,07 to 38,25 m/min. Line speed was divided into three intervals to compare changes at low, medium and high production speeds, since an increase in speed directly reduces the contact time between the board, the adhesive

and the film and may increase the risk of insufficient adhesion and delamination. This range is relatively narrow, but some values fall within the high-risk zone defined in the theoretical section, where effective contact time may decrease due to higher speed. The correlation with DR_{lam} reaches 0,63, while total DR is 0,62 and the FPY is -0,62, as seen in Table 13. The impact of line speed on quality indicators was assessed by grouping the data into three speed intervals: up to 35 m/min, from 35 to 37 m/min, and over 37 m/min. The results are presented in Table 13.

Table 13. Comparison of Defect Level Based on the Difference in Line Speed

Line Speed, m/min	**≤ 36,5**	**36,5 - 37,5**	**≥ 37,5**
No. of observations	4	3	5
Average DR_{lam}, %	1,69	1,40	3,08
Weighted DR_{lam}, %	1,61	1,34	2,55
Weighted DR_{other}, %	0,31	0,29	0,50
Weighted DR, %	1,92	1,63	3,06
Weighted FPY, %	98,08	98,37	96,94
Weighted SR, %	1,24	0,92	2,17

Table 13 shows us that the highest weighted overall defect rate was observed in the when the speed is higher than 37,5 m/min. In this group, the weighted DR reaches 3,06% while the weighted FPY reaches 96,94 %. Compared to the speed group that stays in the 36,5 – 37, 5 m/min interval, the defect rate reaches 1,63 % and the weighted FPY reaches up to 98,37%, as seen in Fig. 21.

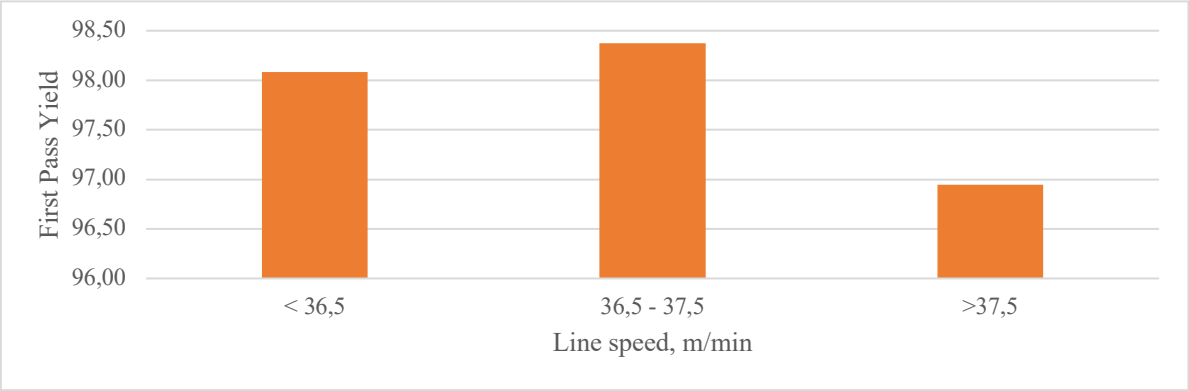


Fig. 21. First Pass Yield Based on Line Speed

This suggests that higher line speed may be associated with poorer quality results, particularly when evaluating lamination defects that are detected in other work centers. This trend is consistent with the technological logic of the lamination process. At higher speeds, the actual contact time between the film, the adhesive, and the substrate decreases, making the conditions for adhesion formation more sensitive to the stability of other parameters. If, at the same time, the adhesive layer is uneven or contact conditions are not optimal, the probability of defects may increase. However, the effect of line speed cannot be evaluated in complete isolation. Different parts and adhesive systems are distributed across speed groups, so part of the variation in defect rates may be related to the part type or other process settings. For this reason, line speed should be considered as one of the parameters within the process window, rather than the sole cause of defects.

3.3.6. Pressure Analysis

In this study, the value of pressure is defined as the setting of the calander used in production. It describes the contact conditions between the film, the adhesive, and the substrate. Theoretically, improper pressure can result in insufficient surface contact, the formation of air gaps, or uneven distribution of the adhesive layer. In this case, pressure is measured based on the thickness of the part. According to the technical parameters of the equipment, it has been determined that the contact pressure must be 0,3–0,7 times less than the thickness of the part.

In the analyzed data, the contact pressure ranged from 17,30 to 17,70. The coefficient of variation was only 0.79%, as shown in Table 9, so this parameter was relatively stable. Due to the small variation range, the correlation analysis did not reveal a strong relationship between the compression value and the main quality indicators.

The effect of the pressure value is further assessed by grouping the data into three compression intervals.

Table 14. Comparison of Defect Level Based on the Difference in Pressure

Pressure, mm	**17,3-17,4**	**17,5-17,6**	**17,7**
No. of observations	3	5	4
Weighted DR_{lam}, %	2,11	1,64	2,49
Weighted DR_{other}, %	0,36	0,41	0,45
Weighted DR, %	2,47	2,05	2,94
Weighted FPY, %	97,53	97,95	97,06

According to Table 14, the highest weighted overall defect rate was found in the 17,7 pressure value group – 2,94 %. The lowest weighted defect rate was found in the 17,5 – 17,6 group – 2,05%. This suggests that the middle part of the analyzed compression range may have been more favourable for quality stability than the highest compression value.

However, this conclusion should be interpreted with caution. The correlation coefficients between the pressure value and quality indicators are very low; therefore, based solely on these data, it cannot be stated that pressure was the primary factor in the change in defect rate. It is more likely that the effect of pressure manifests itself in conjunction with other parameters, particularly line speed and the uniformity of adhesive distribution.

3.3.7. Temperature Parameter Analysis

Adhesive and calander temperatures are important process parameters because they affect adhesive viscosity, flow, surface wetting, and the formation of initial adhesion. However, in this study, the interpretation of temperatures must be approached with caution, because there were two different adhesive systems used and they operate within different temperature ranges. Based on the chemical properties of the adhesive EVA adhesive systems are used at a lower temperature, while the Hot Melt systems are used at a higher temperature. Correlation analysis showed that the relationship between adhesive temperature and the overall defect level is weak, r = 0,22, and calander temperature is r = 0,23. This means that, in the overall dataset, temperature is not the primary factor explaining fluctuations in the defect rate. However, this result should not be interpreted as indicating that

temperature is insignificant. It is likely that the effect of temperature is closely related to the adhesive system and its specific operating temperature range.

Therefore, to more accurately assess the effect of temperature, each adhesive system should be analyzed separately. Combining EVA and Hot Melt temperatures in a single correlation may distort the interpretation, as these systems operate under different technological conditions.

3.3.8. Process Stability Interpretation

The analysis shows that fluctuations in the quality indicators of black film lamination cannot be explained by a single technological parameter. The strongest correlation with quality indicators were found for line speed. Higher line speed is typically associated with a higher overall defect rate and a lower FPY. This allows line speed to be considered one of the most important process stability parameters in this data analysis. The average adhesive amount A_{avg} did not show a strong correlation with the defect level. This means that average adhesive amount is not a sufficient indicator to explain process stability. It is much more important to evaluate the amount of adhesive in conjunction with the uniformity of its distribution. Though correlation between ΔA_{side} and DR_{other} indicate that uneven adhesive distribution may be associated with lamination defects detected later. The pressure value in the analyzed dataset was relatively stable, so its correlation with quality indicators was weak. This does not mean that pressure is not technologically important, but in this dataset, its range of variation was too narrow to clearly assess a strong impact on the defect rate. Temperature parameters were also interpreted with caution, since different adhesive systems operate within different temperature ranges, the overall correlation between temperature and quality indicators cannot be considered direct evidence of temperature's impact. A more accurate assessment would require separate tests or additional analysis within each adhesive system. In summary, it can be stated that controlling only the nominal amount of adhesive is insufficient to ensure process stability, it is necessary to simultaneously control several parameters: line speed, uniformity of adhesive distribution, adhesive amount, temperature range and contact conditions. Based on the results of this subsection, the greatest attention in further analysis and practical recommendations should be given to limiting line speed, controlling the uniformity of adhesive distribution, and verifying adhesion stability through laboratory tests.

3.4. Comparison of Quality Results

This subsection compares the results of black film lamination quality under different process and laboratory conditions. Section 3.2 calculated the key quality indicators, while Section 3.3 assessed their relationship with fluctuations in technological parameters, therefore, the correlation analysis and evaluation of adhesive quantity intervals are not repeated in this subsection. The purpose of Subsection 3.4 is to link production quality results with the logic of laboratory tests and to prepare a basis for comparing different films, adhesive quantities, and temperature effects. The practical research problem concerns not only defects visible immediately after lamination, but also those that become apparent later – at other work centers, during storage or after the product reaches the customer. For this reason, the percentage of manufacturing defects alone is insufficient to assess the final adhesion stability, that is the reason why laboratory tests are necessary to verify whether parts manufactured under different conditions maintain film adhesion after additional thermal exposure. In this study, the structure of the laboratory tests is based on three main factors:

- thermal exposure;

- adhesive amount;
- film type.

