Optimizing Heat Press Parameters to Improve the Quality of DTF Printing

Bachelor Integration Project

Business research project – part of the BSc in Industrial Engineering and Management

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Abstract

Printing on textiles has been around for a while and was always considered an expensive process, that only becomes profitable at scale. Direct-to-Film (DTF) printing really changed the industry by offering flexible, high-quality textile decoration, but Vistaprint's industrial production faces recurring failures in print adhesion and color durability, leading to waste and customer complaints. This study investigates how heat press temperature and dwell time affect the quality of DTF prints on black cotton T-shirts, TPU-based granulates side by side. Using a full-factorial experimental design and a three-stage approach, samples were first screened for adhesion and color stability after washing. Only the best performers advanced to detailed microscopic analysis for fiber contamination. Statistical analysis using ANOVA showed that press temperature is the dominant factor across all quality metrics. Results demonstrate that setting the press to 170 °C with a 10 second dwell time minimizes color change (ΔE), reduces black density loss, and limits white-layer contamination for both granulates tested. The recommended process window enables Vistaprint to standardize DTF settings, thus improve quality control and as a result reduce customer complaints and production waste.

Contents

List of Abbreviations

ANOVA	Analysis of Variance
ΔE_{00}	CIEDE2000 Color Difference Metric
DoE	Design of Experiments
DTF	Direct-to-Film
DTG	Direct-to-Garment
GFR	General Factorial Regression
GLM	General Linear Model
ISO	International Organization for Standardization
PES	Polyester
PU	Polyurethane
QC	Quality Control
R&D	Research and Development
RSD	Relative Standard Deviation
SDS	Safety Data Sheet
SEM	Scanning Electron Microscopy
TDS	Technical Data Sheet
TPU	Thermoplastic Polyurethane
UV	Ultraviolet
VHX	Keyence VHX-7000N Digital Microscope

Introduction

Direct-to-Film (DTF) printing is a new trend in the textile customization market. It offers flexibility at relatively low cost, while being compatible with a wide range of substrates (Khalil et al. 2023). The global market for DTF is forecast to grow from $2.56 billion in 2023 to $3.99 billion by 2030, driven by increasing demand for personalized, on-demand apparel (GlobeNewswire 2024). For industrial players, such as Vistaprint, this technology enables scalable mass customization, but also introduces new quality control challenges when deployed at high volume.

At their Venlo facility, approximately 5% of printed garments are currently scrapped or reworked due to poor adhesion detected at the heat press stage. Some issues are not seen immediately, so customer complaints regarding color fading and peeling after washing follow after the product is sold. While these are not always systematically tracked, they still have a damage on brand reputation. These translate into lost production hours, material waste and a financial loss in case of a refund. The cause is a lack of standardized, research-backed process settings: operators frequently rely on manual, trial-and-error adjustments of heat press temperature and dwell time. This results in process variability and deviations from a desired result.

Although prior studies highlight the role of granulate chemistry in adhesion, there is limited industrial research quantifying how temperature and dwell time interact for different thermoplastic polyurethane (TPU) granulates on production-scale equipment (Zhu et al. 2025). Without such data, process control remains reactive and suboptimal.

This paper aims to close that gap for DTF printing at Vistaprint by finding out how heat press temperature and dwell time affect print quality for granulate used in production. The main goal is to define process settings that consistently deliver strong adhesion and stable color on black cotton T-shirts, so that defect rates can be reduced in real factory conditions.

To do this, the study follows a three-phase workflow. First, each granulate is tested using a full-factorial design of experiment (DoE), varying temperature and time, with other factors kept constant. Samples are screened for visual adhesion and color change after washing, using strict cutoffs based on quality needs. Those that pass both criteria move to the next step. Finally, the best-performing samples are checked under a digital microscope to measure contamination and fiber intrusion, which are factors linked to longer-term print durability. The rest of the report covers the background, goals, experimental setup, results, and clear recommendations for making DTF production more reliable at Vistaprint.

Chapter 1: Research Design

1.1 Problem Analysis

Despite the rapid industrial adoption of Direct-to-Film (DTF) printing, Vistaprint's Venlo facility faces challenges that directly affect productivity and customer satisfaction. In the current workflow, operators are required to manually adjust heat press parameters-namely, temperature and dwell time-based largely on intuition and personal knowledge. This reliance on experience, rather than guidelines, is a critical vulnerability: recent internal estimates show that approximately 5% of all printed garments must be scrapped or reworked due to adhesion defects visible immediately after pressing. Part of the products that pass the first inspection are later rejected due to post-wash color fading or peeling, generating customer complaints and negative feedback.

The DTF process at Vistaprint can be mapped as a series of tightly coupled stages as seen on Figure 1.1. Digital design (1), film printing (2), powder(granulate) application (3), heat transfer to textile (4), and final wash testing (5). Of these, the powdering and heat press stages stand out as two main bottleneck for quality and yield. During powdering, the granulate is applied, which serves as glue when melted during step (4). There are 3 factors that can be varied throughout the process - type of granulate is determined at step (3), while during heat pressing (4), the temperature and dwell time can be varied. Changes in pressing temperature or dwell time can have a strong impact on whether the print adheres securely and retains its color during laundering. Because the optimal parameter window is not precisely known for each granulate, operators must frequently rework garments, experiment with settings mid-shift, and manually sort out defective pieces, compounding delays and waste.

Figure 1.1: DTF Process flowchart (Sublistar 2024)

This issue affects every stakeholder group involved in production. Operators lack clear settings, while planners must constantly adjust schedules and buffer time for unexpected rework. The urgency comes from Vistaprint's production scale. Annual output approaches one million prints, so even marginal defect rates lead to thousands of wasted garments and significant financial loss. Industry literature shows the complexity of DTF process optimization, particularly the nonlinear interactions between heat transfer parameters and thermoplastic polyurethane (TPU) granulate chemistry (Prybeha et al. 2023; Sharma et al. 2005). Yet, published studies rarely address the realities of industrial, high-throughput environments, meaning there is a gap that needs to be closed.

Figure 1.2 visually demonstrates these challenges. The benchmark print pattern (Figure 1.2a) exposes the limits of current practice, while Figure 1.2b shows a typical failed outcome when the settings were wrong.

(a) Test pattern used for evaluating print performance.

(b) Example of poor adhesion: parts of the print did not transfer properly, leading to visible defects.

Figure 1.2: Representative examples of test print layout and a failed outcome. Suboptimal process settings often result in severe print loss or detachment, necessitating costly rework.

Why-What Analysis of DTF Process Failures

A Why-What analysis was conducted (Figure 1.3) to better stucture the problem and dentify the root causes of DTF production challenges (Annamalai et al. 2013). The "Why" side shows the operational motivations: improving both efficiency and end-product quality. The "What" side identifies the blockers: limited data on granulate and parameter interactions as well as the absence of standard procedure for setting selections.

1.2 Stakeholder Analysis

Given that the project is a collaboration between a B.V. and University of Groningen, achieving academic rigor and operational impact in this project required multiple stakeholder alignment. Each stakeholder shaped the definition of the problem and focus of the research itself. Their interactions and influence were mapped using Mendelow's Matrix (Ackermann and Eden 2011), which was then represented in table form and can be seen in Table 1.1.

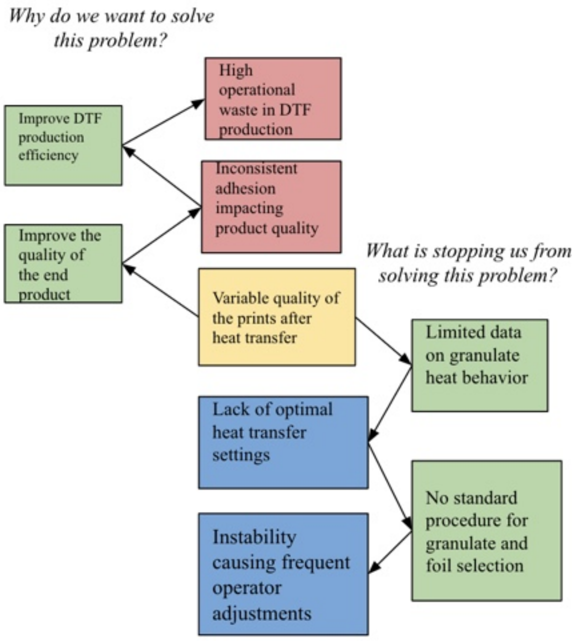


Figure 1.3: Why-What analysis of root causes behind DTF adhesion inconsistencies in production. The left side maps key operational goals; the right shows blockers and technical root causes.

Table 1.1: Key project stakeholders and their main roles.

Stakeholder	**Primary Role / Contribution**
Heike Hafke (Vistaprint)	Project owner; set industrial objectives; validated feasibility
Kirill Hoholko (Student)	Research execution, project management
Plant Director	Operational oversight; resource access
Operators (Production)	Feedback on sample handling, reported real failures
Prof. A. Vakis (RUG)	Methodological rigor; quantitative/physical analysis; critical challenge
Dr. ir. G.H. Jonker (RUG)	Operational focus; clarity;
Vistaprint R&D, QC	Protocol advice; defect data;
Printer Suppliers	Technical process constraints
Granulate Suppliers	TDS/certification; material selection
Univ./Company Stakeholders	Knowledge transfer; reliability benefits

In essence, Prof. Vakis drove scientific rigor and critical challenge (Points 1–3), Dr. Jonker enforced operational realism and clarity (Points 4–5), and Vistaprint supported the process in practical needs and constraints (Points 6–8). Points 9 and 10 were at the intersection of different stakeholders as can be seen on Figure 1.4, with each numbered point described in detail in the legend below.

