

Pareto-based design of experiments for identifying and comparing optimum sealing parameters of heat sealing applications in packaging machines

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ABSTRACT: Sealing is one of the most important process steps in industrial packaging, because the sealed seam is the most sensitive section of a package in terms of quality. For this reason, a major focus in flexible packaging is the sealing process, and among this, heat sealing is the most frequently used technology. In detail, applications of heat sealing processes are confronted with four conflicting objectives: increasing seam quality, reducing dwell time, reducing sealing temperature, and increasing process robustness towards varying conditions. Typical problems, such as identification of the optimum process parameters or selection of the most appropriate packaging film, are subject to these conflicting objectives.

This paper presents a recently published design of experiments for characterizing and comparing heat sealing properties of packaging films based on a multi-objective optimization algorithm. The approach provides easy-to-read charts showing all optimum sealing parameters with regard to the four essential objectives of heat sealing: seam quality, dwell time, sealing temperature, and process robustness. Three case studies show exemplary applications of the new approach: 1) analyzing transport damages of beverage powder packages; 2) identifying and comparing optimum sealing parameter of a standard, mono-material, and fiber based packaging film regarding tightness and visual properties of the produced sachets; and 3) analyzing the effect of additional aluminum layers on sealing characteristics regarding hot-tack.

The new design of experiments may provide the basis of a standard test method for the identification of optimal sealing parameters in the heat sealing processes.

Application: This work describes a new design of experiments that may serve all engineers responsible for quality and productivity of packaging machinery and processes in the flexible packaging industry. It gives a step-by-step introduction on how to apply the new approach and gives three examples from industry and research. The new design of experiments may provide the basis for a new standard test method in addition to ASTM F88 “Standard test method for seal strength of flexible barrier materials,” for instance.

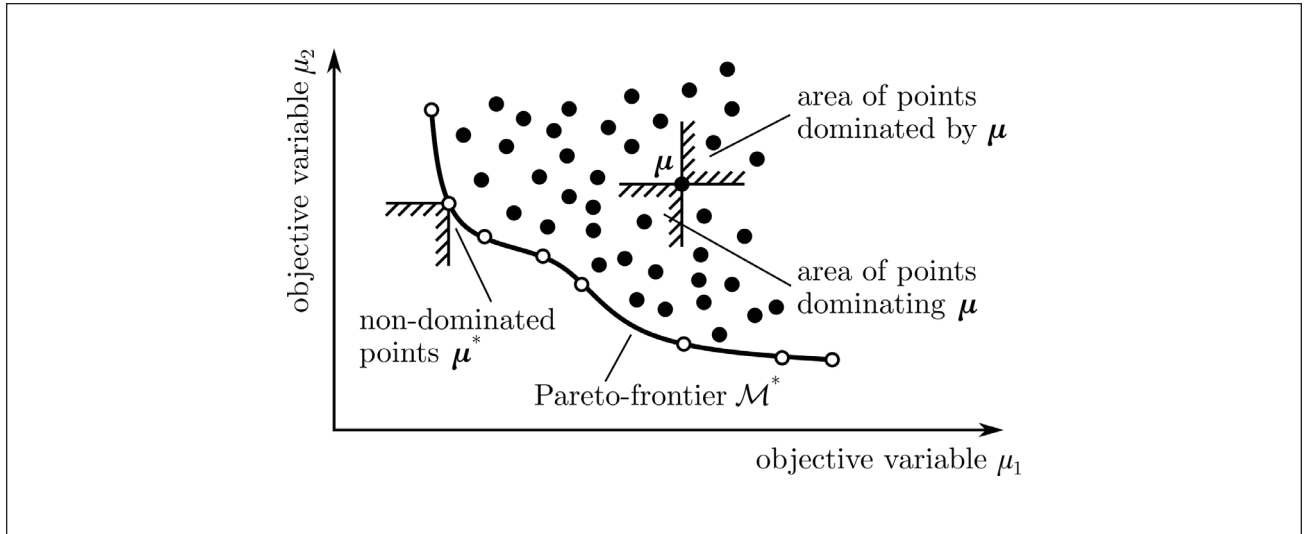
Heat sealing is the most used technology for closing polymer packages in packaging processes for food, cosmetics, pharmaceuticals, and other consumer products [1,2]. By pressing a hot sealing jaw against the packaging film for a certain time, the film layers fuse and form a tight bond. However, the resulting seam is a weak point for mechanical stress, a potential barrier leak for migration of contaminants or aromas, and may inhibit easy opening of the package, so that packaging failures mostly occur at the sealed seam. Hence, the quality of the sealed seam highly affects the protection and accessibility of the packed product. For this reason, heat sealing is one of the most important process steps in industrial packaging of consumer products [3].

Evidently, knowing the sealing characteristic of a polymer film is the key for improving industrial packaging processes. Furthermore, the successful operation of a heat sealing process requires knowledge as to the effect of the

sealing parameters’ sealing temperature, dwell time, and sealing pressure on the quality key figures, such as cold-tack and hot-tack seal strength or tightness. This interrelation between sealing parameters and quality key figures is usually called the sealing characteristic, sealing behavior, or sealability, and is regarded as one of the most important properties of packaging films.

Designs of experiments for identifying heat sealing characteristics

Several publications deal with the design of experiments for characterizing heat sealability of packaging films, and some of them are widely used in packaging industry [4-8]. For instance, the so-called heat seal curve is an international test standard (ASTM F2029 “Standard practices for making laboratory heat seals for determination of heat sealability of flexible barrier materials as measured by seal strength”). However, these designs of experiments have



1. Bi-objective optimization problem; dominance relations between points in the objective space and Pareto frontier as a solution to the optimization problem [9].

significant disadvantages. The authors pointed out two key deficiencies [9]:

- Single parameter approaches, such as the heat seal curve according to ASTM F2029, only provide information about the material response of a packaging film towards a single parameter, while all other sealing parameters occur only as fixed process conditions. For this reason, the results are not valid for other process conditions as specified in the experiments.
- Multiple parameter approaches provide contour plots, which identify all feasible combinations of the sealing parameters for a certain seam quality. However, the corresponding designs of experiments documented in the literature either require many test points and create time consuming experiments or produce significant errors due to defective regression models.

In summary, state-of-the-art design of experiments do not provide appropriate methods for easy and precise identification and comparison of sealing characteristics of packaging films for industrial applications.

Aims and scope of this paper

The authors have recently published a new design of experiments based on Pareto optimization in [9], which eliminates the disadvantages of the state-of-the-art-approaches mentioned before. They presented some use cases regarding the comparison of packaging films at the 18th TAPPI European PLACE Conference in Bratislava [10]. This paper gives a short summary about the new design of experiments and shows how to apply it to certain use cases. The following section outlines the essential basics of the approach and explains how to generate a specific design of experiments. The subsequent section on case studies presents three use cases from industry and research.

PARETO-BASED SEALING PARAMETER CHARACTERIZATION

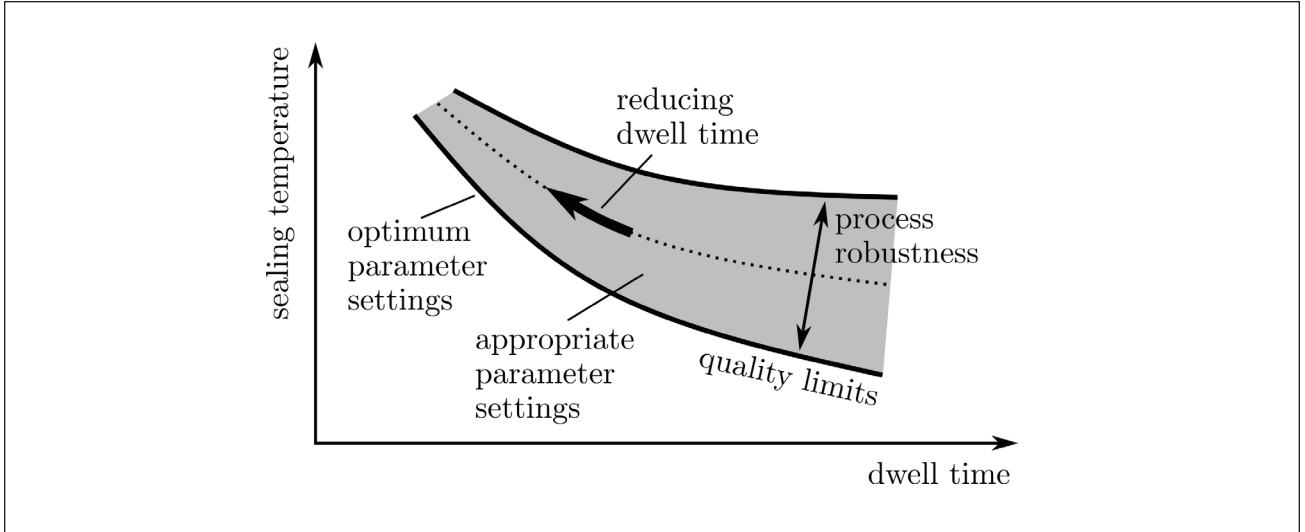
Basics of multi-objective optimization and Pareto-based concept selection