The analysis of production results is used as a reference point for interpreting laboratory test results. So, the laboratory tests were used in this study as an additional check of adhesion stability. Production defect data show the actual defect rate in the real process, but they do not allow for a clear distinction between whether a defect arises from momentary process instability or from insufficient resistance of the film adhesive interface to additional stress. If, under laboratory conditions, a certain amount of adhesive or the film exhibits a higher delamination rate, this will supplement the interpretation of production data and allow for a more precise identification of risky process conditions.

For laboratory tests 150 x 150 mm test samples were used. The moisture content of the panel during testing was 2%. For the EVA adhesive system, adhesive temperature was 135 °C and a calander temperature of 150 °C were used in the lamination line. For hot melt system, adhesive temperature was 185 °C and calander temperature of 190 °C were used. The tests evaluated two different films, with two different adhesive amounts: 25 g/m^2 and 35 g/m^2, and three levels of thermal exposure: 50, 60, 70 °C. At each temperature, the samples were held for one hour. Laboratory tests were done in accordance with ISO 9142 standard. An additional cross hatch test was done with few details.

3.4.1. Structure of Laboratory Tests

Laboratory tests evaluate three main factors: thermal exposure; adhesive amount; film type. This test design makes it possible to evaluate not only the individual effect of each factor, but also their interactions. This is important because the problem of film delamination may be related not to a single isolated parameter, but to a combination of the specific film, the amount of adhesive, and the thermal effects, primary parameters for tests are shown in Table 15.

Table 15. Primary Parameters for Laboratory Tests

Parameter	**Used value**
Sample size, mm	150x150
Moisture content of the panel, %	2
Film type	Film no. 1 Film no. 2
Adhesive amount, g/m^2	25 35
Adhesive system	EVA; Hot melt
Adhesive temperature for EVA, °C	135
Adhesive temperature for Hot melt, °C	150
Calander temperature for EVA, °C	185
Calander temperature for Hot melt, °C	190
Thermal exposure range, °C	50, 60, 70

This test setup is appropriate for the research problem because it directly examines the three potentially most important factors: film sensitivity, adequacy of adhesive quantity, and temperature resistance of the bond. Since the main problem in practical production is film delamination, the primary evaluation criterion in laboratory testing is whether the film remains firmly adhered to the

substrate after exposure to temperature. Two different adhesive systems were used – EVA and Hot melt because they have different technological properties and act differently in lamination process. Both systems react differently to temperature, line speed, adhesive amount and film type. EVA adhesive system has a lower softening temperature and lower viscosity and can provide different wetting and initial adhesion, while the hot melt system has a higher softening temperature, so its thermal stability and behaviour after thermal exposure may differ. For this reason laboratory tests with both types of adhesives allow for a comparison of which adhesive system ensures more stable adhesion, a lower risk of delamination and more suitable resistance to thermal effects for a specific film and production conditions.

3.4.2. Laboratory Result Evaluation Method

The results of laboratory tests are evaluated based on signs of film delamination. Since the test results are presented visually and the size of the delaminated area is not measured numerically, a binary evaluation is applied at this stage: the sample is considered compliant if no film delamination is observed after thermal exposure, and non – compliant if delamination is observed. The non – compliance rate of samples in a specific test group is calculated as follows:

$$FR_g = \frac{N_{fail,g}}{N_{tested,g}} \cdot 100\ \%, \quad (26)$$

Where: FR_g is the non – conformity rate of samples in a specific test group, %; $N_{fail,g}$ is the number of samples in which delamination of the film was observed, pcs; $N_{total,g}$ is the number of samples tested in a specific group, pcs; g is a specific test group that is defined by the film, the amount of adhesive and the adhesive system.

The level of compliance in the samples is calculated:

$$PR_g = \frac{N_{pass,g}}{N_{tested,g}} \cdot 100\ \%, \quad (27)$$

Where: PR_g is the compliance rate of samples in a specific test group, %; $N_{pass,g}$ is the number of samples in which delamination of the film was not observed, pcs; $N_{total,g}$ is the number of samples tested in a specific group, pcs; g is a specific test group that is defined by the film, the amount of adhesive and the adhesive system.

These indicators allow for a comparison of which combination of film, adhesive content, and adhesive system is more stable under thermal stress conditions. In addition, it is possible to calculate the difference in non – conformity caused by thermal stress between different temperatures:

$$\Delta FR_T = FR_{T2} - FR_{T1}, \quad (28)$$

Where: ΔFR_T is change in the level of non – conformity between two temperature conditions, %; FR_{T2} is level of non – conformity at a higher or different reference temperature, %; FR_{T2} is level of non – compliance at the initial or lower temperature, %.

If $\Delta FR_T > 0$, a higher temperature increases the risk of failure. If $\Delta FR_T = 0$, a change in temperature does not result in an additional increase in the risk of failure. In this study, this indicator is important because it allows us to assess whether delamination increases as the temperature rises or whether the defect occurs regardless of the temperature range.

3.4.3. Laboratory Test Result Analysis

The results of laboratory tests are summarized in Appendixes 6, 7, 8, 9. Three temperature levels: 50, 60, 70 °C were applied to each combination of film, adhesive amount and adhesive system. According to the test analysis, in the case of Film No. 1, delamination was observed at almost all temperatures in both adhesive systems, using both 25 g/m^2 and 35 g/m^2. Just one piece in EVA adhesive system at 50 °C, with 35 g/m^2 adhesive amount did not show any delamination. In case of Film No. 2 delamination was observed just in hot melt adhesive system while using g/m^2 with 60 and 70 °C, delamination was not indicated for EVA adhesive system samples with Film no. 2.

Table 16. Laboratory Test Results Based on Used Adhesive System

Film	Adhesive system	Result	Interpretation of the results
Film No. 1	EVA	Edge and local delamination; in cases where 25 g/m^2 was used non – conformities were found at all temperatures; for 35 g/m^2, non – conformities were found at 60 and 70 °C.	EVA reduces the severity of the defect but does not completely eliminate the risk of delamination
	Hot melt	Significant peeling across most of the surface with both 25 g/m^2 and 35 g/m^2.	Film No. 1 is incompatible with the hot-melt system under the tested conditions
Film No. 2	EVA	There are no peeling issues with either the 25 g/m^2 or the 35 g/m^2.	The most stable group of combinations studied
	Hot melt	With 25 g/m^2, visible edge lifting at 60 and 70°C; with 35 g/m^2, no peeling issues are observed.	The second most stable group of combinations studied

Table 16 also shows that the type of film used has a significant impact on the laboratory results, with Film no. 1 showing the highest risk of delamination. With this film, signs of delamination were observed in all test combinations, regardless the adhesive system or adhesive amount used. The difference between the EVA and hot melt systems is not so much the presence of a defect but its nature: with EVA edge or localized delamination is most commonly observed, while the case of hot melt adhesive showed significant film delamination across most of the surface area. While Film No. 2 showed a significantly more stable result. With EVA system, no film delamination issues were observed with either adhesive amount. With the hot melt system, the result depended on the adhesive amount used: with 25 g/m^2, edge delamination was observed in 60 and 70 ℃ samples, while with 35 g/m^2 no delamination issues were observed. This helps us to indicate that a stable result can be achieved with Film No. 2, but it requires the right combination of adhesive system and adhesive content.

Two adhesive application rates were used in the laboratory tests: 25 g/m^2 and 35 g/m^2. These conditions make it possible to assess whether exposure to higher temperatures increases the risk of the film peeling off. The level of non – compliance regarding the amount of adhesive is calculated as follows:

$$FR_A = \frac{N_{fail,A}}{N_{tested,A}} \cdot 100\%, \quad (29)$$

Where: FR_A is non – conformance rate for a specific adhesive amount, %; $N_{fail,A}$ is number of specimens with delamination for a specific adhesive batch, pcs.; $N_{tested,A}$ is total number of specimens tested for a specific adhesive batch, pcs.

The difference in adhesive quantities is calculated as follows:

$$\Delta FR_A = FR_{25} - FR_{35}, \quad (30)$$

Where: ΔFR_A is difference in the level of non – conformance between adhesive quantities, %; FR_{25} level of non – compliance with the adhesive content of 25 g/m^2; FR_{35} level of non – compliance with the adhesive content of 35 g/m^2.

Results are showed in Table 17.