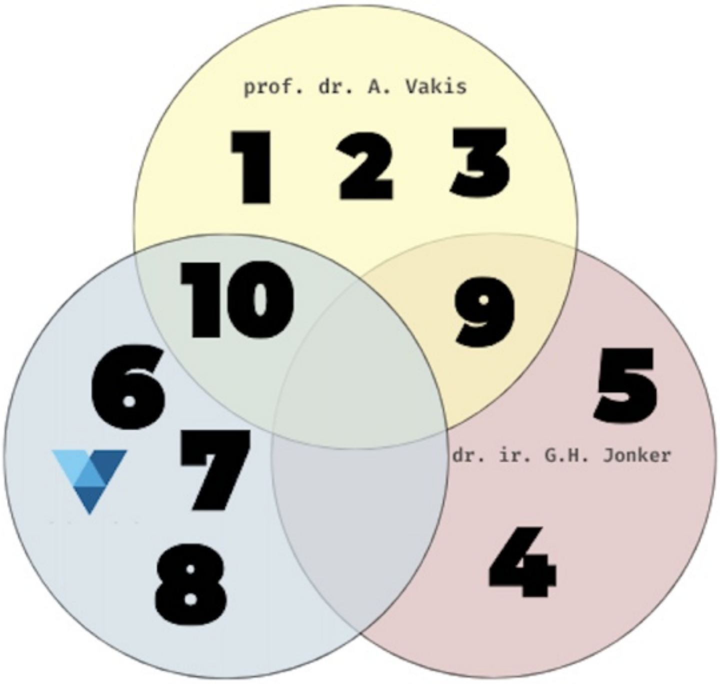


Figure 1.4: Venn diagram showing the distribution and overlap of the most influential project requirements and interventions from each key stakeholder. Numbered points correspond to the explanations in the legend below.

Legend: Numbered Influences Mapped in Figure 1.4

Prof. dr. A. Vakis (Yellow Circle)

1. Required that all findings be quantitatively substantiated and physically interpretable ("quantify or do not bother").

2. Drove deeper color science analysis, e.g. explicit explanation of the ΔE_{00} color difference, CIELAB color axes, and patchwise analysis focusing on 1 color only for "noise" reduction.

3. Insisted on ongoing critical self-reflection, e.g. discussion of methodological limitations, error sources, and physical interpretation of all metrics.

dr. ir. G.H. Jonker (Red Circle)

4. Maintained operational focus and clarity, challenging the choice of factors, substrates, and the transferability of findings to production.

5. Advocated practical, plant-relevant methods and made sure the "real" problem is being solved.

Vistaprint (Blue Circle)

6. Defined the project's business urgency: all recommendations must be actionable and directly relevant to production.

7. Constrained scope to black cotton T-shirts and operator workflows matching core production.
8. Provided operational test feedback to validate the realism and effectiveness of rubrics and measurement protocols.

Vakis × Jonker (Intersection)

9. Required more experimental structure, resulting in three independent full-factorials and enforced accountability in method selection, which led, for example, to a switch from using IM-7000 measurement system to VHX-7000N microscope.

Vistaprint × Vakis (Intersection)

10. Agreed on elimination of "pressure" as a variable based on practical irrelevance.

This push-and-pull between business goals and academic rigor resulted in a project that was more robust and ultimately more valuable to both Vistaprint and the academic community (Enserink et al. 2010). The challenge posed by academic supervisors (e.g., "is this the real problem?") and operational feedback from plant stakeholders (e.g., real-world situation at the shopfloor) resulted in a final deliverable grounded in both theory and practice.

1.3 Research Questions and Objective

This project investigates the impact of heat press parameters-specifically temperature and dwell time-on the quality of Direct-to-Film (DTF) prints produced at scale. The research was guided by the following questions, which evolved in response to practical challenges and direct input from both academic and industrial stakeholders:

1. **How do heat press temperature and dwell time interact to influence adhesion quality and color retention of DTF prints after washing, for each granulate?**
2. **Which parameter combinations yield stable, reproducible, and visually consistent print outcomes-passing both macroscopic (visual/rubric, ΔE_{00}) and microscopic (contamination/fiber intrusion) quality criteria?**
3. *Why does granulate chemistry affect the optimal process window and failure modes observed during production?*
4. *How do microscopic contamination and fiber intrusion relate to visible color changes and adhesion loss in finished prints?*

As new issues were found (e.g. unexpected contamination effects or the need for patch-level color analysis) the research scope and experimental approach were updated accordingly.

The objective of this study is to deliver academically validated guidelines for Vistaprint's industrial DTF printing lines. Specifically, it aims to find stable ranges of heat press temperature and dwell time that optimize both adhesion and color retention for given TPU-based granulate.

1.4 Experimental Procedure

A comparison/selection of alternative experimental designs is beyond the scope of this thesis. However, for reference, an overview table summarizing key advantages and disadvantages of common approaches is provided in Appendix A. For this project, a full-factorial design was selected to capture the effects of temperature and dwell time on DTF print quality, with all other process variables fixed for consistency (Pereira et al. 2021). In this setup, each granulate block received a unique experimental matrix comprising the same factorial structure but differing in absolute temperature values. This allowed to focus on material-specific bonding characteristics of each TPU formulation.

The two variables selected for investigation - press temperature and pressing time were identified as the primary drivers behind adhesion and color retention in process. Other parameters, such as substrate, pressure, and ink, were excluded from the design on the basis of process control limitations or prior evidence indicating limited influence on failure modes of interest.

Each DoE matrix included three levels of press temperature and three levels of press dwell time. Temperature levels were material-specific, scaled around each granulate's manufacturer-recommended setting to ensure fair comparison across distinct chemical formulations. These levels are summarized in Table 1.2. The dwell time factor comprised three settings: 10 seconds (under-press), 15 seconds (nominal press), and a sequential double press of 10 + 5 seconds, since recent studies have explored dual-curing TPU systems for improved process performance (Lin et al. 2024). This matrix was replicated for each of the three TPU-based granulates, yielding a parallel factorial structure tailored to the relevant activation ranges of each material. For clarity on this, refer to the Apendices A2, where the block-structure is visualized in table form.

Table 1.2: Temperature levels used per granulate in the experimental design

Granulate	−1 (Low Temp)	0 (Baseline)	+1 (High Temp)
TPU 4046	150 °C	170 °C	190 °C
Maegis A	150 °C	170 °C	190 °C
Maegis B (Low Temp)	125 °C	140 °C	155 °C

For each parameter combination, three independent replicates were produced, in line with standard DoE practice. Replication serves two purposes: it enables estimation of process and measurement variability (Krumm et al. 2020) and increases the statistical power to detect both main and interaction effects. The use of three replicates was a pragmatic balance between maximizing data reliability and operational feasibility, particularly given the downstream need for extensive post-process measurements.

Within each experimental cell, three benchmark-printed T-shirts were produced: one unwashed (reference) and two subjected to an accelerated wash protocol (three cycles within 24 hours), directly reflecting typical durability expectations and failure conditions in industrial operation.

The total sample count for the study is thus:

$$N = G \times T \times D \times R \tag{1.1}$$

where $G = 3$ is the number of granulates, $T = 3$ the temperature levels, $D = 3$ the dwell time levels, and $R = 3$ the number of replicates. This of course results in $N = 81$ distinct experimental samples.

It should be noted that an initially considered DoE design-using a common matrix for all granulates-was abandoned due to significant differences in optimal activation ranges and observed failure modes. Instead, a parallel full-factorial structure was adopted, maximizing interpretability and statistical validity for cross-material comparisons, in line with current best practice (Vakis and Polycarpou 2010).

1.5 Planning and Project Structure

The experimental workflow was executed as a rigorous, sequential three-phase filtering process, explicitly designed to balance industrial relevance, measurement resolution, and statistical robustness. This structure was developed in response to both operational realities at Vistaprint and ongoing supervisor feedback. Each phase served as a progressively more stringent filter, with increasing analytical depth and selectivity (see Figure 1.5).

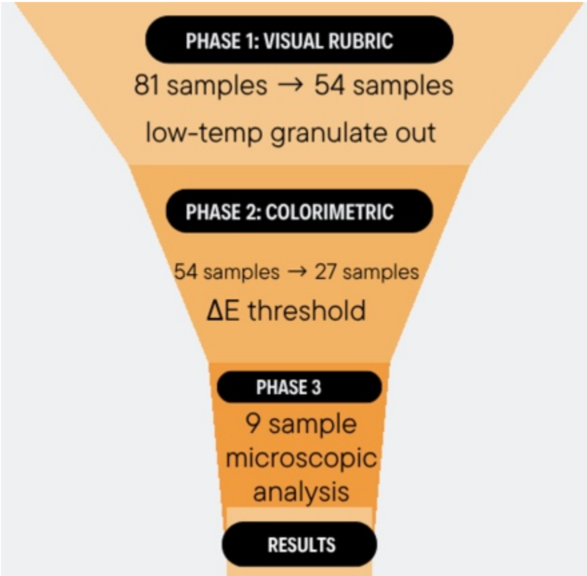


Figure 1.5: Three-stage sample screening funnel used in this study. Each phase selects for a more demanding performance criterion, resulting in focused, resource-intensive analysis only on the best prints.