Multi-objective optimization, or Pareto optimization, deals with problems of a vector of $n \geq 2$ objective variables $\mu = [\mu_1, \mu_2, \dots, \mu_n]^T \in M$. These objectives may be a function of a vector of m decision variables $x = [x_1, x_2, \dots, x_m]^T \in X$, so that $\mu = [f_1(x), f_2(x), \dots, f_n(x)]^T$. M is called the objective space and X is the decision space. **Figure 1** shows a bi-objective example. A multi-objective optimization problem is then defined as:

$$\begin{aligned} &\text{minimize} && \mu = f(x) \\ &\text{subject to} && g(x) \leq 0, \\ & && b(x) = 0, \\ & && a \leq x \leq b \end{aligned} \quad (1)$$

where $g(x)$ is a set of inequality constraints and $b(x)$ is a set of equality constraints. The vectors a and b are the lower and upper bounds of the decision variables vector. A decision vector $x^* \in X$ is called Pareto optimal, if no other vector $x \in X$ exists such that $\mu(x) \leq \mu(x^*)$. This relation refers to the concept of dominance, where the objective vector $\mu^* = \mu(x^*) \in M^*$ is a non-dominated vector. Consequently, the solution of optimization problem consists of (1) a set of Pareto optimal decision vectors, called the Pareto optimal set $x^* \subseteq X$, and (2) the corresponding set of non-dominated objective vectors, called the Pareto frontier $M^* \subseteq M$. Thus, the solution of a multi-objective optimization problem represents the best compromises between conflicting objectives. [11-13].

By applying dominance relations to a set of Pareto frontiers, Mattson and Messac [14] presented an approach for selecting design concepts by comparing and evaluating the



2. Process parameter chart showing appropriate and optimum parameter combinations, indicating the direction of dwell time reduction and increasing process robustness [9].

individual Pareto frontiers. According to this framework, a design concept c is a principal solution represented by a parametric model $\mu=f(x^c)$, where x^c are the specific decision variables of concept c . Following the notations of the previous section, $X^c \subseteq X$ is the Pareto optimal set of the concept, including all Pareto optimal decision vectors $x^{*c} \in X^c$, and $M^c \subseteq M$ is the Pareto frontier of the concept, while $\mu^{*c} = \mu(x^{*c}) \in M^c$ indicates a corresponding non-dominated objective vector. Thus, the selection of preferred concepts results from dominance analysis between the Pareto frontiers of all concepts. A concept A is dominant if no other concept B exists such that $\{\mu^{*B} \leq \mu^{*A} : \forall \mu^{*A} \in M^{*A}, \forall \mu^{*B} \in M^{*B}\}$. Such a concept is called the best concept and represents the preferred choice. A concept A is partially dominant if at least one dominant objective vector of a concept B exists such that $\{\mu^{*B} \leq \mu^{*A} : \mu^{*A} \in M^{*A}, \mu^{*B} \in M^{*B}\}$. In this case, there is no distinct preference and additional criteria are necessary.

The parameter settings optimization problem of heat sealing

The basic idea behind the new characterization approach is to formulate a multi-objective optimization problem and deduce a specific design of experiments for any individual use case. The result is a process parameter chart like **Fig. 2**, which shows all appropriate and optimum process parameter combinations. In this context, sealing temperature T_s and dwell time t_d are both sealing parameters, for which a minimum value is preferable. Sealing pressure has no significant effect on seam quality in most industrial applications [15-17]. Seam quality is given by the acceptable range of a quality key figure with:

$$\Delta q = q_{\text{upp}} - q_{\text{low}} \quad (2)$$

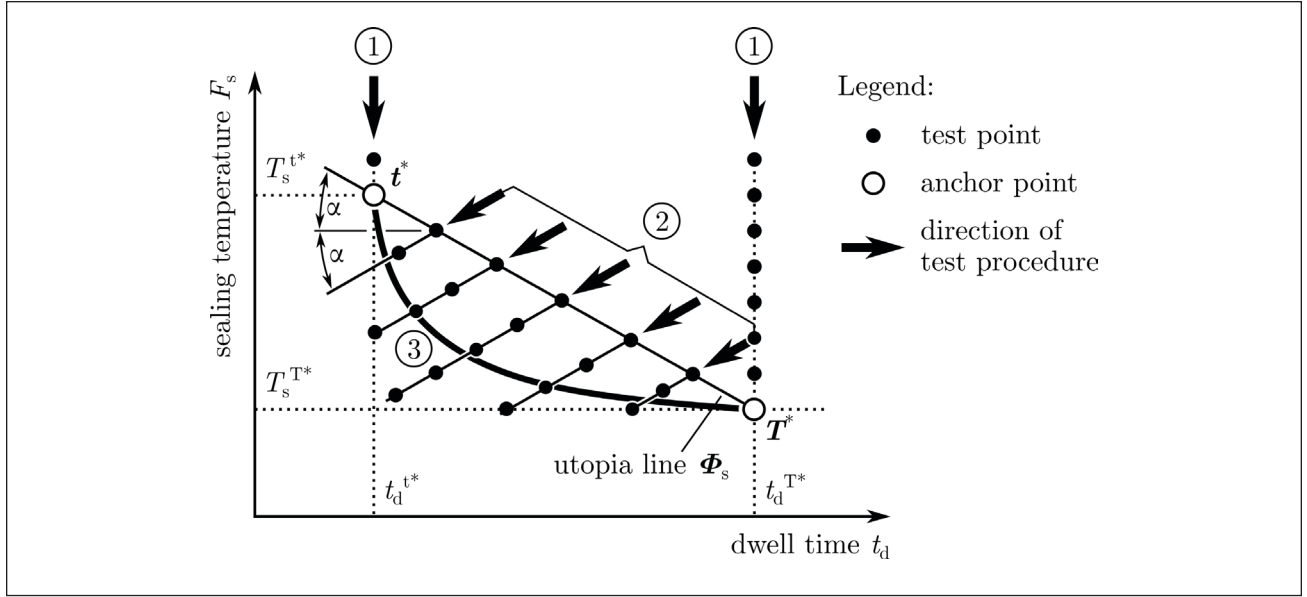
where q_{upp} and q_{low} are the quality criteria q_{crit} to be met. Process robustness is the range of an influencing factor with:

$$\Delta u = u_{\text{upp}} - u_{\text{low}} \quad (3)$$

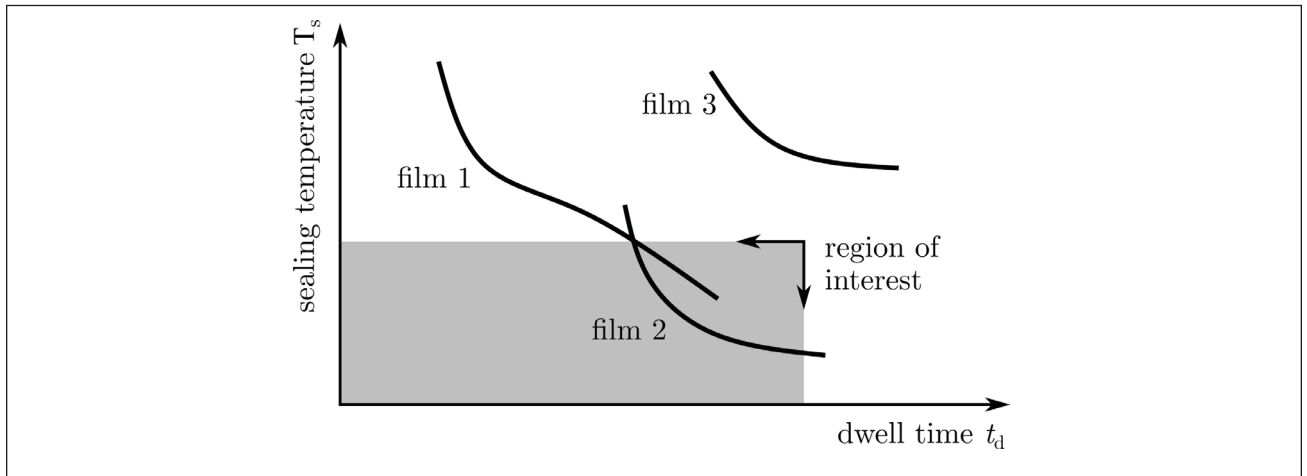
where u_{upp} and u_{low} are the limits u_{crit} for which the quality criteria will be fulfilled. Two corresponding pairs of one quality criterion and one robustness criterion define the upper and lower boundaries of the area of appropriate sealing parameters in Fig. 2. Formalizing this problem gives the following bi-objective parameter settings optimization problem for each boundary [9]:

$$\begin{aligned} &\text{minimize} && \begin{pmatrix} T_s \\ t_d \end{pmatrix} \\ &\text{subject to} && q = f(T_s, t_d, u) \\ &&& q = q_{\text{crit}} \\ &&& u = u_{\text{crit}} \\ &&& T_{s,\text{min}} \leq T_s \leq T_{s,\text{max}} \\ &&& t_{d,\text{min}} \leq t_d \leq t_{d,\text{max}} \end{aligned} \quad (4)$$

where $q = q_{\text{crit}}$ and $u = u_{\text{crit}}$ determine the specific boundary, while $T_{s,\text{min}} \leq T_s \leq T_{s,\text{max}}$ and $t_{d,\text{min}} \leq t_d \leq t_{d,\text{max}}$ specify the feasible range of sealing temperature and dwell time, respectively. Since all objectives of this optimization problem are explicit attributes with $X = M$, it is a special type of multi-objective optimization problem called a multi-attribute decision making problem. The corresponding solution is a set M_s^* of all Pareto-optimal and non-dominated parameter settings $\mu_s^* = [t_d^*, T_s^*]^T$.



3. Design of experiments: (1) identifying the anchor points; (2) executing the test points for identifying the Pareto points; and (3) generating the Pareto frontier by interpolation.



4. Comparing packaging films by means of their Pareto frontiers. Film 1 and film 2 are dominant over film 3. Film 1 and film 2 are partially dominant over each other, while film 2 is dominant over film 1 considering the region of interest, which is represented by the shaded area.

Design of experiments based on the Normal-boundary-intersection method

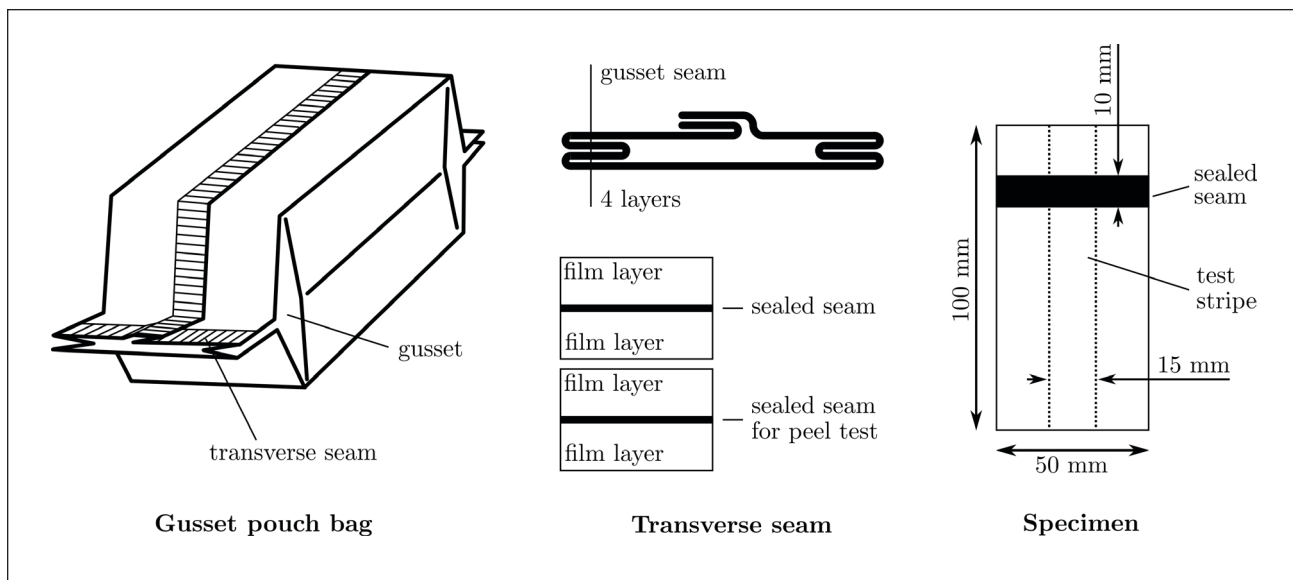
Solving the parameter settings optimization problem means generating the Pareto frontier M_s^* , which includes all optimum parameter settings $\mu_s^* = [t_d^*, T_s^*]^T$. Based on the Normal-boundary-intersection method by Das and Dennis [18], generating the design of experiments comprises three steps, as illustrated in **Fig. 3**:

1. Identifying anchor points T^* and t^*
2. Identifying Pareto points μ_s^*
3. Interpolating the Pareto frontier M_s^*

In the following list, a simplified notation of this test scheme is presented. For detailed mathematical explanations and validation, see [9].

Step 1: The anchor points $T^* = [t_d^{T^*}, T_s^{T^*}]^T$ and $t^* = [t_d^{t^*}, T_s^{t^*}]^T$ are those parameter combinations that separately achieve minimum sealing temperature $T_s^{T^*}$ and minimum dwell time $t_d^{t^*}$. These points are located on the dwell time boundaries $t_{d,min}$ and $t_{d,max}$, as shown in Fig. 3, step (1). Executing tests along these boundaries provides the anchor points. The so-called utopia line Φ_s links the anchor points and serves as reference points for the following test sequences.

Step 2: A Pareto point $\mu_s^* = [t^*, T^*]$ is a parameter combination of the sealing parameters, for which sealing temperature and dwell time are both minimal. Executing sealing tests as given in Fig. 3, step (2) provides these points. These test sequences follow the so-called utopia normals, which are lines of equal distance to each other



5. Gusset pouch bag according to the case study, corresponding transverse seam, and specimens for the laboratory tests.

that form the same angle α with the dwell time axes as the utopia line does. This is the geometric equivalent to the pay-off matrix mentioned in [9]. The experimenter may determine the number of test sequences according to his or her preferences towards precision of the results and costs of the experiments.

Step 3: The Pareto frontier M_s^* includes all Pareto points, and represents one boundary of the area of appropriate parameter settings. By simply interpolating between the Pareto points, the Pareto frontier is generated, as may be seen in Fig. 3, step (3). Drawing all Pareto frontiers in one chart completes a parameter chart, as shown in Fig. 2.

Pareto-based comparison of packaging films

Dominance analysis of Pareto frontiers allows effective comparison of different packaging films [10]. Following the concept selection method introduced previously, any packaging film c is characterized by the Pareto frontier M_s^{*c} , including all optimum parameter combinations $\mu_s^{*c} = [t_d^*, T_s^*]^T$ for the heat sealing process. Thus, a Pareto frontier is dominant over another if all its sealing parameter combinations are better than those of the other Pareto frontiers. **Figure 4** shows an example of three Pareto frontiers representing three packaging films: Pareto frontiers 1 and 2 are both dominant over Pareto frontier 3, i.e., films 1 and 2 are better than film 3. However, Pareto frontier 1 and frontier 2 are only partially dominant over each other, i.e., there are regions in which film 1 is better than 2 and vice versa. In this case, defining a region of interest may give a distinct result.

CASE STUDIES

Transport damage and failure analysis

The scenario setting

A dairy produces instant beverage powder for two different clients, A and B. In the last process step, a vertical form-fill-

seal machine (VFFS machine) fills gusset pouch bags of 1 kg filling weight with the powder. The clients order two different pouch formats, A and B, where circumference of format B is about 5 cm smaller than that of A. The packaging films for A and B are provided by two different film suppliers. Film A is a PET12/Al9/PE70 laminate of a 12 μm polyethylene terephthalate (PET) layer, a 9 μm aluminum (Al) layer, and a 70 μm polyethylene (PE) layer. Film B is a similar PET12/Al9/PE60 laminate, but has a 60 μm polyethylene layer. However, a more detailed specification of the resins is not available. Both clients require safe shipping and complain if packages burst. In this context, it turned out that the pouches for client B tend to burst significantly more often. This has been confirmed by the quality assurance department of the dairy by executing drop impact tests according to ISO 2248 “Packaging — Complete, filled transport packages — Vertical impact test by dropping.” The gusset section of the transverse seam was identified as the weak point, as shown in **Fig. 5**. So far, all attempts failed to fix this problem and to achieve better results for pouch B. For this reason, the packaging engineer of the dairy suspected the cause to be the sealing properties of film B. In order to verify this assumption, laboratory tests were used to identify and compare the optimum sealing parameters for both films.