Table 17. Test Results

Adhesive amount, g/m^2	No. of tested samples	No. of samples with delamination	FR_A, %	PR_A, %
25	12	7	58,33	41,67
35	12	5	41,67	58,33

Based on the Table 17 higher adhesive amount improved the overall laboratory result. When the adhesive amount was increased from 25 g/m^2 to 35 g/m^2 the non – conformance rate decreased from 58,33 % to 41,67 %, as seen in Fig 22.

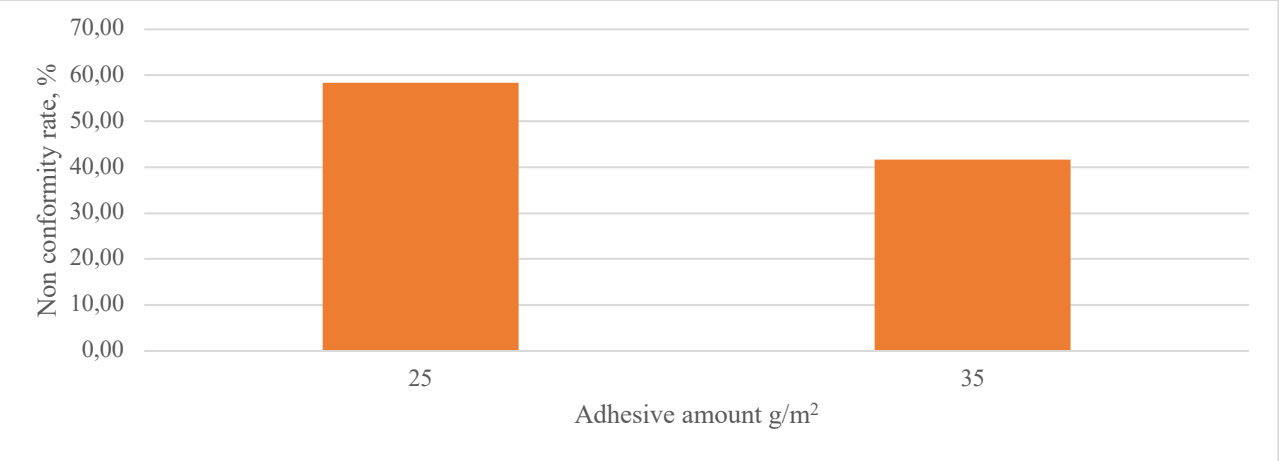


Fig. 22. Non – Conformity Rate Between Different Amount of Adhesive

This suggests that a nominal adhesive content of 35 g/m^2 is more favourable in terms of adhesion stability than the reduced amount of 25 g/m^2. But higher adhesive amount did not completely eliminate the risk of delamination, that is why only increasing the adhesive amount is not a sufficient solution if a problematic film or an unstable adhesive system is used. This conclusion is particularly clear in the case of Film No. 1 because even with the higher adhesive amount significant delamination was observed with the hot melt adhesive system and edge lifting at 60 and 70 °C with the EVA system. The effect of the adhesive amount must therefore be evaluated not in isolation but in conjunction with the film type and adhesive system. An amount of 35 g/m^2 improves the overall result but ensures stable adhesion only when the interaction between the film and adhesive system is appropriate.

Three temperatures were used in the laboratory tests: 50, 60, and 70 °C. These conditions make it possible to assess whether exposure to higher temperatures increases the risk of the film peeling off. The temperature deviation is calculated as follows:

$$FR_T = \frac{N_{fail,T}}{N_{tested,T}} \cdot 100\%, \quad (31)$$

Where: FR_T is non – conformance rate for a specific temperature, %; $N_{fail,T}$ is number of specimens with delamination for a temperature, pcs.; $N_{tested,T}$ is total number of specimens tested for a specific temperature, pcs.

Results are showed in Table 18.

Table 18. Test Results Based on Temperature

Temperature, °C	No. of tested samples	No. of samples with delamination	FR_A, %	PR_A, %
50	8	3	37,50	62,50
60	8	5	62,50	37,50
70	8	5	62,50	37,50

Based on the Table 18 it can be seen that temperature used during the laboratory oven test had a significant impact on the occurrence of delamination defects. The obtained results demonstrate a clear tendency showing that increasing temperature negatively affects the stability of the adhesion bond, this trend can be seen in Fig. 23. When testing temperature was set to 50 °C, 3 out of 8 tested samples showed delamination, thus resulting in a non – conformity rate of 37,5 %, while samples that were tested at 60 and 70 °C it increased to 62,50 %. Also, these results show that increase in temperature from 50 °C to 60 °C significantly reduced the thermal stability of the laminated structure, while 70 °C did not produce an additional increase of failed samples. It shows that delamination risk comes when the temperature is higher than 50 °C, this can suggest that when the temperature reaches 60 °C, the film and adhesive system loses the sufficient bonding stability to resist thermal loading. The calculated result confirms that elevated temperature is an important factor which influences delayed delamination and defect detection. Higher temperatures can soften the adhesive layer, reduce cohesiveness and adhesive strength while increasing internal stresses between laminated layers. As a consequence, the bond becomes more sensitive to separation, especially in areas where the adhesion quality was weaker, where pressure was lower or where process inconsistencies happened during production. This conclusion is important because if the surface of the product is exposed to higher temperatures during use, storage or transportation if unstable film and adhesive combinations are used the surface may delaminate even when no defect is apparent after production. Therefore, a laboratory tests allow for the identification of the risk of delayed delamination before it reaches the customer.

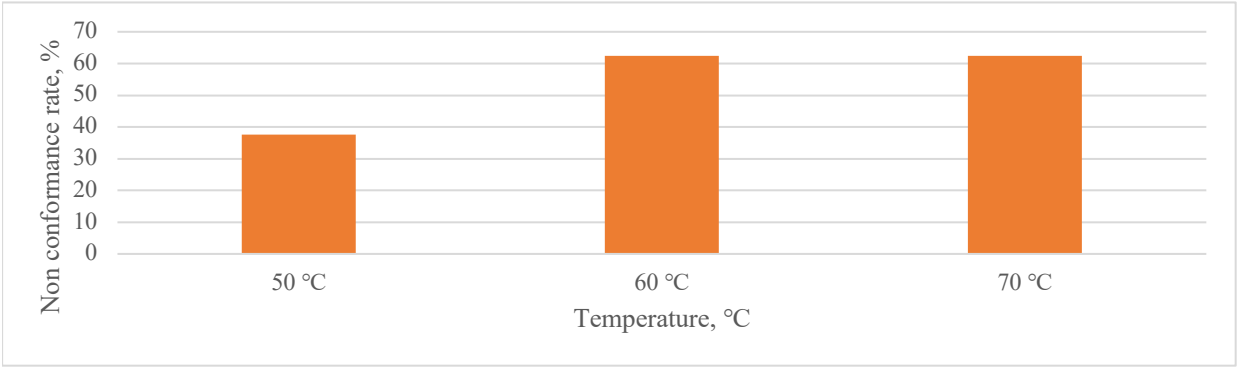
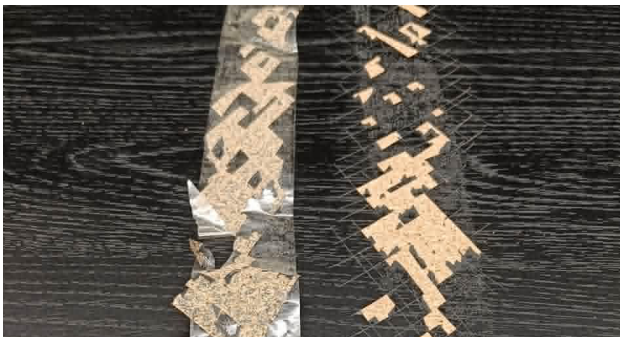
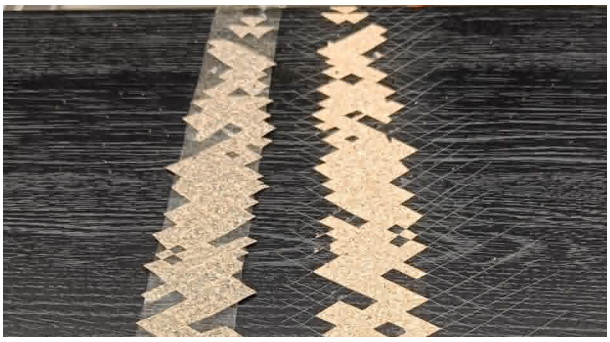


Fig. 23. Non – Conformity Rate Between Different Temperatures

Additional cross – cut test was used for Film no. 1 with EVA adhesive system while using 25 g/m^2 amount of adhesive and for Film No. 1 with Hot melt adhesive system while using 25 g/m^2 amount of adhesive. While ISO 2409:2020 describes the test to use a small cutter with 5 blades, they mostly make lines 1 mm or 3 mm apart which is just too small for real life production. Because tested pieces were quite large in area in real life, the standardized test does not show the full picture, in practice this test is made with a blade making a diamond shape and using an adhesive tape. In Table 19, the result can be seen. The pictures show that with both adhesive systems, the film detaches from the panel quite easily, which complements the results done with thermal testing. The substrate fragments remaining on the tape and the exposed panel surface indicate insufficient mechanical adhesion stability of the laminated system.