Phase 1: Visual Rubric Screening. All $N = 81$ samples-produced via three independent full-factorial DoEs (one per granulate)-were first subjected to standardized visual assessment. Each sample, post-wash, was scored on a 1–5 scale using a specifically developed adhesion rubric (see Appendix A). This rubric targeted partial detachment, edge failure, and major delamination, mapping directly to known customer complaint and rework failure modes. Only samples achieving a score ≥ 4 advanced to subsequent analysis, resulting in a reduced pool of $N = 54$.

Phase 2: Colorimetric Filtering. Samples passing the visual screen were then evaluated using spectrophotometric color difference (ΔE_{00}). Color retention after washing was quantified patch-by-patch, referencing pre-wash CIE Lab coordinates. A conservative acceptance threshold of $\Delta E_{00} \leq 1.5$ was set, consistent with industry best practice for visually perceptible color shift. This stage eliminated an additional 27 samples, prioritizing only those with both visual and objective color stability ($N = 27$).

Phase 3: Digital Microscopy and Contamination Analysis. The final subset of 9 top-performing samples underwent advanced surface inspection with the Keyence VHX-7000N digital microscope, replacing the initially planned IM-7000 after pilot validation. The focus was on quantifying fiber intrusion ("contamination") in the white layer of the print-a known failure precursor in industrial DTF. This phase provided a microscopic link between process settings, wash durability, and long-term field performance.

Timeline and Role Allocation. Project planning was continuously updated in response to operational feedback, dataset expansion, and supervisor challenge. Table 1.3 details major project phases and adaptations. Responsibilities were distributed as follows: the student led experimental execution and reporting; Vistaprint operators and R&D contributed process and technical feedback; supervisors (Prof. Vakis, Dr. Jonker, Hafke) ensured scientific rigor, practical relevance, and timely adaptation.

Table 1.3: Project Timeline and Major Activities

Period	**Activity / Milestone**
Weeks 1–3	Stakeholder meetings, initial research framing, metric selection
Weeks 4–7	Full-factorial DoEs, Phase 1 visual rubric scoring
Weeks 8–9	Phase 2 colorimetric analysis, exclusion of Maegis B, interim review
Weeks 10–11	Dataset refinement, patchwise ΔE_{00} analysis, error estimation
Weeks 12–13	Phase 3 Keyence VHX-7000N contamination analysis
Weeks 14–15	Final synthesis of results, reporting, thesis writing

Chapter 2: Materials and Methods

This study was conducted for the three TPU granulates central to Vistaprint's DTF operations: **TPU 4046**, **Maegis Granulate A**, and **Maegis Granulate B** (a low-temperature variant). All experiments utilized 100% black cotton T-shirts, representing the primary application at the Venlo production site. While initial compatibility checks included polyester shirts, cotton-polyester hoodies, and tote bags, systematic testing was restricted to cotton T-shirts to ensure comparability and statistical rigor. Printing was performed on industrial-grade DTF printers and heat presses, all settings matched to Vistaprint production parameters to guarantee operational relevance. A custom benchmark print was designed to probe all major failure modes observed in industrial DTF. The design combines high-contrast microtext, dense black/white fields, standardized color scales, and photographic panels. Each element directly supports at least one phase of the three-stage workflow as seen and explained below:

- **Phase 1: Visual Rubric Screening**-Large black fields and detailed text blocks enable rapid visual detection of edge lift, partial adhesion and delamination.
- **Phase 2: Colorimetric Evaluation**-The color patch array provides standardized, quantifiable targets for pre- and post-wash CIE Lab measurement and ΔE_{00} analysis for objective color retention assessment.
- **Phase 3: Microscopic Contamination Analysis**-The white and areas offer clear zones to see the cotton fibers coming through. Thsoe can be seen with Keyence VHX-7000N microscopy.

Figure 2.1: Schematic illustration of the benchmark print and according phases of the project

Measurement and Evaluation Tools. All samples underwent an accelerated wash protocol (multiple cycles, standardized conditions) to simulate real-world wear. Post-wash evaluation was performed using:

- **X-Rite Spectrophotometer with MeasureColor software**-Objective, repeatable CIE Lab color measurements for ΔE_{00} computation.
- **Keyence VHX-7000N Digital Microscope**-High-resolution imaging to quantify micro-contamination and surface integrity.

Visual scoring followed a standardized 1–5 rubric; full details and calibration images are provided in the Appendix A. As summarized in Figure 2.1, the materials, printing platform, and benchmark print design were deliberately aligned with the three-phase workflow (Section 1.5): initial visual filtering, quantitative color screening, and in-depth microstructural analysis.

2.1 Phase 1: Adhesion Score Evaluation

The first stage of sample assessment involved visual inspection to identify poor performers early in the process. Since the experimental set included 81 samples, it was critical to implement an efficient and standardized screening method before proceeding to more time-consuming quantitative analysis. To this end, a five-point adhesion score was used to evaluate how well the transferred film adhered to the textile surface after undergoing an extreme wash test.

This scoring system is subjective in nature and relies on human judgment. However, it was applied using a clear and consistent visual rubric (Appendix A), which served to minimize evaluator bias and ensure comparability across samples.

Each washed sample was visually compared to its corresponding unwashed reference. Evaluators looked for visible signs of detachment, cracking, edge lift, or discoloration. Based on these observations, a score between 1 and 5 was assigned:

- **Score 5**: No visible damage. Fully adhered.
- **Score 4**: Minor edge lifting or cracks affecting less than 5% of the surface.
- **Score 3**: Noticeable but non-critical defects (5–25% affected area).
- **Score 2**: Partial delamination, with 25–50% area affected.
- **Score 1**: Major adhesion failure affecting more than 50% of the printed area.

This scoring step was not intended to provide precise measurement but rather to act as a filter. Samples with scores below 4 were excluded from further analysis, as they exhibited obvious defects incompatible with acceptable product quality. Only samples scoring 4 or 5 proceeded to the next phase involving spectrophotometric ΔE_{2000} evaluation.

A visual reference table used during the scoring process is included in Appendix A.

2.2 Phase 2: Colorimetric Evaluation

Accurate assessment of print quality after washing requires a robust, quantitative measure of color change. In this study, colorimetric evaluation was performed by comparing each washed sample to its matched unwashed reference, using a calibrated X-Rite i1 Pro 2 spectrophotometer and MeasureColor software (D50 illumination, 2° observer angle). Measurements targeted the standardized color bar included on every benchmark print, ensuring comparability across all process conditions.

CIELAB Color Space: A 3D Model for Color Perception

All color data were represented in the CIELAB color space, an internationally standardized model which encodes human visual perception in three orthogonal axes: lightness (L^*), red-green (a^*), and yellow-blue (b^*). This structure enables a physical and intuitive interpretation: every measured color corresponds to a unique point in a three-dimensional space, as visualized in Figure 2.2.

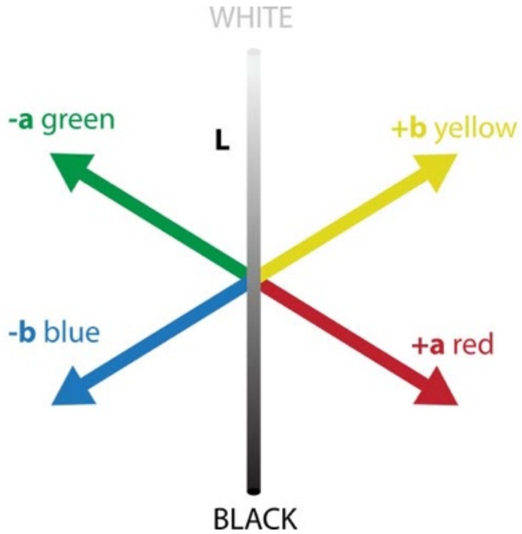


Figure 2.2: CIELAB color space axes: L^* (lightness), a^* (green–red), b^* (blue–yellow). Each color is a point in this 3D space.

Axis definitions:

- L^* (lightness): 0 = perfect black, 100 = perfect white.
- a^*: negative → green, positive → red.
- b^*: negative → blue, positive → yellow.

Thus, color differences between two samples correspond to the Euclidean distance between their respective points in this 3D space - a principle that forms the mathematical and perceptual foundation for the ΔE metric (Golden Artist Colors, Inc. 2021a).

Color Difference: ΔE as a Distance in 3D

The magnitude of color change after washing was quantified using the ΔE color difference metric, defined as the straight-line (Euclidean) distance between the CIELAB coordinates of the reference and test sample:

$$\Delta E = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2} \tag{2.1}$$

This geometric concept is illustrated in Figure 2.3.