Methods and materials

Experimental heat sealing and peel tests were used for characterization of the sealing properties of the two films. The preparation of the specimens is illustrated in Fig. 5. For creating representative test results, the test scenario imitates the sealing conditions in the gusset seam section by sealing four film layers and peeling the seam of the bottom two layers. Dimensions of the specimens are 50 mm to 100 mm. A laboratory seal machine, Kopp Labormaster 3200 (Willi

	Client	$q_{crit,A}$	u_{crit}	$t_{d,min} \leq t_d \leq t_{d,max}$	F
Test series 1	A	$q_{crit,A} = 35 \text{ N/15 mm}$	4	$0.2 \text{ s} \leq t_d \leq 1 \text{ s}$	800 N
Test series 2	B	$q_{crit,B} = 35 \text{ N/15 mm}$	4	$0.2 \text{ s} \leq t_d \leq 1 \text{ s}$	800 N
Test series 3	B	$q_{crit,B} = 40 \text{ N/15 mm}$	4	$0.2 \text{ s} \leq t_d \leq 1 \text{ s}$	800 N

$q_{crit,A}$ = quality criteria, client A; $q_{crit,B}$ = quality criteria, client B; u_{crit} = limits for which the quality criteria is fulfilled; t_d = dwell time.

I. Test settings for laboratory sealing test.

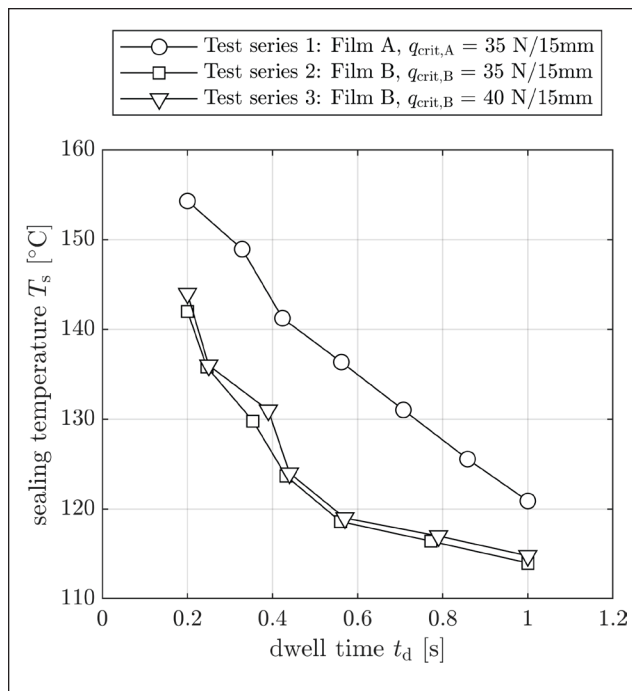
Kopp e.K. Verpackungssysteme; Reichenbach an der Fils, Germany), equipped with 10 mm wide, flat, coated seal jaws, served for making seams following ASTM F2029. The specimens were stored for 24 h at standard atmosphere of 23°C air temperature and 50% relative humidity according to ISO 291 “Plastics — Standard atmospheres for conditioning and testing.” Seal strength was measured by peel tests based on ASTM F88 “Standard test method for seal strength of flexible barrier materials,” at a constant peel rate of 100 mm/min using 15 mm wide stripes cut from the middle of the specimens. Five samples were made of every parameter setting and checked for normal distribution using the Jarque-Bera test.

Design of experiments followed the Pareto-based approach introduced in the earlier “Design of experiments” section. A specific seal strength represents the quality criteria q_{crit} for both films. The robustness criterion refers to the number of the film layer at the gusset seam section, where $u_{crit} = 4$. Dwell time limits were set $0.2 \text{ s} \leq t_d \leq 1 \text{ s}$, because this corresponds with the desired operating range of 28 to 40 bags/min of the VFFS machine, according to the process engineer. Since sealing pressure at the VFFS machine was fixed at 1.6 MPa, a sealing force of $F = 800 \text{ N}$ was used for all tests at the laboratory sealer. **Table I** summarizes the test settings. Test series 1 and 2 identified the optimum sealing parameters for maximum seal strength of both films. In order to compare both films at the same seal strength level, test series 3 additionally identified the optimum sealing parameters of film B for maximum seal strength level of film A.

In total, 55 test points were necessary to accomplish all three Pareto frontiers. Identifying the anchor points required 10 test points for both films A and B. Generating the Pareto frontier for film A required 18 test points, and generating both Pareto frontiers for film B needed 17 test points. A statistical test plan would require 16 test points for each packaging film, or 32 in total, if a centralized, orthogonal, and rotatable full factorial design of experiments for maximum precision is taken as a reference.

Results

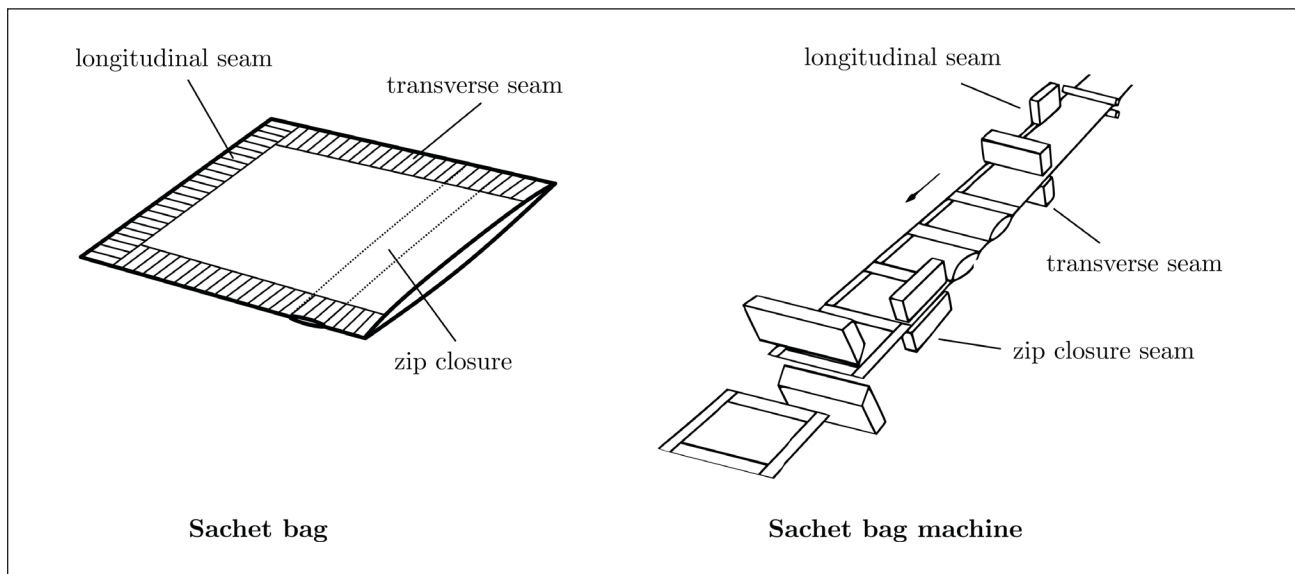
The results disproved the initial assumption that film B is less suitable than film A for creating strong sealed seams. While sealing and testing under laboratory conditions, film



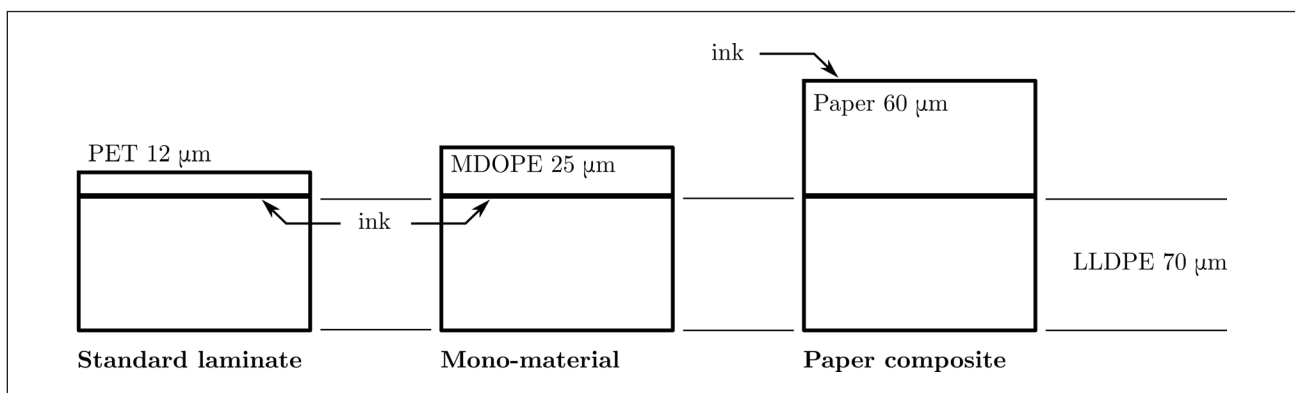
6. Comparison of two packaging films for beverage powder pouch bags. Maximum seal strength 35 N/15mm for film A and 40 N/15mm for film B (q_{crit} = quality criteria).