Table 19. Cross - Cut Test

Film no. 1 with EVA using 25 g/m^2	**Film no. 1 with Hot melt using 25 g/m^2**
	

Thermal tests shows whether the film delaminates due to temperature effects, while the cross – cut test showed how the laminated system reacts to localized mechanical stresses. Because both tests were done on the same panel and both show delamination after thermal exposure and cross – cut test, this just reinforces the assumption that the problem is systematic rather than random. In the panel which was laminated with Hot melt adhesive the foil removes from the board fully and there is just a small amount of panel left on the film. This means that whole adhesion mechanism did not work fully and the film did not stick on to the panel. The same result can be seen on EVA adhesive system but not so strong. This leads to a conclusion that the amount of adhesive is not sufficient enough to fully stick the film to the panel.

3.4.4. Interpretation of Laboratory Results

Based on Table 16, Film no. 1 showed the most signs of delamination with both adhesive systems, this could suggest that the problem with this type of film is not solely a matter of adhesive quantity. This result is confirmed by cross – cut test, the fragments of the substrate and coating remained on the tape which helped to indicate that adhesion instability occurs not just with thermal testing but also when the laminated surface is subjected to localized loading. Because delamination occurred with both used adhesive amounts in both adhesive systems the likely cause is that the films surface is not compatible with the adhesives, the films structural properties or its sensitivity to temperature.

The hot melt adhesive system showed the worst result with the Film no. 1 as significant delamination was observed across most of the surface, this type of defect indicates that it is not just a localized edge problem but a systematic lack of adhesion across the entire surface of the laminated piece. In this case, it is likely that the adhesive did not sufficiently wet the surface of the film or the substrate

or that adhesion was lost due to thermal effects. On the other hand, Film no. 2 shows a different trend, with EVA adhesive system it was stable at both adhesive application rates, and this allows to evaluate the combination between EVA adhesive system and Film no. 2 as the most technologically favourable of all tested options. With hot melt adhesive system, Film no. 2 was sensitive to the amount of adhesive – 25 g/m^2 was insufficient to ensure stability at higher temperatures, while 35 g/m^2 caused no problems. It is also important to note that, temperature exposure increased the risk of delamination. The failure rate increased from 37,50 % at 50 °C to 62,50 % at 60 and 70 °C, this indicates that weak bonds between the film and the adhesive become apparent as early as 60 °C. This result is significant because, under real-world conditions of use or transport, the product may be exposed to elevated temperatures, particularly during storage, transport, or operation. Also, the location and severity of the defect are also important for interpreting the cause of the defects. Edge delamination can be related to cut edges, edge stresses, the film's fold zone, or locally weaker adhesion. Meanwhile, delamination across most of the surface indicates a systemic lack of adhesion across the entire area. Therefore, the combination of Film No. 1 and hot melt should be considered the highest-risk combination.

3.5. Practical Recommendations

Based on the analysis of production data, the calculation of quality indicators and the results of laboratory tests, the quality stability of film laminated panels must be improved by adjusting not a single parameter but by managing the entire system. The results of this analysis showed that the formation of defects is related to line speed, the amount of adhesive, film type and the compatibility of the film with the adhesive system.

First and foremost, it is recommended to limit the line speed and use the 36,5 – 37,5 m/min range as the most stable production mode. Analysis of quality indicators showed that the lowest weighted defect rate of 1,63 % was reached within this range, while FPY reached 98,37 %. When the line speed exceeded 37,5 m/min, the weighted defect rate increased to 3,06%. This indicates that a higher line speed shortens the contact time between the board, adhesive and film, making the formation of the bond more sensitive to other process fluctuations. For this reason, speed should not be increased solely for productivity purposes unless it is confirmed that the adhesive amount, temperature and film properties ensure stable adhesion.

Film No. 2 with EVA adhesive system is considered the most stable of the combinations tested. In laboratory tests, this combination showed no delamination when using either 25 g/m^2 or 35 g/m^2 of adhesive. This indicates a better compatibility between the film, adhesive and panel system. In production where long-term surface stability is important, this combination should be considered a priority, especially when parts may be subjected to additional mechanical or thermal stress. If a hot melt system is used with Film No. 2, it is recommended to apply an adhesive amount of no less than 35 g/m^2, as edge delamination was observed at higher temperatures when using 25 g/m^2.

It is essential to include thermal stability tests as a standard verification procedure for new film and adhesive systems. Laboratory tests have shown that as the temperature increased from 50 °C to 60-70 °C, the failure rate increased from 37,5 % to 62,5 %. This means that weak adhesive bonds become apparent as early as 60 °C. In practice, such temperatures can occur during transportation, storage or use, especially if products are kept in warmer environment or exposed to direct sunlight. Therefore, testing immediately after lamination is not sufficient, and it is necessary to assess whether the adhesion remains stable after thermal exposure. And that is why quality control should be carried out

not only immediately after production, but also at later stages of production. The study found that 16,70 % of defects were identified at other workstations, this means that some defects become visible after additional mechanical stress, temporary storage or the redistribution of internal stresses. Therefore, it is recommended to include an additional random inspection after a certain period of time or after the next process stage, especially when manufacturing high-risk combinations of film and adhesive systems.

It is also important to control temperature settings for EVA and hot-melt adhesive systems separately. These adhesive systems operate within different temperature ranges and therefore cannot be evaluated based on a single common temperature criterion. Adhesive temperature determines viscosity, surface wetting and adhesive penetration into the panels surface, while calander temperature affects heat transfer and initial bond formation. Also, if temperature is too low it can lead to excess adhesive absorption, damage to the film surface or a deterioration in the adhesive's properties. Another factor to consider, is to maintain the pressure parameters within a stable mid-range and avoid extreme values. In the analysed data, the pressure values varied only slightly, so there was no strong direct correlation with the defect rate. However, the most favourable results were observed in the 17,5 - 17,6 mm range. Insufficient pressure may not ensure adequate contact between the film, adhesive and panel, while excessive pressure may displace the adhesive from the bonding zone or cause surface deformations. Therefore, temperature and pressure settings should be considered as an additional stability parameters that have to be coordinated with line speed, adhesive quantity and temperature.

The introduction of new films into production must be carried out in accordance with an approval procedure that includes not only a visual assessment of the surface but also adhesion and thermal stability tests. It is recommended to use the principles of the cross-cut adhesion test specified in ISO 2409:2020 and the thermal aging conditions specified in ISO 9142. Such a procedure would allow for determining in advance whether a specific film is compatible with the selected adhesive system, whether it maintains adhesion after thermal exposure and whether there is an increased risk of delamination. This is particularly important because laboratory tests have shown that different films, even when used under similar conditions, can exhibit very different levels of adhesion stability.

It is recommended to view the stabilization of the lamination process not only as a means of improving quality but also as a measure of economic and environmental efficiency. It has been calculated that by reducing the defect rate 2,63% to 1,00 %, approximately 1304 defective parts could be avoided annually, the cost index could be reduced 61,97 % prevent approximately 27,61 tons of material from being returned to an additional recycling cycle and save approximately 275,32 kg of adhesive and 37432,48 m^2 of decorative film. This demonstrates that defect prevention has a direct impact on production efficiency, material usage and process sustainability. Therefore, the primary practical focus for future production should not be on correcting defects, but on maintaining a stable process window and preventing risky parameter combinations.

3.6. Chapter Summary

Chapter 3 analyses the practical quality stability of film-coated panels, focusing on the problem of black decorative film delamination under real production conditions. The chapter focuses on the lamination process in which defects manifest not only immediately after lamination process but also in subsequent production stages, transportation or after the final product reaches the customer. This

indicates that the quality issue at hand is not solely related to immediate surface defect, but also the long – term adhesion stability between the panel, adhesive and the film.

An analysis of the production process revealed that the formation of the defect can be caused by several interrelated factors: the amount of adhesive, the uniformity of adhesive distribution, the temperature of adhesive and calander, line speed, pressing conditions, properties of the film and the adhesive system used. Calculated quality indicators showed that overall weighted defect rate reaches 2,39 % while FPY reaches 97,61 %. This means that the majority of the products are manufactured correctly the first time, but the defect rate is still significant when assessing the stability of mass production. The majority of the defects (83,30 %) are detected immediately after lamination, while 16,70 % are found in other work centers. The latter position is particularly important because it indicates that some lamination defects become visible after some time. This conclusion was supported by laboratory tests that were done.