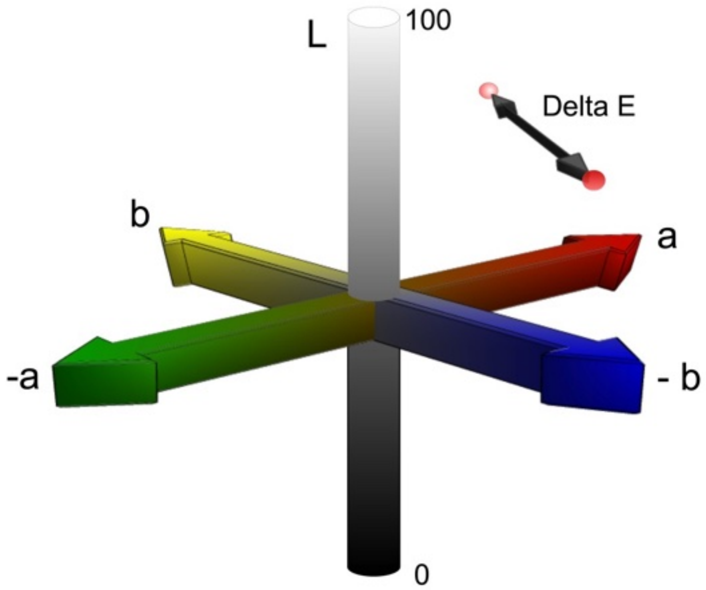


Figure 2.3: Visualization of ΔE as the Euclidean distance between two points in CIELAB space, corresponding to the reference and post-wash measurements.(Golden Artist Colors, Inc. 2021a)

Calculation of Color Difference (ΔE_{00})

However, aforementioned ΔE is not the most accurate way of calculating the color difference. To evaluate the **actual** (perceived by human eye), CIEDE2000 formula was developed. For each sample, nine color patches from the benchmark print's color bar were analyzed. Each patch produced a triplet of CIELAB values (L^*, a^*, b^*) before and after washing, resulting in nine color differences per sample.

These nine (ΔE_{00}) values were then averaged to yield a single representative color difference score per condition. This process aligns with the protocol described in (Sharma et al. 2005), where multiple patch-wise differences are aggregated to account for variation across the printed surface.

Formula and Parameters

The CIEDE2000 formula improves on older ($\Delta E_)$ formulations by incorporating perceptual non-uniformities in the L*, a*, and b* dimensions. It adjusts for differences in lightness, chroma, hue, and their interactions. The standard equation is:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)} \qquad (2.2)$$

Here:

- $\Delta L'$, $\Delta C'$, and $\Delta H'$: weighted differences in lightness, chroma, and hue
- S_L, S_C, S_H: weighting functions for perceptual uniformity
- k_L, k_C, k_H: parametric weighting factors (set to 1 under standard conditions)

- R_T: rotation term accounting for interaction between chroma and hue

CIEDE2000 Color Difference Calculation
A full derivation and implementation of the formula can be found in (Sharma et al. 2005). This formula is implemented in MeasureColor, which uses the CIE Lab inputs to compute ΔE_{00} directly for each patch based on the colorimetric difference between washed and unwashed samples.

Interpreting ΔE_{00} Values
The final ΔE_{00} score represents the total perceptual deviation between each washed sample and its unwashed reference. It aggregates lightness, chroma, and hue deviations into a single scalar. The following thresholds are commonly used in textile and print evaluation:

- $\Delta E_{00} < 1.0$: Not perceptible to the human eye
- $1.0 \leq \Delta E_{00} \leq 2.0$: Slightly perceptible, but acceptable
- $\Delta E_{00} > 2.0$: visible degradation

In this study, a conservative threshold of $\Delta E_{00} = 1.5$ was chosen for screening. It allows for slight industrial variation while also filters out weak-performing samples (Golden Artist Colors, Inc. 2021b).

SolidK Patch Selection: Isolating Granulate Effects
Initial analysis explored several approaches for summarizing color retention: either averaging ΔE across all color patches, or focusing on a representative subset. Averaging over the entire color bar was found to introduce significant noise , since not all patches respond equally to process or material changes. There are simply too many factors that could all mask the true impact of the granulate under test.

Thus, the focus was shifted on a single, high-sensitivity indicator: the "solid K" (black) square. This patch consistently exhibited the largest color shifts after washing, with 85% of all samples showing their maximum ΔE value in this region.

Measurement Repeatability and Error Estimation
To confirm the reliability of spectrophotometric readings, nine randomly selected samples or approximately 11% of the full dataset-were remeasured. Each remeasurement was conducted using the same spectrophotometer and lighting conditions (D50/2°), targeting the same print patches.

The average absolute difference between the original and repeated ΔE_{00} values was calculated using the following equation:

$$\varepsilon = \frac{1}{n} \sum_{i=1}^{n} \left| \Delta E_{00}^{(1)} - \Delta E_{00}^{(2)} \right|$$

For example, if the initial ΔE_{00} of a patch was 1.437 and the second measurement yielded 1.420, the absolute difference being 0.017. Averaging all such deviations across the nine remeasured samples resulted in a mean deviation of 1.5%.

This level of variability is considered negligible in textile applications and falls well within acceptable error margins for visual color difference analysis. Consequently, no correction factor was applied, and all primary ΔE_{00} values were treated as valid and directly comparable.

2.3 Phase 3: Microscopic Contamination Analysis

Microscopic analysis of post-wash contamination was conducted exclusively using the Keyence VHX-7000N digital microscope. This workflow was designed for quantitative, repeatable measurements of print degradation focusing on the high-contrast white region of the printed benchmark. To create the testing protocol, textile samples were conditioned according to ISO 139:2022 and ISO 3801:1977 ((International Organization for Standardization 1995), (International Organization for Standardization 2022)). The protocol for each analyzed sample comprised the following steps:

1. **Sample Preparation:** Each retained sample was mounted on the microscope stage, ensuring flat positioning and consistent orientation. Identical illumination and magnification settings were applied throughout the entire batch to ensure comparability.

2. **Manual Area Selection:** The white benchmark patch was manually isolated from colored or multi-tonal regions by drawing a rectangular selection directly on the microscope image. This restriction was essential to avoid contamination artifacts arising from the background (colored print elements) or the underlying textile structure. The process is illustrated in Figure 2.4.

3. **Automated Brightness-Based Analysis:** Within the defined white area, the Keyence software performed global thresholding to identify dark regions (exposed fibers, cracks) exceeding a predefined size and darkness threshold.

4. **Manual Color-Picking (Cherry-Picking):** For select samples, a secondary manual analysis was performed, isolating pixels whose color profile matched that of exposed black cotton fibers. This method was specifically used to mitigate false positives arising from shadowing and wrinkling, particularly in TPU 4046 samples.

5. **Metric Recording:** For each measurement, the following contamination metrics were done:

    - **Number of cracks**: Automatically detected dark spots within the selection.

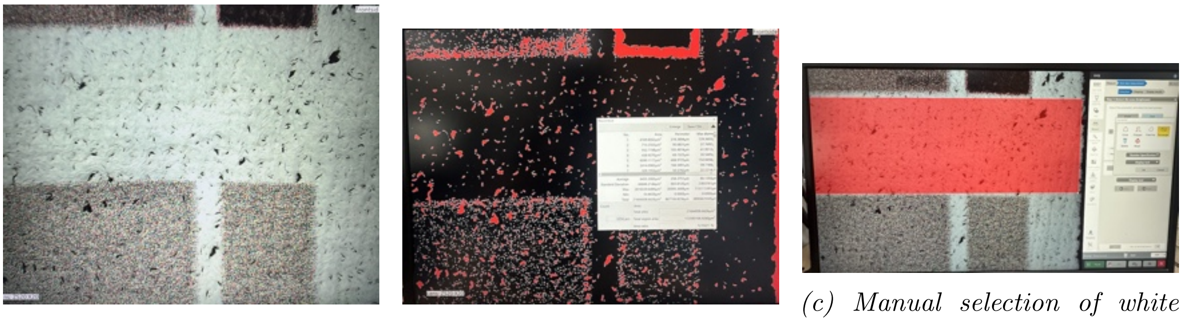
    - **Edge damage (%)**: Proportion of the measured edge length exhibiting visible breach or delamination.

    - **Total area measured (μm^2)**: Total pixel area within the selected white region.

    - **Total area contaminated (μm^2)**: Total area flagged as dark intrusion (either by brightness or color profile).

    - **Adjusted area (μm^2)**: Contaminated area, corrected for edge artifacts or background features.

    - **Mean contamination (%)**: Ratio of (adjusted) contaminated area to total measured area, reported as the primary indicator of print integrity.



(a) Reference washed sample (b) Artifacts in colored regions (c) Manual selection of white print area

Figure 2.4: (a) Washed sample under the microscope. (b) Example of color-induced noise/artifacts in non-white benchmark regions. (c) Manual rectangular selection restricting analysis to the white area, enabling valid contamination quantification.

Limiting the analysis to the white print area enabled reliable detection of genuine surface defects-primarily cracks and exposed fibers-while minimizing confounding from the colored patchwork or the fabric's base structure. (Gazibarić et al. 2023) However, this manual step introduced a potential for operator bias and inconsistency across the sample set. Despite strict adherence to a standardized protocol, the uncertainty associated with this step is acknowledged and further discussed in the Limitations section.

All subsequent contamination quantification, including both automated thresholding and manual color-picking, was performed exclusively within this manually defined region for each sample. This protocol gives a set of contamination metrics (see above) later used in the Results section.

Chapter 3: Results

3.1 Phase 1: Adhesion Filtering

All 81 samples were prepared and evaluated according to the experimental matrix described in Chapter 2. Phase 1 consisted of visual adhesion screening, where each washed sample was scored on a standardized 1–5 rubric (see Appendix A). Only samples with an adhesion score of 4 or higher were considered sufficiently robust for further evaluation.