B reached a maximum seal strength that is about 5 N/15 mm higher than the maximum seal strength of film A, which is $q_{crit,A} = 35 \text{ N/15 mm}$ for film A and $q_{crit,B} = 40 \text{ N/15 mm}$ for film B. Additionally, **Fig. 6** shows that film A required longer dwell times and higher sealing temperatures to reach the same seal strength $q_{crit,A} = q_{crit,B} = 35 \text{ N/15}$. Film B reached a seal strength equivalent to the maximum seal strength of film A at significantly shorter dwell times and lower temperatures. This means that film B is better concerning the factors of seal strength, dwell time, and sealing temperature, if compared by laboratory test under the same conditions.

The first inclination of the packaging engineer at the dairy was that the thinner sealing layer of film B must result in a weaker seam. However, some other factors affect the seam resistance of a sealed flexible package, such as type and grade of the PE resin and adhesive layers of the packaging film, or load type and stress ratio during peel-



7. Sachet bag according to the case study, and schematic production process of the sachet machine, using DIN EN 415-3:2022 "Safety of packaging machines — Part 3: Form, fill and seal machines."



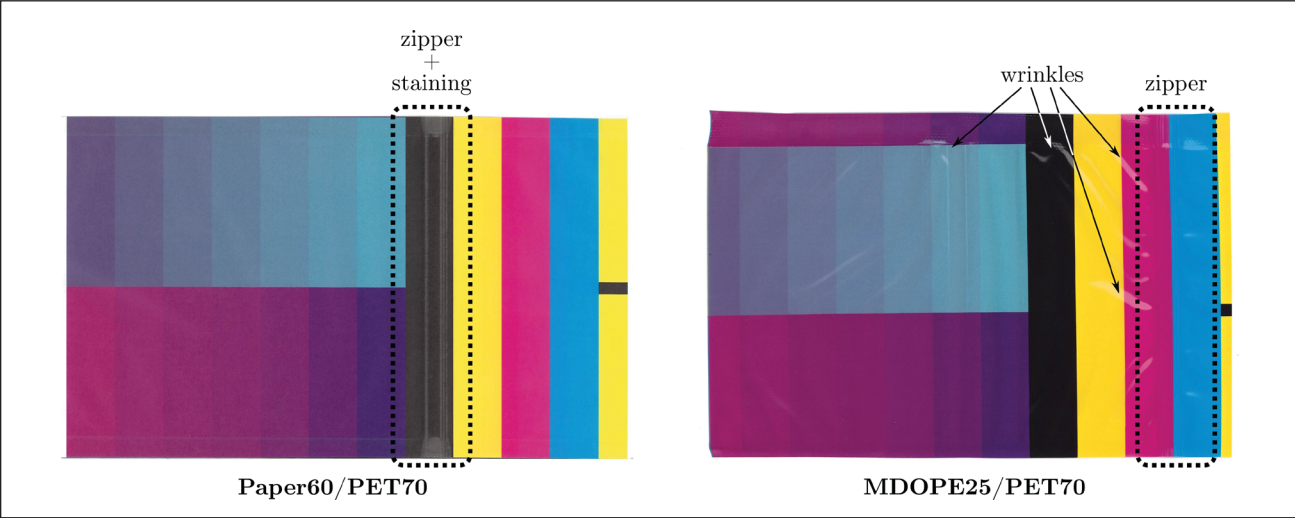
8. Laminate structures of the three packaging films for sachet bags (PET = polyethylene terephthalate; MDOPE = machine-direction orientated polyethylene; LLDPE = linear low-density polyethylene).

ing the seam. Since the thinner film B unintentionally performs better than the thicker film A under equal sealing and peeling conditions in laboratory tests, different material properties of the sealing and adhesive layer of film B seem to advance seal strength. However, film B performs worse than film A under production conditions. Since sealing conditions in the packaging machine are the same for both pouches A and B, and transport stress was tested by drop impact tests under equal conditions, this discrepancy with the laboratory tests may stem from different load types at the pouches and stress ratio in the seam. Presumably, the weaker resistance of pouches B against transport stress is due to the smaller circumference of pouches B, which creates a smaller filling volume. Since both pouches contain 1 kg beverage powder, this may lead to higher stress at the seams of pouches B, which would negate the better sealing properties of film B.

Optimum sealing parameters for new packaging films

The scenario setting

A printing company specialized in individually designed packages produces sachet bags with zip-closure as shown in **Fig. 7**. Customers may design the imprint for their bag on their own, upload the design file to a website of the company, and order 50 to 10000 bags. At first, the company prints the motif on the carrier film layer and laminates the carrier layer on the sealing layer. After that, a sachet bag machine makes the bags according to the process shown in Fig. 7. The customers require wrinkle-free, airtight bags with immaculate imprint. So far, the company offers a standard PET/LLDPE packaging film with 12 μm polyethylene terephthalate (PET) and 70 μm linear low-density polyethylene (LLDPE). The zipper is made from low-density polyethylene (LDPE). Recently, new regulations and customer preferences request mono-material and paper-based packaging films. Given certain considerations, the company has chosen to replace the PET



9. Pouch bag with test motif: Upper quality criteria staining and wrinkles.

	q_{low}	q_{upp}	u_{crit}	$t_{d,min} \leq t_d \leq t_{d,max}$
PET12/PE70	Airtight at 500 mbar	No wrinkles	Transverse seam	$0.35 \text{ s} \leq t_d \leq 1 \text{ s}$
MDOPE25/PE70	Airtight at 500 mbar	No wrinkles	Transverse seam	$0.35 \text{ s} \leq t_d \leq 1 \text{ s}$
Paper60/PE70	Airtight at 500 mbar	No staining	Transverse seam	$0.35 \text{ s} \leq t_d \leq 1 \text{ s}$

q_{low} = lower quality criterion; q_{upp} = upper quality criterion; u_{crit} = limits for which quality criteria are fulfilled; t_d = dwell time; PET = polyethylene terephthalate; MDOPE = machine-direction orientated polyethylene; PE = polyethylene.

II. Test settings for pouch production.

Number of Test Points	q_{low}		q_{upp}	
	Anchor Points	Pareto Points	Anchor Points	Pareto Points
PET12/PE70	5	17	4	4
MDOPE25/PE70	3	19	4	10
Paper60/PE70	4	22	5	8

q_{low} = lower quality criterion; q_{upp} = upper quality criterion; PET = polyethylene terephthalate; MDOPE = machine-direction orientated polyethylene; PE = polyethylene.