Also, a comparison in two different adhesive systems revealed that EVA adhesive system performs slightly better than the Hot melt adhesive system based on the weighted metrics. The EVA system had a lower overall defect rate, while also having a higher FPY rate. However, this difference could not be interpreted as definitive proof that the adhesive system is the primary cause of the defects, as the number of observations for EVA system was lower and Hot melt result varied across different production batches. This led to the conclusion that the adhesive system must be evaluated in conjunction with other parameters, particularly film type, adhesive quantity, line speed and temperature regimes.

Laboratory tests further demonstrated that the type of film and its compatibility with adhesive system are critical factors in determining the stability of the bond. Film no. 1 exhibited the highest risk of delamination, the defect was observed in nearly all test combinations, regardless the amount of adhesive used, or which adhesive system was used. When using hot melt system with Film no. 1, a significant film delamination was observed across most of the surface, indicating a systematic adhesion failure rather than just a local edge defect. While the results for Film no. 2 were significantly more stable: with EVA system no delamination was observed at either 25 g/m^2 or 35 g/m^2 of adhesive, while with hot melt system stability depended on the amount of adhesive – 25 g/m^2 was insufficient at higher temperatures, but 35 g/m^2 yielded a better result. Therefore, in future production, it is recommended to avoid the combination of Film no. 1 and hot melt adhesive system.

Laboratory results also showed that a higher adhesive application rate improved overall bond stability. With the lower amount of adhesive, the failure rate was 58,33 %, with the higher amount of adhesive it decreased to 41,67 %. This helped to indicate that an adhesive amount of 35 g/m^2 is more favourable for adhesion stability than the reduced amount of 25 g/m^2. However, a higher adhesive amount did not completely eliminated the risk of delamination, especially when a problematic film or an unsuitable combination was used. Therefore, increasing the adhesive amount should not be applied as the sole measure for improving quality, it must be combined with proper selection of the film, control of line speed, temperature stability and uniformity of adhesive distribution. Chapter 3 establishes that defects in black film lamination are not related to a single isolated parameter but rather to the interaction of several factors, in future production, defect reduction should be based not only on adjusting the amount of adhesive but on integrated process control.

4. Economical and Environmental Impact

This subsection evaluates the economic and environmental impacts of stabilizing the black film lamination process. Previous subsections have established that the primary quality issue is delamination defects that are related to the stability of film adhesion. That is why the problem has not only a quality related impact but also economic and environmental implications. Economic impact is assessed using an index – based methodology. A target rate of 1 % has been selected in this study as a process stabilization scenario, allowing for an assessment of the potential economic and environmental impacts. This value is not treated as a production result that has already been achieved but is used as benchmark against which the current state of the process is compared. The current overall defect rate stands at 2,63 %, so reducing it to 1 % would represent not only a modest process improvement but a clear step toward quality stabilization. Environmental impact in this study is not assessed through a reduction in waste disposal, as defective parts are returned to the circular recycling cycle. That way defective parts are not directly disposed of as waste but are returned to the production cycle, where they are recycled and used in further production. Therefore, the environmental benefits in this study are understood as a reduction in unnecessary additional recycling cycles, repeated use of materials, consumption of adhesives and film and the workload on production resources. The 1% threshold was chosen because it is sufficiently stringent yet more realistic than the assumption of zero defects. In industrial production, completely eliminating defects is often not feasible due to variations in material batches, fluctuations in adhesive quantity, temperature conditions, pressure, line speed and other process variables.

4.1. Economical Impact Analysis

In this subsection one scenario is evaluated - reducing the current defect rate to a target defect rate of 1%.

The key assumptions for the analysis is shown in Table 20.

Table 20. Key Values Used in Economical Impact Analysis

Parameter		**Value**
Annual production volume	Part X_1	26700
	Part X_2	26650
	Part X_3	26650
Current defect rate, %		2,63
Target defect rate, %		1

The main objective is to assess the economic and environmental impact of reducing the current overall defect rate from 2,63% to 1,00%. This analysis applies to all three parts under consideration, as the primary goal of process stabilization is to reduce the overall defect rate across the entire stream of parts under consideration. Overall yearly defected detail amount is calculated:

$$N_{def,current} = N_{annual,total} \cdot \frac{DR_{current}}{100}, \quad (32)$$

Where: $N_{def,current}$ is current annual number of defective items, pcs; $N_{annual,total}$ is total annual produced quantity, pcs; $DR_{current}$ is current defect rate, %.

$$N_{def,current} = 80000 \cdot \frac{2{,}63}{100} = 2104\, pcs$$

Estimated number of defective parts:

$$N_{def,target} = N_{annual,total} \cdot \frac{DR_{target}}{100}, \quad (33)$$

Where: $N_{def,target}$ is targeted annual number of defective items, pcs; DR_{target} is current defect rate, %.

$$N_{def,current} = 80000 \cdot \frac{1{,}00}{100} = 800\, pcs$$

The number of defective parts avoided:

$$N_{saved} = N_{def,current} - N_{def,target}, \quad (34)$$

$$N_{saved} = 2104 - 800 = 1304\, pcs$$

Table 21. Primary Basis for Economic Impact

Parameter	**Value**
Annual yearly production volume $N_{annual,total}$, pcs	80000
Current defect rate $DR_{current}$, %	2,63
Target defect rate DR_{target}, %	1
Current amount of defected pieces $N_{def,current}$, pcs	2104
Targeted amount of defected pieces $N_{def,target}$, pcs	800
No. of avoided defective parts N_{saved}, pcs	1304

According to Table 21, reducing the defect rate from 2,63% to 1,00% would prevent approximately 1304 defective parts per year, this is the primary basis for calculating the economic and environmental impact, as this amount was chosen for calculation of reducing the need for reprocessing, adhesive and film consumption. To evaluate the economic impact, it was chosen to assess to do it using an index – based method. Each defective piece is assigned a uniform cost index:

$$CI_{unit} = 1$$

Where: CI_{unit} is cost index for a single defective part.

The cost index for current situation is calculated:

$$CI_{current} = N_{def,current} \cdot CI_{unit}, \quad (35)$$

Where: $CI_{current}$ is current cost index; $N_{def,current}$ is current annual number of defective items, pcs.

$$CI_{current} = 2104 \cdot 1 = 2104$$

The cost index for the target scenario is calculated as follows:

$$CI_{target} = N_{def,target} \cdot CI_{unit}, \quad (36)$$
$$CI_{target} = 800 \cdot 1 = 800$$

The reduced cost index is calculated as follows:

$$CI_{saved} = CI_{current} - CI_{target}, \quad (37)$$
$$CI_{saved} = 2104 - 800 = 1304$$

The relative decrease in the cost index is calculated as follows:

$$CI_{reduction} = \frac{CI_{saved}}{CI_{current}} \cdot 100\%, \quad (38)$$

Where: $CI_{reduction}$ is decrease in the cost index, %; CI_{saved} is reduced cost index; $CI_{current}$ is current cost index.

$$CI_{reduction} = \frac{1304}{2104} \cdot 100\% = 61{,}97\ \%$$

Table 22. Calculated Indicators

Indicator	**Value**
Current cost index $CI_{current}$	2104
Target situation cost index CI_{target}	800
Cost reduction index CI_{saved}	1304
Decrease in the cost index $CI_{reduction}$, %	61,97

The index-based assessment shows that reducing the defect rate to 1% would decrease the cost burden associated with defective parts by 61,97%, as seen in Table 22. This indicator reflects not an absolute monetary benefit, but a relative improvement in process efficiency. The fewer defective parts generated in the process, the lower the burden of additional internal production activities: sorting parts, returning them to the recycling cycle, reusing materials, and preparing new parts.

4.2. Environmental Impact Analysis

Environmental impact in this study is assessed based on the amount of material that would not need to be returned to recycling cycle. Since defective parts are not directly disposed of as waste but are returned to the production cycle, reducing defects would mean a lower burden of unnecessary reprocessing. The annual volume and mass of the parts are calculated and shown in Table 23.