A clear distinction emerged between the three granulates. **Maegis Granulate B** (low-temperature) exhibited widespread adhesion failure under all tested process conditions, with none of its 12 washed samples meeting the minimum threshold (all scored below 4; Table 3.1). The remaining granulates—**TPU 4046** and **Maegis A**—demonstrated acceptable performance, with all samples meeting or exceeding the required adhesion standard. Maegis A achieved the strongest adhesion overall, while TPU 4046 showed consistent, but not maximal, results.

Table 3.1: Adhesion scores across all washed samples (reference samples excluded)

Granulate	Score 5	Score 4	Score 3	Score 2 or lower
Maegis A (current)	6	12	0	0
TPU 4046 (old)	0	18	0	0
Maegis B (low temp)	0	0	8	4

As a result, only samples with a score of 4 or 5 - a total of 54 across both qualifying granulates - were advanced for quantitative color deviation analysis. In contrast, Maegis Granulate B consistently underperformed across all tested settings. Most samples exhibited incomplete adhesion, resulting in visual scores below 4 on the rubric (Appendix A). According to the technical data sheet (Appendix B), this adhesive has a melting range of 110–120 °C, which is below or near the lower limit of the applied press temperatures (125–155 °C). Although activation occurred, the adhesive did not form a bond strong enough to withstand washing.

This outcome is supported by prior research. Studies found that brittle adhesives at low temperatures are more sensitive to stress concentrations, limiting plastic deformation and increasing the risk of early failure under thermal and mechanical loads (Cognard et al. 2013). Based on these observations, Maegis B was excluded from further testing. Only TPU 4046 and Maegis A-both of which produced acceptable results-were retained for continued analysis in Phase 2.

This selective filtering, illustrated in the sample funnel diagram (Figure 1.5) is the first narrowing of the experimental workflow.

Transition to Phase 2. The 54 retained samples formed the basis for Phase 2, where each was subjected to detailed spectrophotometric and statistical analysis using Minitab. The next section details the methodology and filtering logic applied in this quantitative evaluation step.

3.2 Phase 2: Color Retention Filtering

Following the initial adhesion-based screening, all washed samples with an adhesion score of 4 or higher (total $N = 54$) were further evaluated for color retention. The key performance indicator was the post-wash color deviation, quantified by the ΔE_{00} metric. As detailed in Section 2.2, ΔE_{00} captures the perceptual color difference between each washed sample and its unwashed reference, measured over a standardized set of nine color patches per benchmark print.

To ensure that only prints with visually imperceptible color change advanced to the next stage, a conservative threshold of $\Delta E_{00} \leq 1.5$ was imposed. This value reflects a level of color deviation generally considered undetectable to the human eye under normal viewing conditions, thus providing a stringent filter for high-quality outputs.

Screening Results and Distribution Analysis of the 54 washed samples subjected to spectrophotometric evaluation:

- **TPU 4046**: 6 samples passed the $\Delta E_{00} \leq 1.5$ criterion.
- **Maegis A**: 3 samples passed the same threshold.
- **Maegis B**: Not evaluated at this stage due to exclusion after adhesion failure in Phase 1.

Table 3.2: Sample retention after colorimetric (ΔE_{00}) screening

Granulate	**Washed Samples**	**Retained** ($\Delta E_{00} \leq 1.5$)	**Excluded** ($\Delta E_{00} > 1.5$)
TPU 4046 (old)	18	6	12
Maegis A (current)	18	3	15
Maegis B (low-temp)	18	0	18
Total	54	**9**	**45**

Patchwise ΔE_{00} and SolidK Selection Logic.
Initial analysis averaged ΔE_{00} values across all nine patches per sample, but this approach proved excessively sensitive to color variety, foil artifacts, and local print variability. This averaging tended to dilute the effect of true granulate-driven degradation, and in some cases, mask the failure of critical regions due to the influence of more stable patches.

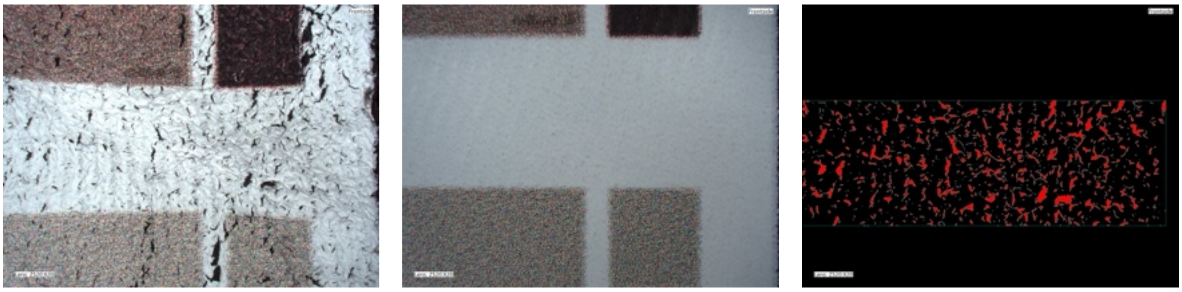
To address this, a patch-specific analysis was introduced. Among all patches, the solid black ("SolidK") region was found to be the most sensitive indicator of print degradation. In 85% of evaluated samples, SolidK exhibited the highest ΔE_{00} post-wash. By focusing analysis on this patch, the workflow isolated the granulate effect with higher signal-to-noise and provided a clearer diagnostic tool for operational decision-making.

Summary and Transition to Phase 3.
In summary, after two rounds of stringent filtering-first by adhesion, then by color retention-only nine settings (comprising 27 samples across the retained parameter matrix) qualified for advanced surface contamination analysis in Phase 3. This approach made sure that resource-intensive microscopy was reserved exclusively for the highest-performing candidates.

3.3 Phase 3: Contamination Analysis

A major analytical challenge in Phase 3 were the different post-wash failure mechanisms observed between the two high-performing granulates, Maegis A and TPU 4046. While both showed strong overall adhesion, Maegis A samples predominantly developed micro-cracks after washing but retained a relatively smooth surface profile. In contrast, TPU 4046 exhibited significant wrinkling and undulation in the print layer, a phenomenon that introduced extensive shadowing and optical artifacts under high-magnification microscopy.

These different degradation behaviors are illustrated in Figure 3.1: the left image shows a sample with pronounced cracks and exposed fibers (typical of Maegis A), while the middle image presents a well-preserved print with minimal contamination. The right panel displays the result of automated binarization, highlighting detected cracks and contaminant regions.



(a) Extensive cracks and fiber intrusion *(b) Minimal contamination (well-preserved)* *(c) Automated binarization (crack detection)*

Figure 3.1: Microscopy of washed samples: (a) Cracking and fiber intrusion typical of Maegis A; (b) Well-adhered, undamaged print; (c) Automated detection of contaminant regions.

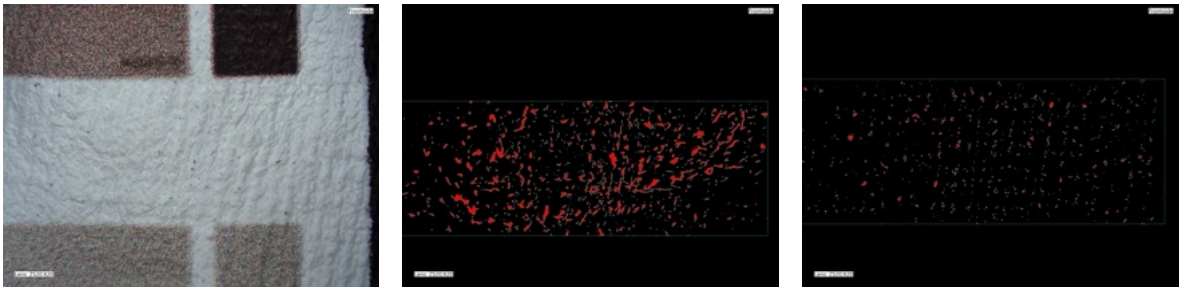
The Dual Quantification Challenge The surface of Maegis A allowed automated brightness-based algorithms to reliably quantify contamination, as dark cracks stand out clearly against the white field. However, the wrinkling in TPU 4046 resulted in artificial dark regions (shadows) that the software falsely interpreted as contamination, often inflating contamination estimates to above 10% even for visually intact samples.

To address this, a complementary **manual color-picking ('cherry-picking")** approach was introduced. By selecting only those pixels matching the signature of black cotton fibers (as opposed to shadowed or wrinkled white film), the analysis minimized false positives in highly wrinkled TPU 4046 samples. This color-based method risked underestimating contamination in Maegis A when cracks were faint or dark regions were very subtle.

Reconciling the Two Methods Given these limitations, the contamination score for each sample was ultimately defined as the mean of the two approaches:

$$\text{Contamination}_{\text{final}} = \frac{1}{2}(\text{Contamination}_{\text{brightness}} + \text{Contamination}_{\text{color-picking}})$$

This averaging was an attempt to make sure that neither cracks nor wrinkling artifacts dominate the contamination result and gave a more meaningful estimate for both material types.



(a) Highly wrinkled TPU 4046 sample

(b) Brightness-based: overestimation due to shadows

(c) Color-picking: true fiber contamination only

Figure 3.2: Wrinkling artifact management in TPU 4046: (a) Pronounced wrinkling after washing; (b) Automated detection incorrectly classifies shadows as contamination; (c) Color-picking isolates only genuine black fiber intrusion.

Missing Data and Methodological Limitations

By design, only a subset of samples surviving the first two screening phases were advanced to Phase 3 microscopy. As a result, the factorial data set for contamination analysis necessarily included empty values for all samples excluded after Phase 2 (colorimetric filtering). To maintain statistical robustness and enable a complete analysis of factor effects, it was necessary to assign contamination values for these missing entries.