III. Number of test points for each Pareto-frontier.

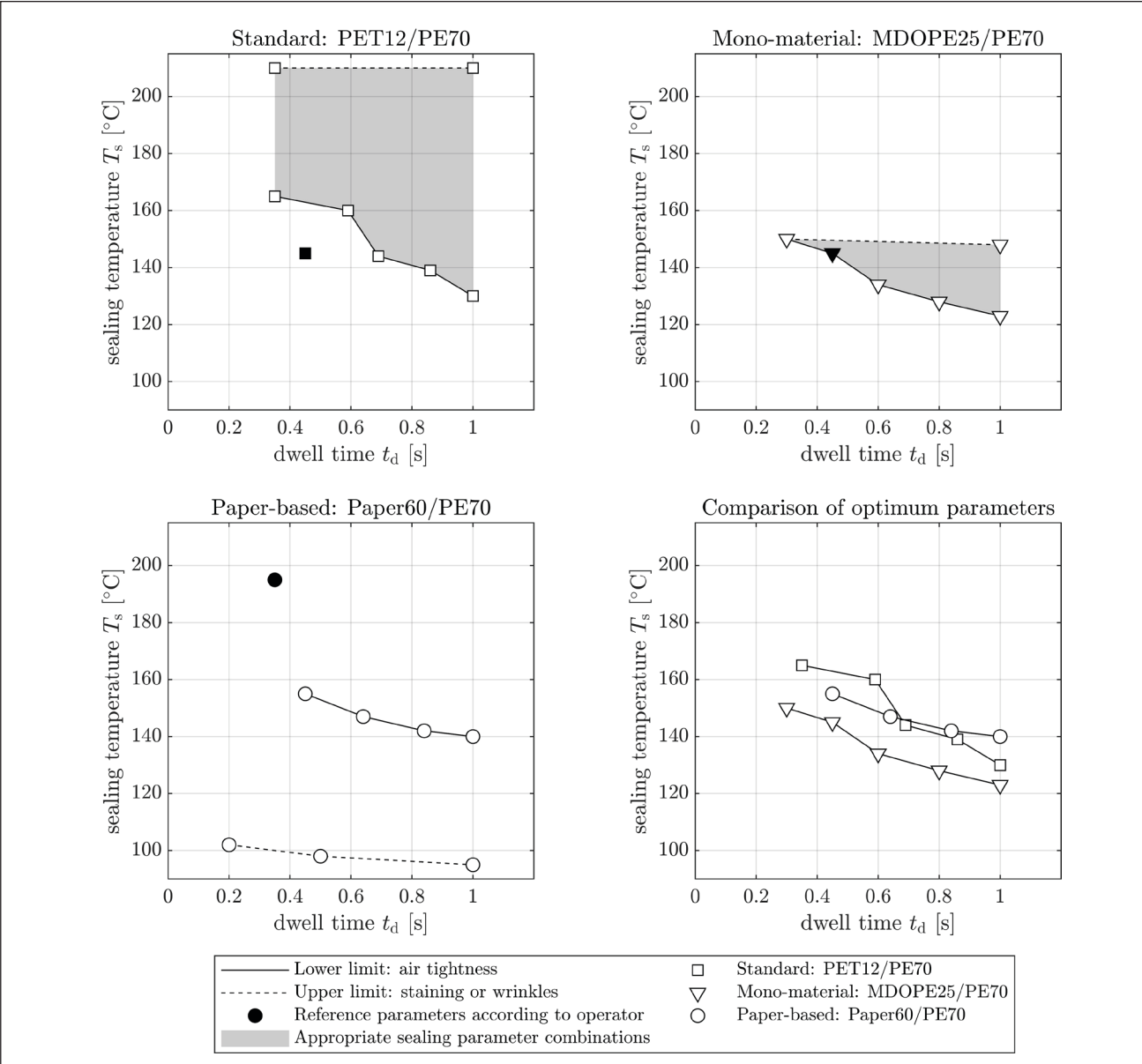
by a 25 μm machine-direction orientated polyethylene (MDOPE) and a 60 μm machine glazed kraft paper. Based on the LLDPE sealing layer, the company plans to offer a MDOPE/PE and a paper/PE laminate. All three laminates are shown in **Fig. 8**. However, recent tests show significant wrinkles with the MDOPE/PE laminate and staining with the paper/PE laminate, which the operators could not eliminate. In order to check if both laminates can be processed on the existing machine, and to find appropriate sealing parameters, the optimum sealing windows were identified and compared.

Methods and materials

Printing, laminating, and bag making was all done under real production conditions. An HP Indigo 20000 direct dig-

ital printer serves for printing the test motif on the carrier layer. The printing machine uses the so-called liquid electrophotography technology, which is based on electrostatic inks that are applied to the carrier layer material by a thermic bonding effect at 95°C to 110°C [19]. The test motif includes all four basic colors — black, yellow, blue and magenta — as well as a blue, red, and green gradient color section (see **Fig. 9**). The PET and MDOPE film is printed reverse, so that the print is on the inner side of the transparent carrier layer. This side is laminated against the sealing layer in the next process step. With the non-transparent paper backing, the motif must be printed on the outside.

A Karlville KS-DSUP-400-GSW (Karlville Technologies; Miami, FL, USA) bag making machine is used to produce



10. Optimum and appropriate sealing parameters for each packaging film and comparison of Pareto frontiers of optimum sealing parameters.

sachet bags of dimensions 14 cm x 21 cm. The machine has one sealing station for the longitudinal seam, one station for the zip-closure, and five stations for the transverse seam. The transverse sealing stations operate synchronously at the same sealing temperature and dwell time. Minimum dwell time is 0.35 s.

Air tightness of the pouches is required for all four packaging films and was tested at 500 mbar vacuum according to DIN 55508-5 “Packaging test – Leakage test on flexible packagings – Part 5: Water bath method (bubble test).” Wrinkles of the PET and MDOPE carrier layers and staining of the prints on the paper carrier layer were identified with visual inspection by the machine operator and the authors of this paper. Examples of pouches not compliant

with quality requirements are shown in Fig. 9. Since the transverse seam was identified as the weak point, the study focused on this sealing station.

Design of experiments followed the Pareto-based approach introduced in the earlier “Design of experiments” section, where air tightness, wrinkles, and staining are the quality criteria. **Table II** summarizes the corresponding test settings. The scenario included six test plans and required 105 test points in total. **Table III** lists the number of test points for each packaging film and quality criterion. As a reference for this scenario, a set of centralized, orthogonal, and rotatable full factorial test plans would use 16 test points for each packaging film and quality criterion, which is 96 in total.

FLEXIBLE PACKAGING

Results

Figure 10 shows the sealing characteristics of each laminate and a comparison of the minimum sealing parameter combinations. The shaded areas indicate all appropriate sealing parameters producing a seam that fulfills the lower and upper quality criteria. This area was significantly larger for the standard PET12/PE70 laminate than for the mono-material MDOPE25/PE70, which implies that the mono-material is less robust for sealing applications. This result confirms other published studies [6,16]. Regarding the Paper60/PE70 laminate, a quality conformant package is not able to be produced, because the Pareto frontier indicating staining of the test imprint is significantly below the Pareto frontier indicating an airtight bag. This result seems feasible, since printing temperature of the ink is from 95°C to 110°C. Comparing the minimum sealing parameter by its corresponding Pareto frontiers does not show significant differences, which may be due to the fact that all three laminates use the same sealing layer.

It is noted that quality evaluation for all Pareto frontiers underlie inaccuracies because of subjective assessment of the experimenters and binary characteristics of the quality key figures. For this reason, the Pareto frontiers showed discontinuous gradients and deviated from the reference parameter combinations according to the operator's experience. However, this does not affect the fundamental statements of the case study.

Effect of additional aluminum layers on hot-tack

The scenario setting

In vertical form-fill-seal machines, filling takes places immediately after closing the lower seam of the package. By this, the hot seam is significantly loaded, and may open completely or partially while filling. For this reason, the

seal strength of the hot seam, the so-called hot-tack, significantly affects productivity of such packaging machines [20]. In order to improve hot-tack strength of packaging films, manufacturers add aluminum layers between the sealing and carrier layer. Presumably, this affects hot-tack strength in two ways [21-23]:

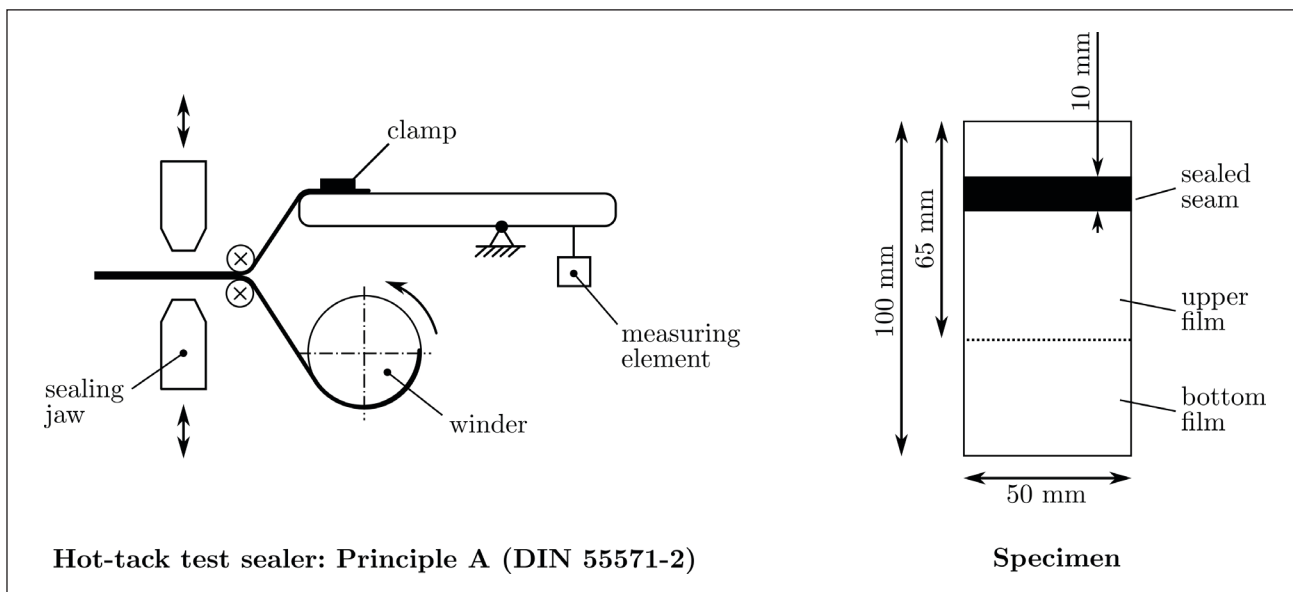
- The aluminum layer supports conduction and distribution of heat to the sealing layer and improves homogeneous melting and bonding.
- The aluminum layer positively affects fracture mechanics and increases peel strength.