Table 23. Primary Parameters for Economical Assessment

Detail	**Density of the board ρ, kg/m^3**	**Dimensions, mm**	**Volume of one detail V, m^3**	**Mass of one detail M, kg**	**Annual amount, pcs**	**Yearly Volume V_{annual}, m^3**	**Yearly Mass M_{annual}, kg**
X_1	2640	467x600x18	0,00504	13,32	26700	134,57	355644
X_2		908x630x18	0,01030	27,18	26650	274,50	724347
X_3		868x560x18	0,00875	23,10	26650	233,19	615615
Total:		-	0,02409	63,60	80 000	642,26	1 695 606

Since the defect rate is reduced by 1,63 %, the volume of rework avoided is calculated:

$$V_{saved} = V_{annual,total} \cdot \frac{\Delta DR}{100}, \quad (39)$$

Where: V_{saved} is avoided rework volume, m^3; $V_{annual,total}$ is total annual volume of parts analyzed, m^3; ΔDR is reduction in the defect rate, %.

The mass of material saved in the processing cycle is calculated as follows:

$$M_{saved} = V_{saved} \cdot \rho \,, \tag{40}$$

Where: M_{saved} is avoided rework mass, m^2; $M_{annual,total}$ is total annual mass of parts analyzed, m^2; ρ is average density of the board, kg/m^3.

Table 24. Calculated Base Parameters for Environmental Impact Analysis

Indicator	**Value**
Total annual volume of parts analyzed $V_{annual,total}$, m^3	642,26
Total annual mass of parts analyzed $M_{annual,total}$, m^3	1695606
Reduction of defect rate ΔDR, %	1,63
Avoided rework volume V_{saved}, m^3	10,46
Avoided rework mass M_{saved}, kg	27614,4
Avoided rework mass M_{saved}, t	27,61

According to Table 24, reducing the defect rate to 1,00 % would prevent approximately 10,46 m^3 or 27,61 t of material from being returned to an additional recycling cycle each year. This result is significant from an environmental perspective, because the additional processing is not a neutral process, even if the material is theoretically returned to production in practice each additional cycle entails:

- additional energy consumption;
- greater equipment load;
- additional transportation costs;
- longer processing time;
- greater process variation.

Therefore, process stabilization reduces not only direct material losses but also the overall complexity of the production system. It is also important to note that the consumption of auxiliary materials also decreases, thereby reducing the economic impact and lowering material consumption.

Per month for the whole lamination process 27069 kg of adhesives is used, the analyzed details per month accounts for 5 %. Monthly and yearly adhesive usage for analyzed details is calculated:

$$M_{adh,month} = M_{adh,total,month} \cdot k_{adh} \,, \tag{41}$$

$$M_{adh,annual} = M_{adh,month} \cdot 12, \tag{42}$$

Where: $M_{adh,month}$ is monthly used adhesive amount for analyzed details, kg; $M_{adh,total,month}$ is monthly adhesive usage, kg; k_{adh} is the proportion of adhesive in the parts being analyzed; $M_{adh,annual}$ is annual adhesive usage, kg.

$$M_{adh,month} = 27069 \cdot 0{,}052 = 1407{,}59\ kg$$

$$M_{adh,annual} = 1407{,}59 \cdot 12 = 16891{,}06\ kg$$

The potential savings in adhesive are calculated based on the reduction in the defect rate:

$$M_{adh,saved} = M_{adh,annual} \cdot \frac{\Delta DR}{100}, \quad (43)$$

Where: $M_{adh,annual}$ is annual adhesive usage, kg; $M_{adh,saved}$ is potential savings in adhesive, kg.

$$M_{adh,saved} = 16891{,}06 \cdot \frac{1{,}63}{100} = 275{,}32\ k$$

Table 25. Savings in Adhesive

Indicator	**Value**
Monthly adhesive usage $M_{adh,total,month}$, kg	27069
Proportion of adhesive in analyzed parts k_{adh}	5,2
Monthly adhesive usage for analyzed details $M_{adh,month}$, kg	1407,59
Annual adhesive usage $M_{adh,annual}$, kg	16891,06
Reduction of defect rate ΔDR, %	1,63
Potential savings in adhesive $M_{adh,saved}$, kg	275,32

Based on Table 25, reducing defect rate to 1% would result in annual reduction of approximately 275,32 kg in adhesive consumption for defective products. This helps us to show that quality improvement has a direct impact not only on the number of defective parts but also on the flow of auxiliary materials.

It is also important to take into consideration film usage for produced parts. Film savings are calculated based on the amount of film used per part, since both the top and bottom layers of film are used in the lamination process, the amount of film used per part is calculated as follows:

$$S_{film,j} = L_j \cdot \left(W_{top,j} + W_{bottom,j}\right), \quad (44)$$

Where: $S_{film,j}$ is the area of film used for a single part of a specific type, m^2; L_j is the length of the part, m; $W_{top,j}$ is the width of the top film, m; $W_{bottom,j}$ is the width of the bottom film, m.

The film widths used for each part are listed in Table 26.

Table 26. Film Used for Each Detail

	Length of part L_j, m	**Width of the top film W_{top}, m**	**Width of the bottom film W_{bottom}, m**	**Film area $S_{film,j}$, m^2**
X1	0,467	0,630	0,560	0,56
X2	0,908	0,706	0,630	1,21
X3	0,868	0,670	0,600	1,10
In total:				2,87

The annual used film area is calculated:

$$S_{film,annual} = S_{film,product} \cdot N_{product}, \quad (45)$$

Where: $S_{film,annual}$ is annual film area, m^2; $S_{film,product}$ is film area for analyzed parts, m^2; $N_{product}$ is annual production volume, pcs.

$$S_{film,annual} = 2{,}8712 \cdot 80000 = 229600\ m^2$$

The potential film savings are calculated as follows:

$$S_{film,saved} = S_{film,annual} \cdot \frac{\Delta DR}{100}, \quad (46)$$

Where: $S_{film,saved}$ is potential film savings, m^2.

$$S_{film,saved} = 229600 \cdot \frac{1{,}63}{100} = 3742{,}48\ m^2$$

Table 27. Potential Film Savings per Year

Indicator	**Value**
Film area per product $S_{film,product}$, m^2	2,87
Annual product volume $N_{product}$, pcs	80000
Annual film area $S_{film,annual}$, m^2	229600
Reduction in defect rate ΔDR, %	1,63
Potential film area savings $S_{film,saved}$, m^2	3742,48

According to Table 27, reducing the defect rate to 1% would prevent the use of approximately 3742,48 m^2 of film per year. This indicator is important because the film is used even before the final defect is identified, therefore, each defective part represents not only the consumption of base material but also the consumption of film and adhesive for production that does not result in a suitable final production. From an economic perspective, this means lower operating costs and from an environmental perspective, it means lower consumption of single use consumables and less waste.

4.3. Integrated Economical and Environmental Assessment

Integrated assessment allows for the consolidation of key indicators of process stabilization in a single Table: the number of defective parts avoided, the reduction in the cost index, the volume and weight of rework avoided, and savings in adhesive and film. These indicators are shown in Table 28.

Table 28. Impact of Economical and Environmental Assessment

Indicator	**Value**
Current defect rate $DR_{current}$, %	2,63
Target defect rate DR_{target}, %	1
Reduction in defect rate ΔDR, %	1,63
No. of avoided defective parts N_{saved}, pcs	1304
Decrease in the cost index $CI_{reduction}$, %	61,97
Avoided rework volume V_{saved}, m^3	10,46
Avoided rework mass M_{saved}, kg	27614,4
Avoided rework mass M_{saved}, t	27,61
Potential savings in adhesive $M_{adh,saved}$, kg	275,32
Potential film area savings $S_{film,saved}$, m^2	3742,48

According to Table 28, reducing the defect rate from 2,63% to 1,00% would prevent approximately 1304 defective parts per year. This would reduce the cost index associated with defective parts by 61,97%, prevent approximately 10,46 m^3 or 27,61 t of material from being returned to an additional processing cycle, reduce adhesive consumption by approximately 275,32 kg, and reduce film consumption by approximately 3742,48 m^2. These indicators show that process stabilization has a broader impact than just an improvement in quality metrics. Reducing defects directly reduces the load on internal production flows, as fewer parts need to be identified as defective, removed from the process, returned to the recycling cycle, and replaced with new parts.