In consultation with the daily supervisor, the chosen approach was to assign all such samples the worst-case observed contamination value, specifically 9.93% of the measured area. This strategy of populating the data set is required for factorial analysis and minimizes the risk of underestimating failure rates in the overall dataset. While this method ensures continuity and operational completeness of the Design of Experiments, it does introduce a downward bias in statistical power and may overstate contamination in some conditions.

These methodological decisions and their implications for interpreting the results are addressed in the Limitations section. Full details of the imputation scheme, along with all raw and processed microscopy outputs, are available in the Appendix C for transparency and reproducibility. That data set is the basis for the subsequent statistical modeling and interpretation of factor effects in the next section.

3.4 Statistical Analysis of Factor Effects

The goal of the statistical analysis in this study is to quantify how key process variables-pressing temperature, dwell time, and granulate type-influence color stability and surface contamination in DTF-printed textiles. To this end, two classes of models were employed: the General Factorial Regression (GFR) and the General Linear Model (GLM).

Rationale for Statistical Modeling Approach

General Factorial Regression (GFR) is a statistical technique designed to analyze experiments where multiple categorical variables (factors) and their interactions may influence a quantitative outcome. GFR allows for the explicit modeling of both main effects and interaction effects, making it especially well-suited to factorial designs such as the present study. In this project, GFR was used to detect whether the impact of temperature on print quality depends on the specific granulate or dwell time, and to capture higher-order interactions.

General Linear Model (GLM) provides a complementary framework for quantifying the influence of categorical predictors on a continuous response. Unlike GFR, GLM is typically used to estimate main effects under the assumption of additivity (i.e., that factors act independently unless interactions are included). GLM serves as a robustness check for the findings of the GFR by confirming whether observed trends persist when only main effects are considered.

Phase-Specific Implementation

Each key response variable in this study was analyzed separately, following the narrowing structure of the experimental workflow:

- **Phase 2:** Both GFR and GLM were used to model the average color deviation (ΔE_{00}) as well as the maximum color shift in the solidK patch across all retained settings.
- **Phase 3:** The same modeling strategy was applied to surface contamination percentage, using the dual-metric data described earlier.

All statistical analyses were performed in Minitab 21, which was selected for its robust support of factorial design analysis, ease of visualizing categorical factor effects, and transparency in reporting both model fits and diagnostic statistics.

Model Metrics and Their Interpretation

- Coefficient (β): Quantifies the effect of a factor or interaction on the response variable; a positive/negative sign indicates the direction of the effect.
- R^2 and Adjusted R^2: Proportion of response variance explained by the model; adjusted R^2 corrects for model complexity.
- Standard Error (S): Measures average deviation of observed values from model predictions.
- P-value: Probability that the observed effect (or stronger) arises by chance; $p < 0.05$ is generally interpreted as significant.
- ANOVA (Analysis of Variance): Table reporting the relative contribution of each factor and interaction to the total variance in the response.
- Main effect: The isolated impact of a single factor (e.g., temperature) on the response, averaged over all levels of other factors.

3.4.1 Colour Stability (ΔE)

In this project, colour change after washing was measured with the ΔE_{00} metric discussed before. Smaller ΔE values mean better colour retention. Three factors were tested: pressing temperature, dwell time, and the type of granulate used.

The statistical models show that pressing temperature has the largest effect on ΔE. At 170°C, the average colour loss is the lowest. This is seen in both the full factorial and main-effects models, where the coefficient for 170°C is -0.065 (with $p = 0.019$ in the factorial model, $p = 0.031$ in the main-effects model). The adjusted R^2 values are 30.3% and 10.4%, which means the models explain a moderate amount of the variation.

A second important finding is the interaction between temperature and granulate. Maegis A suffers more colour loss at lower temperatures, but TPU 4046 is less affected. This means that choosing the right granulate matters most if the press temperature has to be reduced, for example due to sensitive fabrics.

Dwell time between 10 s and 15 s does not change the colour result in a clear way ($p = 0.253$). This is interesting, because many operators expect that longer pressing gives better colour retention, but the data here shows that, at least in the tested window, using 10 s is enough. This saves time and increases production speed.

The Pareto chart in Figure 3.3 helps to visualise the importance of each factor. The highest bars are for temperature and for the temperature–granulate interaction. Other effects are much smaller.

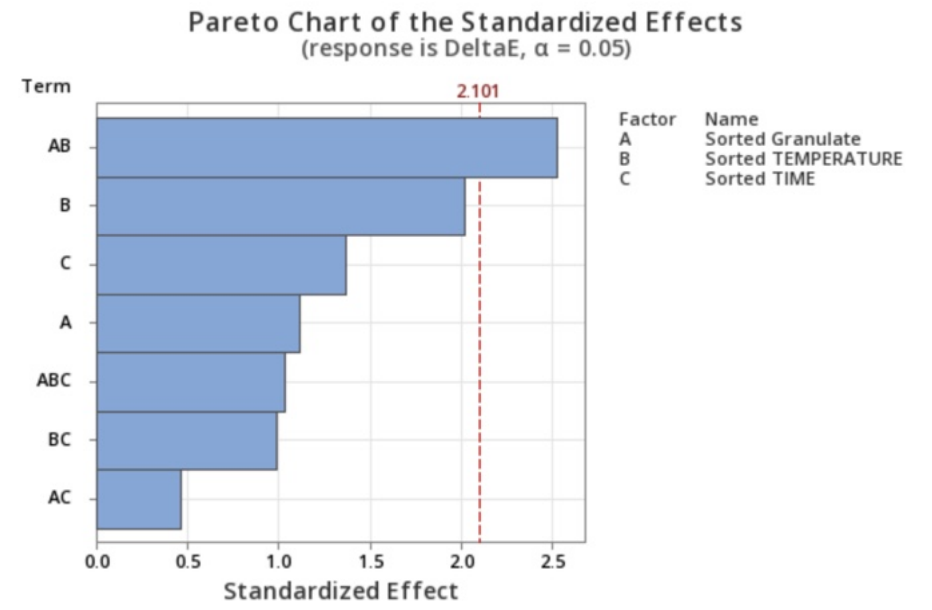


Figure 3.3: Pareto chart of standardized effects for ΔE. Temperature and the interaction between temperature and granulate are the main drivers of colour stability.

The main effects plot (Figure 3.4) shows that colour change is lowest at 170°C. The difference between 10 s and 15 s dwell time is very small. Maegis A usually shows higher ΔE than TPU 4046.

The interaction plot in Figure 3.5 gives more detail about how temperature and granulate work together. The blue line (Maegis A) rises sharply at lower temperatures, showing more colour loss, while the red line (TPU 4046) stays flatter. This confirms that the choice of granulate is especially important if the temperature is lower than 170°C. There is no strong interaction between dwell time and the other factors.

There were two samples (runs 2 and 13) with lower ΔE than expected. These are shown in the fits and diagnostics table in the appendix. No clear error was found, so they were kept in the analysis.

Interpretation:

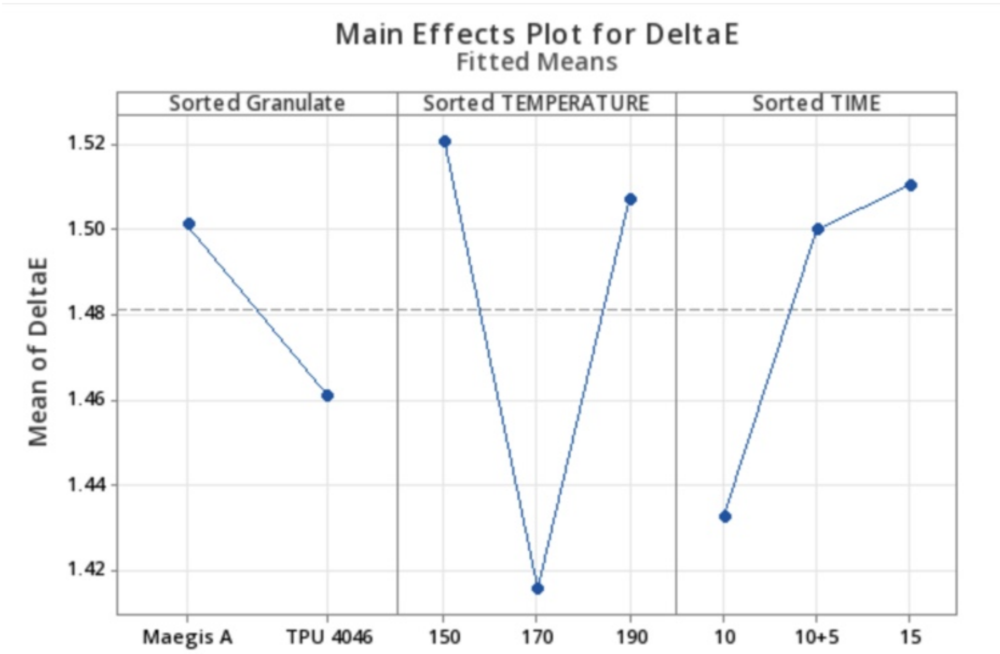


Figure 3.4: Main effects plot for ΔE. The lowest mean value is at $170°C$. Changing dwell time has little effect on colour stability.