This assumption was validated by using the new design of experiments.

Methods and materials

Four different laminates were used for the comparative study: two laminates have a 50 µm PE sealing layer, and two have a 50 µm polypropylene (PP) sealing layer. One of each has an additional 9 µm aluminum layer between the sealing and carrier layer. The carrier layer of all laminates is a 12 µm PET. Thus, the four laminates were PET12/PE50, PET12/Al9/PE50, PET12/PP50, and PET12/Al9/PP50.

Sealing and hot-tack testing followed the standard test method according to DIN 55571-2 "Hot-Tack – Part 2: Peel strength measuring devices, principle A," as shown in **Fig. 11**. A laboratory seal tester Kopp Labormaster 3200, equipped with 10 mm wide, flat, coated seal jaws and a hot-tack device, served for making and testing the seams. Cooling time between sealing and testing was 0.2 s, and peel velocity was 12 m/min. As shown in Fig. 11, the specimens consisted of a 50 mm² x 60 mm² upper and a 50 mm² x 100 mm² bottom packaging film due to geometric requirements of the seal tester. Five samples were made



11. Seal tester and specimen for analyzing hot-tack, using DIN 55571-2.

Number of Test Points	Anchor Points	Pareto Points		
	Total	Maximum	Minimum	Delamination Limit
PET12/PE50	35	15	5	8
PET12/Al9/PE50	54	18	18	10
PET12/PP50	55	17	3	3
PET12/Al9/PP50	35	13	3	3

PET = polyethylene terephthalate; Al = aluminum; PE = polyethylene.

IV. Number of test points for each Pareto-frontier.

of every parameter setting and checked for normal distribution using the Jarque-Bera test.

Three different quality criteria were analyzed:

- Maximum hot-tack $q_{\max} = \max_{t_d, T_s} F_{s, \text{hot}}$, which indicates absolute maximum stress that may be applied to the seam. This directly affects machine performance.
- Delamination limit q_{del} , at which delamination of the film layers appears for the first time. This limit indicates interlayer and laminate failure of the packaging film.
- Minimum hot-tack $q_{\min} = 5\text{N}/50\text{mm}$, which is a reference value for an air and liquid tight seam [20].

The design of experiments, as introduced in the earlier section by that name, was executed for all three quality criteria and all four packaging films. **Table IV** lists the number of test points required for all 12 test plans corresponding to each packaging film and quality scenario. In total, 295 test points were necessary to generate all Pareto-frontiers, where 179 of these were allotted to the anchor points and 116 to the Pareto points. This disproportionately high number of test points for identifying the anchor points was needed, because the feasible ranges of sealing temperature $T_{s, \min} \leq T_s \leq T_{s, \max}$ and dwell time $t_{d, \min} \leq t_d \leq t_{d, \max}$ were completely unknown at the beginning of the study. Alternatively, a centralized, orthogonal, and rotatable full factorial design of experiments may merge the maximum and minimum hot-tack criterion into one test plan, so that eight test plans with 16 test points each and 128 test points in total would have been necessary.

Results

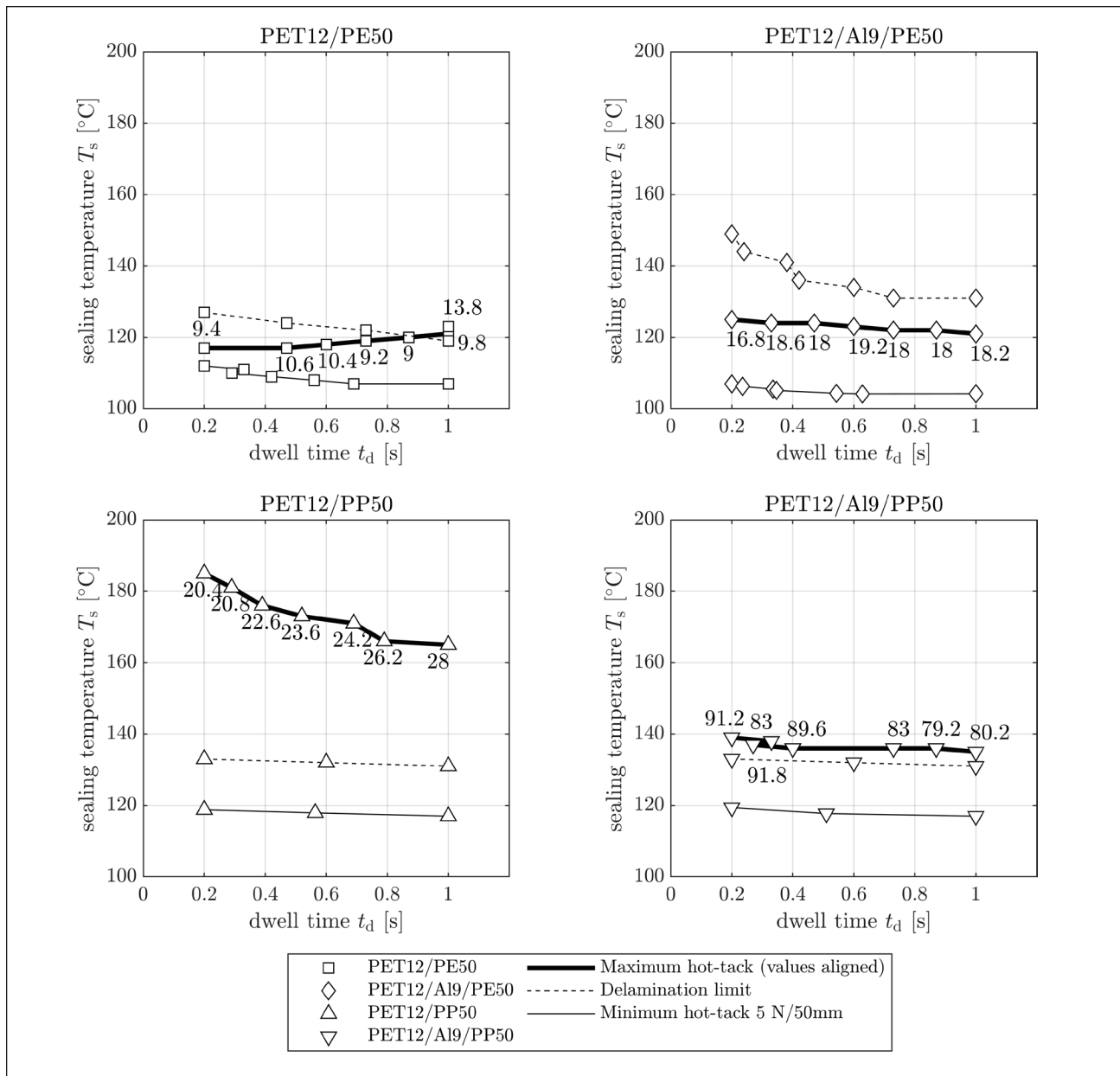
Figure 12 shows the hot-tack characteristics for all four laminates separately. The following results should be highlighted:

- 1) There was little dependency on dwell time, except for hot-tack of the PET12/Al9/PE50 laminate at the delamination limit criterion and for hot-tack of the PET12/PP50 laminate at maximum hot-tack strength. This indicates that shorter dwell times are possible without significant increase of the sealing temperature.

- 2) Both PE50 laminates reached maximum hot-tack strength for lower sealing temperatures and shorter dwell time rather than reaching the delamination limit, while both PP50 laminates reached maximum hot-tack strength for higher sealing temperatures and longer dwell times rather than reaching the delamination limit. This difference in failure mechanics was possibly due to worse adhesion between the PE50 sealing layer and the laminating adhesive compared with adhesion to the PP50 sealing layer. **Figure 13** depicts the hot-tack characteristics for all three quality criteria separately.
- 3) The 3D-plot shows that the PP50 laminates generated higher maximum hot-tack strength than PE50 laminates. However, the effect of the additional aluminum layer on both the PP50 and the PE50 laminate was significant and improved maximum hot-tack strength by about 400% and 80%.
- 4) The delamination limit significantly shifted towards higher sealing temperatures, if an aluminum layer was added to a PE50 laminate. Regarding the PP50 laminate, an additional aluminum layer did not change the position of the Pareto frontier.
- 5) The comparison of the Pareto frontiers indicating sealing parameters for the minimum hot-tack strength criterion gave a similar result. An additional aluminum layer shifted the Pareto frontier towards lower sealing temperatures and dwell times for PE50 laminates, but did not for PP50 laminates.

In summary, adding an additional aluminum layer to a packaging film laminate significantly increased maximum hot-tack strength, but did not necessarily shift the sealing parameter to lower sealing temperature and shorter dwell times. Evidently, an additional aluminum layer mainly changes failure mechanics by affecting the internal stress, while peeling the seam. Heat conduction and distribution seem to be a secondary effect regarding hot-tack, while some publications emphasize this effect [21-22]. However, both effects are highly dependent on the other layers constituting a packaging film.