4.4. Chapter Summary

Chapter 4 evaluates the economic and environmental impacts of stabilizing the lamination process for black decorative film. Since previous chapters have established that the main quality issue is film delamination, in this section, defect reduction is evaluated not only as a means of improving quality but also as a factor that reduces the load on the production system, the use of additional materials, and the need for rework. The scenario selected for the assessment involves reducing the current defect rate from 2,63% to a target defect rate of 1,00%. A 1 % defect rate is considered in this study to be a practical criterion for process stability, allowing one to distinguish between a merely acceptable process and a more controlled and stable one. This change represents a reduction of 1,63 % and allows for an assessment of the practical benefits that a more stable lamination process could provide. The economic impact analysis was conducted based on an annual production volume of 80 000 units of the parts under analysis. At the current defect rate of 2,63%, approximately 2104 defective parts would be produced annually. By reducing the defect rate to 1,00%, the number of defective parts would decrease to 800 per year. This means that stabilizing the process would prevent approximately 1304 defective parts per year. The fewer defects that occur in the lamination process, the lower the burden of additional internal production activities: fewer parts need to be identified as defective, removed from the production flow, returned to the recycling cycle, or replaced with newly manufactured parts. In the environmental impact analysis, defective parts are not considered direct waste because they are returned to the circular recycling loop. However, additional recycling is not a neutral process, as it requires energy, equipment, transportation, labour, and additional production resources. For this reason, the environmental benefit in this section is understood as a reduction in unnecessary additional recycling cycles, consumption of auxiliary materials, and the load on the production system. Based on the annual quantities of the analysed X_1, X_2, and X_3 parts, the total annual volume of parts is 642,26 m^3, and the total annual mass is 1695606 kg. Reducing the defect rate by 1,63% would prevent approximately 10,46 m^3 or 27,61 t of material from being returned to an additional processing cycle per year. These results indicate that stabilizing the quality of the lamination process is not merely a matter of quality control. It is directly related to production efficiency, material utilization, internal process load, and the environmental footprint of production. Chapter 4 substantiates the practical significance of defect reduction for the production system. Even a relatively small percentage reduction in defect levels in mass production has a significant impact, as annual production volumes are high. A stabilized lamination process would reduce not only the amount of scrap but also the unnecessary use of adhesive, film, panel material, energy and labour time. Therefore, in future production, quality stabilization should be viewed not only as a technological or quality management objective but also as a means of improving economic efficiency and environmental performance.

Conclusions

1. An analysis of the film lamination has shown that the quality stability of film laminated furniture components depends on multilayer system, and bond formation is determined by three key adhesion conditions: sufficient surface wetting, proper penetration of the adhesive into the board surface and stable contact between the panel, adhesive and the film. Relative humidity and temperature affect the dimensional stability of the panel while technological parameters determine the adhesive viscosity, contact time and final bond strength.
2. It was determined that the process parameters causing critical quality fluctuations are line speed, the uniformity of adhesive application, the amount of adhesive, the temperature of adhesive and calander, the pressure conditions, type of film and its compatibility with the adhesive system. In the production data line speed and uneven adhesive distribution had the greatest practical significance.
3. The calculated overall weighted defect rate was 2,39 % and the FPY reaches 97,61%. The strongest correlation with defect rate was found for line speed: the correlation with defects after lamination was 0,63 %, with the total defect rate 0,62 and with FPY -0,62. The average amount of adhesive did not significantly explain the defect level, but the unevenness of adhesive distribution was associated with defect detected later.
4. Laboratory tests showed that Film no. 1 has the highest risk of delamination, especially when used with a hot melt adhesive system. The most stable results were obtained using Film no. 2 with an EVA adhesive system, where no delamination was observed with either a 25 g/m^2 or a 35 g/m^2 adhesive application rate. As the temperature increased from 50 ℃ to 60 – 70 ℃, the failure rate rose from 37,50 % to 62,50 %, therefore, 60 ℃ is considered the critical threshold for adhesive stability.
5. The most stable production range was determined to be at a line speed of 36,5 – 37,5 m/min: within this range, the defect rate was 1,63 % and the FPY was 98,37 %. When the line speed exceeded 37,5 m/min the defect rate increased to 3,06 %. Therefore, it is recommended to limit the line speed, maintain an adhesive application rate of 35 g/m^2, control the uniformity of adhesive distribution and avoid the combination of Film no.1 and Hot melt adhesive system. Reducing defect rate from 2,63 % to 1,00 % would prevent approximately of 1304 defective parts per year, 27,61 tons of additional processing, 275,31 kg of adhesive per year and 3742,47 m^2 of film consumption.

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Appendices

Appendix 1. Critical Environmental Parameter Intervals

Parameter	Optimal zone	Critical threshold	Critical upper limit	Physio-chemical mechanism	Typical defect
Relative humidity (RH)	45 – 60 %	< 40%	> 70 – 75%	Changes in the moisture content of the panel, interaction of adhesive with the surface	Slow curing, brittle bond (when RH <40%), swelling, edge lifting (when RH >70%)
Moisture content of substrate	6 – 10 %	< 5%	> 10 – 12%	Dimensional stability, changes in internal bonds	Brittle surface, poor adhesion (<5 %); swelling, delamination (>10 – 12 %)
Environment temperature	18–25 °C	< 15 °C	>30 °C	Adhesive viscosity, heat transfer	Too quick setting, poor wetting (< 15 °C); unstable process (> 30°C
Temperature fluctuations	±2–3 °C	> ±5 °C	>±10 °C	Thermal expansion, adhesive behaviour	Instability of adhesion, internal stresses
Humidity fluctuations	±5 % RH	> ±10 % RH	>±20 % RH	Moisture content changes, deformations	Edge lifting, delayed delamination
Panel curing time	≥24–48 h	< 12 h	—	Reached moisture balance	Dimensional changes after lamination
Film conditioning	≥12–24 h	< 6 h	—	Stabilization of internal stresses	Wrinkles, deformations
Ambient dust levels	Minimal	Average	High	Reduced contact area	Loss of adhesion, local defects
Air circulation	Even	Too weak	Too strong	Temperature and RH distribution	Uneven process, local defects

Appendix 2. Critical Ranges of Thermal and Adhesion Parameters

Parameter	**Typical Interval**	**Critical threshold**	**Effect on process**	**Defects**
Line Speed (m/min)	10 - 30	> 35	Determines the contact time between the film and the panel	Excessive speed leads to insufficient grip, delamination, and air gaps
Contact time (s)	0,5 - 2,0	< 0,3	Determines the time required for the adhesion mechanisms to take effect	Insufficient contact time results in incomplete wetting and poor adhesion
Pressure force	0,3 - 0,8 less than panel thickness	< 0,2 or >1	Affects the contact area and the distribution of the adhesive	If the pressure is too low, air pockets will form; if it is too high, it may squeeze out the adhesive
Pressure time (s)	0,5 - 1,5	< 0,3	Determines the penetration and contact of the adhesive	Insufficient holding time results in poor mechanical bonding
Uniformity of roller pressure	Uniform across the entire piece	Uneven	Ensures uniform contact	Local defects, air gaps, delamination
Workpiece thickness tolerance (mm)	± 0,1 - 0,2	> ±0,3	Affects actual pressure	If the workpiece tolerance is too large, the pressure will be too low; if it is too small, the pressure will be too high
Surface cleanliness	Dust free	Any contamination	Determines the actual contact area	Surface defects, localized peeling
Feed stability	Uniform	Vibrations	Affects adhesive distribution	Waviness, uneven adhesion
Condition of the rollers	Clean, with no wear	Damaged surface	Determines pressure distribution	Surface defects, unstable adhesion

Appendix 3. Critical Ranges of Thermal and Adhesion Parameters

Parameter	Optimal zone	Critical threshold	Critical upper limit	Physio-chemical mechanism	Typical defect
Adhesive temperature (EVA)	170 – 190 °C	<160 °C	>200 °C	Change in viscosity, wetting efficiency, thermal degradation	Weak adhesion, delamination (<160 °C); adhesive degradation, brittleness (>200 °C)
Adhesive viscosity	10 000 – 50 000 mPa·s	>60 000 mPa·s	<8 000 mPa·s	Flow-absorption balance	Insufficient irrigation (high viscosity); excessive absorption (low viscosity)
Adhesive amount	80 – 100 g/m²	<60 g/m²	>120 g/m²	Formation of the contact surface, layer thickness	Formation of the contact surface, layer thickness; Poor adhesion (<60); Adhesive "bleeding" on the surface (>120)
Substrate temperature	20 – 30 °C	<15 °C	>40 °C	Heat absorption, adhesive setting speed	Too rapid setting, poor water absorption (<15 °C); unstable process (>40 °C)
Temperature of the film	60 – 100 °C	<50 °C	>120 °C	Film flexibility, UV varnish stability	Poor adhesion, stress cracking (<50 °C); paint degradation, loss of gloss (>120 °C)
Contact pressure	0,3 – 0,5 MPa	<0,2 MPa	>0,6 MPa	Increasing the contact area, removing air gaps	Air gaps, poor adhesion (<0,2); adhesive extrusion, deformation (>0,6)
Contact time	1,0 – 2,0 s	<0,5 s	>3,0 s	Implementation of locking mechanisms	Insufficient adhesion (<0,5); excessive absorption (>3,0)
Line speed	15 – 25 m/min	<10 m/min	>30–35 m/min	Contact time and heat balance	Excessive absorption (<10); poor adhesion (>30)
Surface cleanliness	Minimal	Average	High	Reduction in contact area	A decrease in adhesion to 20–40%, local defects