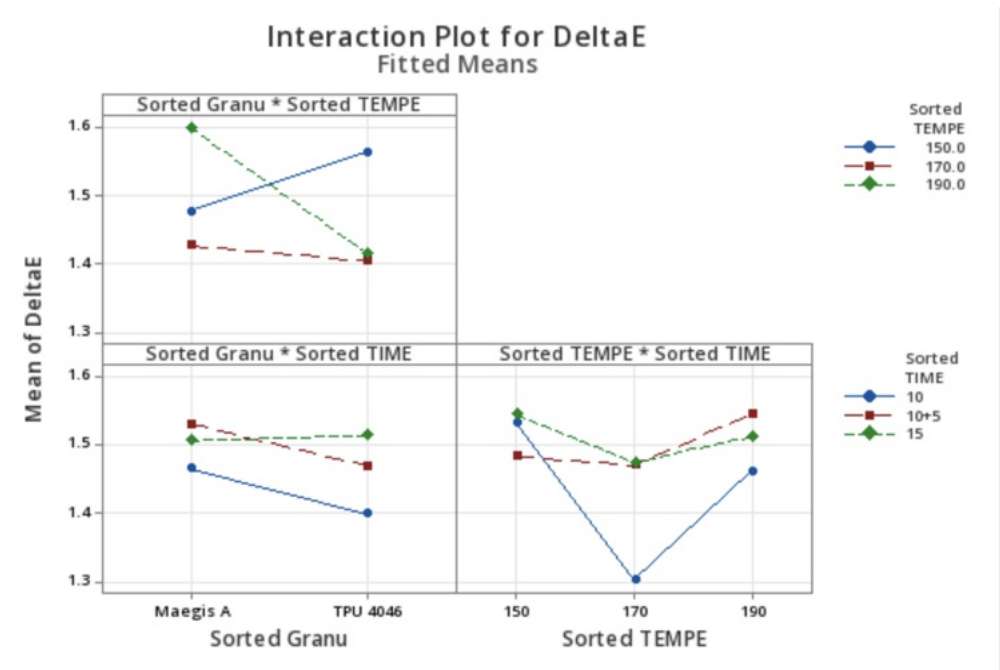


Figure 3.5: Interaction plots for ΔE. The main interaction is between granulate and temperature. Maegis A loses more colour at lower temperature.

- 170°C is the best temperature for keeping colours stable in DTF prints.
- Using a dwell time of 10 s is enough and makes production faster, as longer times do not help.
- If the process must use 150°C, Maegis A granulate is the better choice for keeping colour loss low.

Full model details, including coefficients and residual analysis, are given in Appendix D.

3.4.2 Black-Density Loss (Δ solid K)

Maintaining strong black density is important for print quality in DTF production. In this study, we looked at the loss of solid black (solid K) after washing. Lower loss means better durability and appearance. Like for colour stability, the models tested the effect of pressing temperature, dwell time, and granulate.

The factorial regression model found that the best results for solid K were again at 170°C and 10 s dwell time. The interaction between temperature and time was the only term close to significance (coefficient −0.379, $p = 0.045$ for 170°C/10 s). This shows that the lowest loss of black happens at this combination. At 170°C, increasing dwell time to 15 s or using a split 10+5 s press does not help and can even worsen the result. The main effect of temperature alone was not significant ($p = 0.094$), and neither was granulate. The adjusted R^2 was low (about 12%), so a lot of variation remains unexplained by the tested settings.

The main effects plot in Figure 3.6 shows a sharp dip in solid K loss at 170°C. The difference between granulates is small, and changing dwell time from 10 s to 15 s increases black loss slightly.

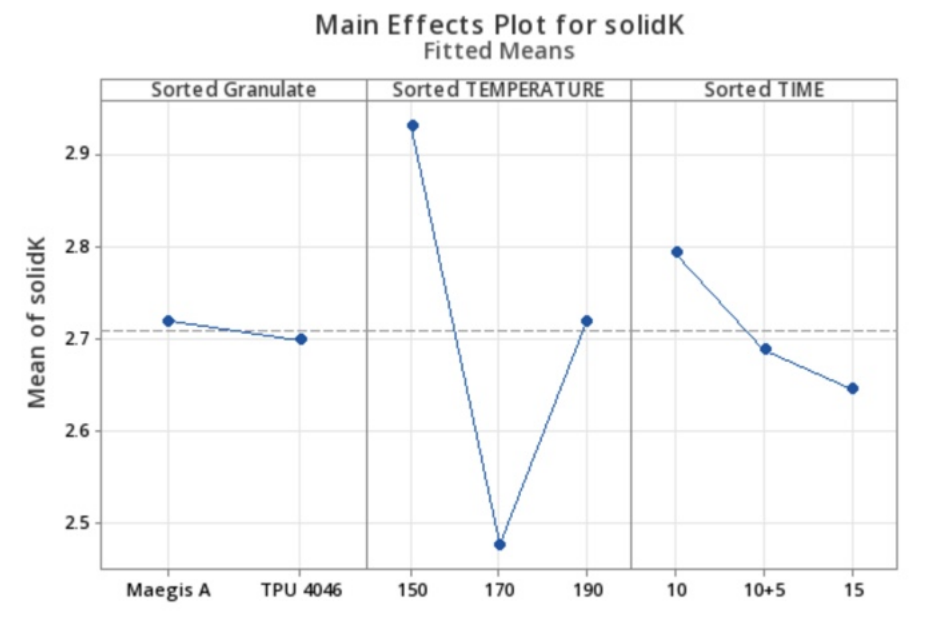


Figure 3.6: Main effects plot for solid K loss. The lowest loss is seen at 170°C and 10 s dwell time.

The interaction plot in Figure 3.7 gives more detail. The bottom right panel shows the deep trough at 170°C and 10 s. All other combinations, especially longer dwell times at 170°C, result in higher loss. The top left panel shows there is no important interaction between granulate and temperature. Again, this means that, for black durability, the choice of granulate is less important than getting the temperature and time right.

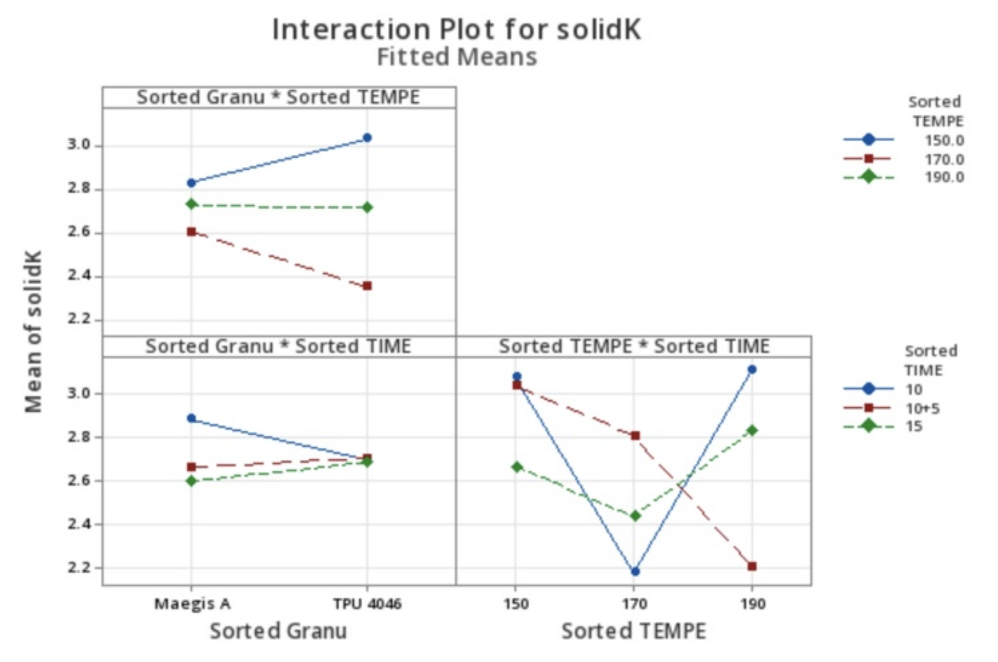


Figure 3.7: Interaction plot for solid K loss. The lowest loss is found at 170° *C with 10 s dwell time. The effect of granulate is small.*

There are two samples (runs 17 and 23) with much higher loss than expected. This could be due to local press problems or measurement noise. They are listed as outliers in the appendix and should be checked again in the lab.

Interpretation:

- The same 170°C and 10 s recipe that helps colour stability also minimises black-density loss.
- Increasing dwell time above 10 s at 170°C does not reduce black loss and may even worsen it.
- Because the model leaves much of the variation unexplained, it is important to keep solid K as a routine QC check in production. Factors like press pressure or ink amount, which were not tested here, likely affect results.

Simlarly to previous subsection, all details about model fit, coefficients, and outliers can be found in Appendix D.

3.4.3 White-Layer Contamination

Another important quality check for DTF prints is the amount of fibre contamination that shows up in the white base after transfer. High contamination makes the print look dirty and weakens adhesion. In this study, contamination was measured as the percentage of white area covered by fibres after washing.

The statistical model with real data (not imputed) shows that pressing temperature is the most important factor. Lower contamination is always found at 170°C (coefficient −0.0154, $p = 0.012$). Neither granulate ($p = 0.108$) nor dwell time ($p = 0.856$) had a significant effect, which means these settings can be adjusted for other reasons, like cost or throughput, without making contamination worse. The adjusted R^2 for this model is 18%, so there is still a lot of noise in the data.