Aside from these findings, some measurement artifacts



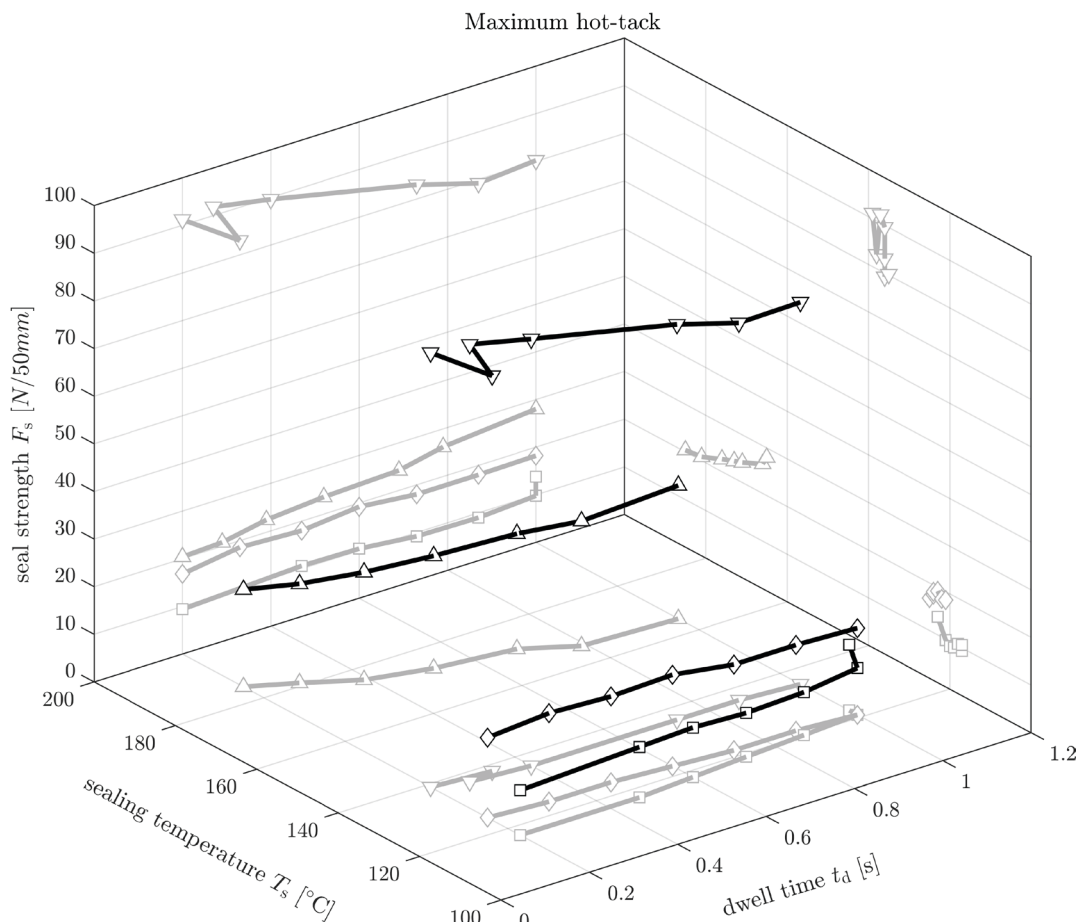
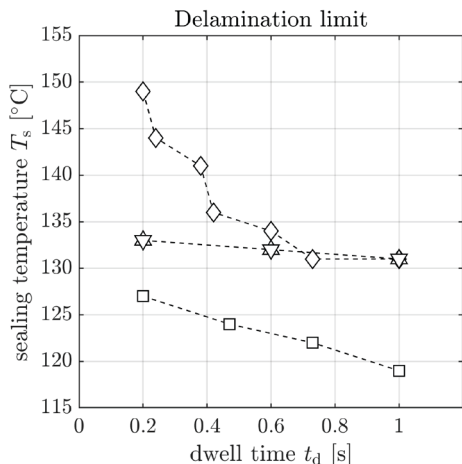
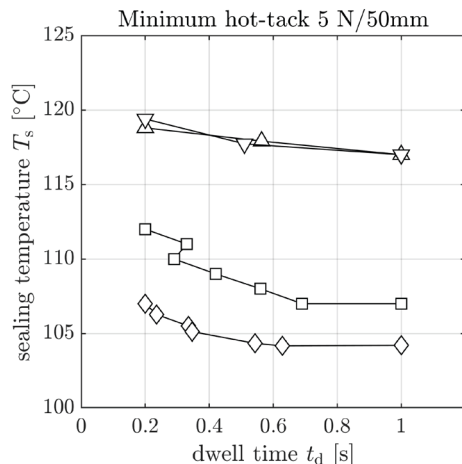
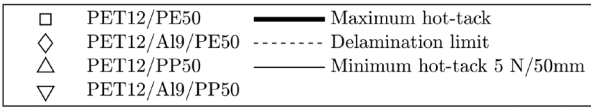
12. Optimum hot-tack curves of each laminate for maximum hot-tack, delamination limit, and minimum hot-tack.

are worth noting. The Pareto frontiers of the PET12/PE50 minimum hot-tack strength criterion, the PET12/Al9/PE50 delamination limit criterion, and the PET12/Al9/PP50 maximum hot-tack strength criterion showed unsteady and discontinuous trends in Fig. 12 and Fig. 13. These items stemmed from large increments of the discrete scale of the sealing temperature and the binary characteristic of the delamination limit and maximum hot-tack strength criterion. Thus, a Pareto point skips over a long distance in the chart when switching from the last point not compliant with the quality criterion to the first point fulfilling the quality criterion, whereas the Pareto point would actually lie between both points.

CONCLUSION

This paper has presented a recently published design of experiments identifying optimum sealing parameters for heat sealing in packaging applications and a method for comparing heat sealing characteristics of different packaging films by dominance analysis of Pareto frontiers. By executing a deterministic design of experiments based on the Normal-boundary-intersection method for generating Pareto frontiers, the optimum sealing parameters are identified. Using a Pareto-based concept selection method, the Pareto frontiers are compared and evaluated.

Three case studies verified the new approach: a beverage powder packaging case study proved that the new ap-



13. Comparison of all laminates in respect of maximum hot-tack, delamination limit, and minimum hot-tack (PET = polyethylene terephthalate; Al = aluminum; PE = polyethylene).

proach may serve for failure analysis of packaging processes. A sachet bag making case study showed that the new approach may help for evaluating sealing properties of new packaging films against established materials under real production conditions. Finally, a hot-tack case study focusing on the effect of additional aluminum layers demonstrated that the new approach enables detailed analysis of failure mechanics in an R&D environment.

In contrast to established characterization and comparison methods that provide very limited insight into practical issues of sealing behavior or require extensive experimenting, the new approach provides easy-to-read parameter charts without any regression model. It must be taken into account that the number of test points depends on the specific test scenario. It is similar to a centralized, orthogonal, and rotatable statistical design of experiments if the approximate range of feasible sealing temperatures and dwell times is known. In the case that sealing properties of the tested packaging film are completely unknown, the number of test points exceeds a comparable statistical test plan. However, the optimum sealing parameters identified with the Pareto-based design of experiments are exact results within the limits of measurement inaccuracies. Hence, discrete sealing parameter scales and binary quality key figures may limit accuracy of the Pareto-frontiers representing the optimum sealing parameters. As a conclusion, the Pareto-based identification and comparison of sealing char-

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acteristics provide more precise and usable results for industrial applications than the commonly used statistical design of experiments, but requires a larger number of testpoints in some cases. **TJ**

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Upcoming, sustainable packaging films have significantly smaller process windows for packaging processes, e.g., heat sealing. To give an estimation on the properties of the new packaging films, a precise method for comparing sealing characteristics of packaging films is helpful.

The presented design of experiments differs from established statistical design of experiments in two aspects: (1) the data points of the process window are generated directly from experiments without using any regression model; and (2) the provided charts indicate real optimum and process settings, as well as process robustness, for each parameter set.

The most difficult aspect of this work was finding a universal formulation of the design of experiments and the method for comparison of packaging films. It was addressed by transforming the comparison problem into a multi-objective optimization problem.

We discovered that mathematical methods that were intended for solving with computers are also appropriate for experimental solving. The provided process windows clearly show the different sealing properties and characteristics that are necessary for industrial heat sealing. It was interesting to find that there are alternatives for statistical design of experi-

ments that are more precise but do not require significantly more testing than the common statistical method.

A packaging film manufacturer may use this new approach to give its customers a precise characterization of how its packaging films behave with heat sealing. The design of experiments and comparison method is not limited to heat sealing, but may serve for other processes as well.

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