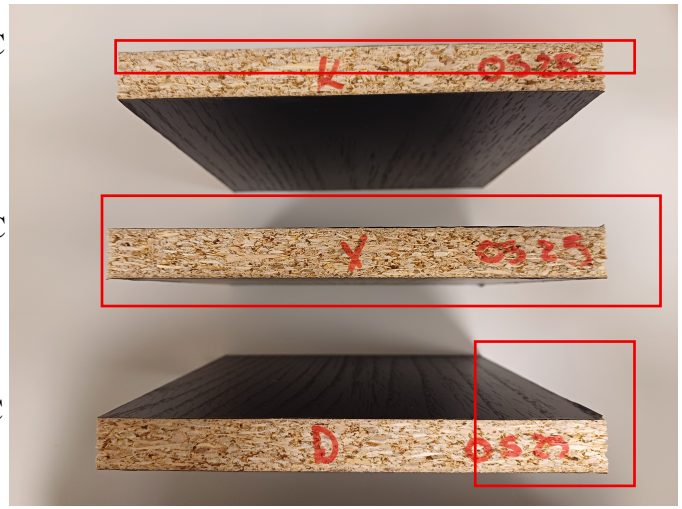
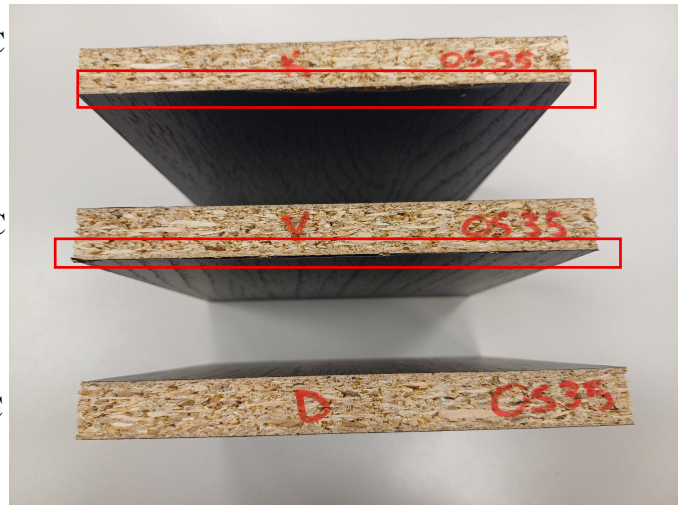
Appendix 4. Primary Data for Calculations

Detail type	Adhesive type	Adhesive upper limit, g/m²	Adhesive lower limit, g/m²	Adhesive temperature, °C	Calander temperature, °C	Pressure	Line speed, pcs/min	Line speed, m/min
X_1	EVA	37,6	37,5	130	150	17,4	10,76	37,66
	Hot melt	36,5	32,7	185	195	17,5	10,93	38,255
	Hot melt	31,9	31,4	190	195	17,7	10,42	36,47
	Hot melt	30,7	29,3	180	190	17,6	10,59	37,065
X_2	EVA	36,6	34,7	140	150	17,6	10,64	37,24
	Hot melt	36,2	38,5	190	195	17,3	10,76	37,66
	Hot melt	34,4	33,6	195	200	17,7	10,35	36,225
	Hot melt	33,6	34,6	190	195	17,5	10,43	36,505
X_3	EVA	36,9	37,5	135	140	17,4	10,89	38,115
	Hot melt	34,8	33,2	185	190	17,7	10,41	36,435
	Hot melt	33,7	32,7	190	195	17,7	10,86	38,01
	Hot melt	31,1	30,3	185	190	17,6	10,02	35,07

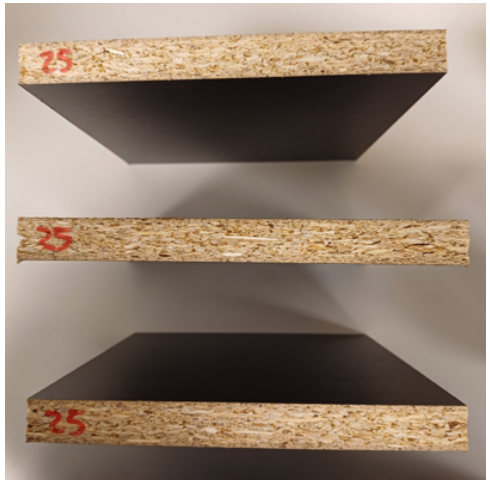
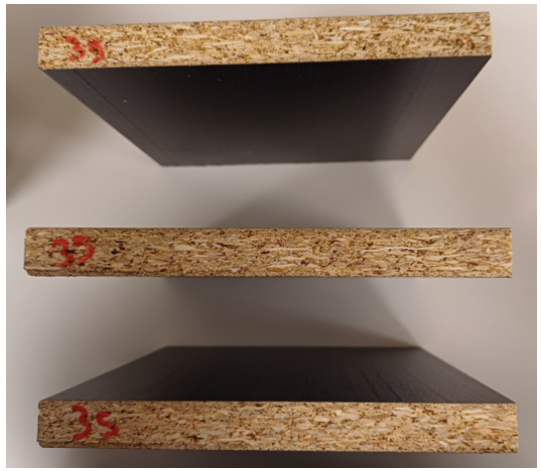
Appendix 5. Primary data for Calculations

Detail type	**Adhesive type**	**Total** manufactured **unit**	**Defective units, after lamination**	**Defective units in other work centers**	**Total defected pieces**	**Amount of good pieces**	**Reworked pieces**	**Scrapped amount**
X_1	EVA	13691	264	27	291	13400	158	133
	Hot melt	4586	198	59	257	4329	76	181
	Hot melt	3271	59	11	70	3201	19	51
	Hot melt	6983	104	17	121	6862	52	69
X_2	EVA	14574	167	42	209	14365	87	122
	Hot melt	8150	168	24	192	7958	115	77
	Hot melt	4131	87	11	98	4033	54	44
	Hot melt	7637	119	26	145	7492	68	77
X_3	EVA	18372	416	94	510	17862	46	464
	Hot melt	7496	124	22	146	7350	64	82
	Hot melt	4270	207	43	250	4020	42	208
	Hot melt	7298	87	25	112	7186	14	98

Appendix 6. Laboratory Results with Film No. 1 Using EVA Adhesive System

Test group	Film type	Adhesive amount, g/m²	Temperature, ℃	Samples with delamination	Samples with delamination	Interpretation of results
No. 1 EVA	Film nr. 1	25	50	1	50 ℃ 60 ℃ 70 ℃ 	There is no overall surface delamination, but slight peeling of the film can be visible at the cut edges.
			60	1		
			70	1		
No. 2 EVA	Film nr. 1	35	50	0	70 ℃ 60 ℃ 50 ℃ 	Slight peeling of the film is visible on the cut edges of parts that were stored at temperatures 60 and 70 ℃
			60	1		
			70	1		

Appendix 7. Laboratory Results with Film No. 2 Using EVA Adhesive System

Test group	Film type	Adhesive amount, g/m²	Temperature, ℃	Samples with delamination	Samples with delamination	Interpretation of results
No. 3 EVA	Film nr. 2	25	50	0	50 ℃ 	There are no visible issues with the film peeling off
			60	0	60 ℃	
			70	0	70 ℃	
No. 4 EVA	Film nr. 2	35	50	0	50 ℃ 	There are no visible issues with the film peeling off
			60	0	60 ℃	
			70	0	70 ℃	

Appendix 8. Laboratory Results with Film No. 1 Using Hot Melt Adhesive System

Test group	Film type	Adhesive amount, g/m²	Temperature, °C	Samples with delamination	Samples with delamination	Interpretation of results
No. 1 Hot Melt	Film nr. 1	25	50	1	50 °C 	Significant peeling of the film across most of the surface area
			60	1	60 °C	
			70	1	70 °C	
No. 2 Hot Melt	Film nr. 1	35	50	1	50 °C 	Significant peeling of the film across most of the surface area
			60	1	60 °C	
			70	1	70 °C	

Appendix 9. Laboratory Results with Film No. 2 Using Hot Melt Adhesive System

Test group	Film type	Adhesive amount, g/m²	Temperature, ℃	Samples with delamination	Samples with delamination	Interpretation of results
No. 3 Hot Melt	Film nr. 2	25	50	0	50 ℃	Slight peeling of the film is visible on the cut edges of parts that were stored at temperatures of 60 and 70 ℃
			60	1	60 ℃	
			70	1	70 ℃	
No. 4 Hot Melt	Film nr. 2	35	50	0	50 ℃	There are no visible issues with the film peeling off
			60	0	60 ℃	
			70	0	70 ℃	