When missing measurements were replaced with worst-case values, the model gave a perfect fit ($R^2 = 100\%$), but this is not a real effect. This happened because the same bad value was used for each missing sample, making the model think there is no natural variation. This approach is safe for the business, but it hides the real process risks.

The main effects plot in Figure 3.8 shows the lowest contamination at 170°C. There is a small difference between granulates and a flat line for dwell time.

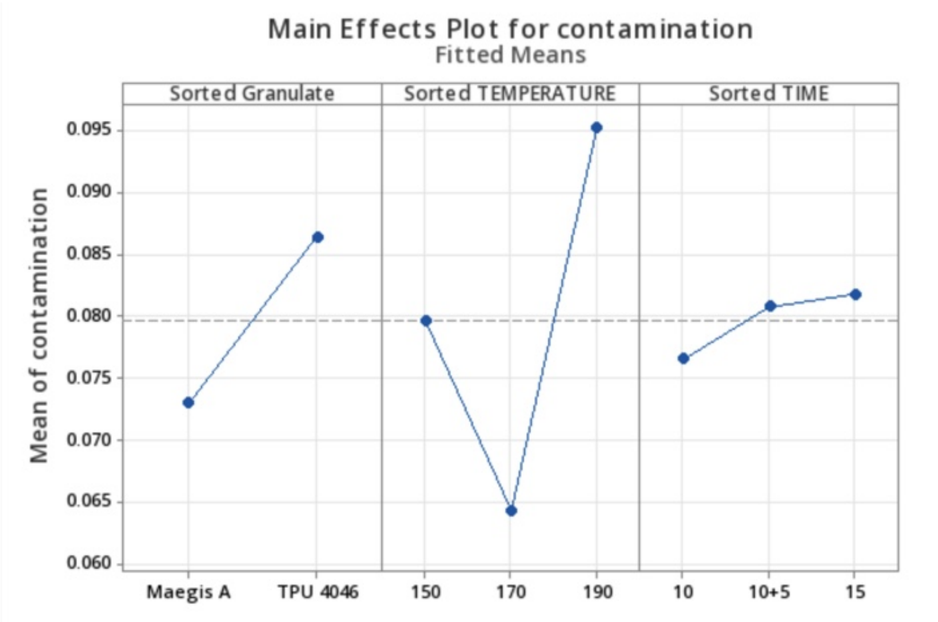


Figure 3.8: Main effects plot for contamination. The lowest mean value is at 170° C. Dwell time does not have a clear effect.

The interaction plot in Figure 3.9 supports this result. The biggest drop in contamination happens at 170°C, no matter which granulate or dwell time is used. This means temperature control is the main way to reduce contamination.

Interpretation:

- Hold the press at 170°C to keep lint contamination low.
- There is no need to change dwell time to improve contamination, so use the shortest possible time for faster output.
- Because the statistical model with imputed data shows an artificially perfect fit, Vistaprint should schedule a confirmation run using only real measurements and check the accuracy of the imaging method.

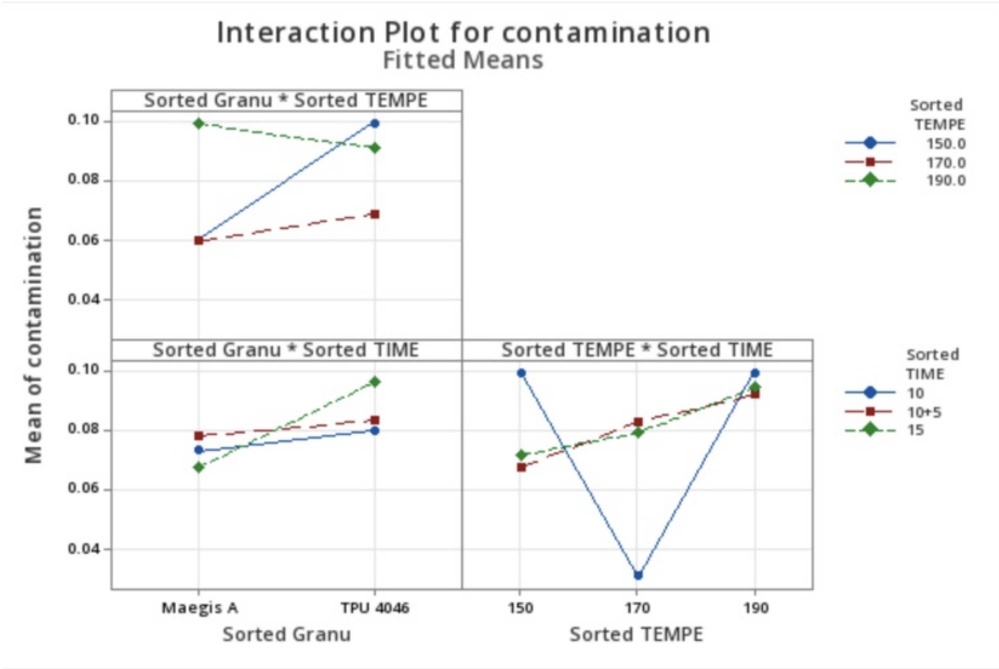


Figure 3.9: Interaction plot for contamination. The strongest effect is for temperature at 170° *C. Granulate and dwell time have small or no interaction.*

3.5 Multivariate and Global Process Effects

Most of the analysis in this report looked at each KPI—colour change, black-density loss, and contamination—separately. However, in production, operators need a process window that works for all three at once. To check this, a multivariate analysis (MANOVA) was performed using temperature, dwell time, and granulate as factors.

The results are shown in Table 3.3. Both granulate and temperature have p-values close to 0.05, meaning they are on the edge of statistical significance when all three responses are combined. Dwell time, on the other hand, has no global effect.

Table 3.3: Summary of MANOVA results across all three KPIs.

Factor	**Wilks' Λ**	**F**	**p-value**	**Interpretation**
Granulate	0.762	2.92	0.051	Borderline global influence
Temperature	0.654	2.21	0.056	Nearly significant joint effect
Time	0.850	0.79	0.583	No multivariate impact

The key point here is that temperature is the one factor that improves colour, black density, and contamination all at the same time. Setting the press to 170°C and using a 10 s dwell time leads to the best overall performance on all three KPIs, with no trade-off between them. Granulate type matters only in some combinations with temperature. Dwell time can be kept short for higher throughput since it has no meaningful impact on any of the key outputs.

Because the p-values for granulate and temperature are close to the 0.05 threshold, these results should be confirmed in a follow-up run without imputation. This would help make sure the chosen settings remain best when using real data only.

Chapter 4: Discussion and Limitations

This study was set out to determine how heat press temperature and dwell time affect the durability and visual quality of DTF prints, especially across different TPU granulates. Through several phases of analysis, the following questions were answered:

1. How do temperature and dwell time interact to affect adhesion and colour retention for each granulate? Statistical analysis confirms that press temperature is the single most important factor for all key performance indicators (KPIs). Running at 170°C led to the lowest ΔE, best black-density retention (solid K), and lowest contamination. Dwell time, across the tested 10–15 s range, showed no significant effect. There was a clear interaction: Maegis A granulate is sensitive to low temperature, while TPU 4046 is more stable. This means a single recipe cannot always be applied to both powders at the process extremes.

2. Which parameter combinations yield stable, reproducible, and visually consistent outcomes? The best print quality was found at 170°C and 10 s dwell time, using either Maegis A or TPU 4046. In this setting, all samples that passed the initial visual rubric also passed colour and contamination thresholds after washing. This shows that process control can focus on a single temperature and short dwell time to achieve reproducible quality.

3. Why does granulate chemistry affect the optimal process window and failure modes? Granulate chemistry shapes process sensitivity, mainly through interactions with temperature. Maegis A is more vulnerable to low-temperature failures, as confirmed by both colour and contamination results. Maegis B (the “low temp” granulate) failed even at its supposed activation range, as TDS and observed adhesion showed it did not form a reliable film under actual production conditions. This aligns with literature: TPU formulation and real melting behaviour, not just the advertised “activation point”, set process limits.

4. How do microscopic contamination and fibre intrusion relate to visible colour changes and adhesion loss? High contamination in the white base is often paired with higher ΔE and lower adhesion scores. While some decoupling was observed (i.e., contamination without major colour change), most poor-performing samples failed all gates. This shows that fibre intrusion and visible changes often share a root cause—poor TPU melting or incomplete fibre coverage.

Factor Importance, Data Processing, and Practical Limitations

The results of this project show that temperature is the single factor with a consistent and significant impact across all three KPIs—colour stability, black-density retention, and contamination. Dwell time, within the tested 10–15 s range, did not affect any quality metric, allowing for faster press cycles without loss of performance. Granulate chemistry becomes important only at lower temperature, where Maegis A is more sensitive to underheating. Some of the remaining day-to-day variation in black density (solid K) could be explained by factors like press pressure or ink lay-down, which were not studied here.

Some of the methodological choices and data processing steps shaped these outcomes and introduce practical limitations:

- **Subjectivity in scoring and image analysis:** Both the visual adhesion scoring and manual region selection for contamination analysis involved human judgement. Even with standardised rubrics and imaging protocols, borderline cases or hard-to-define white regions could lead to differences if repeated by other operators or plants.

- **Artefacts from wrinkling and cracking:** The two main granulates degraded differently after washing. Maegis A tended to crack, while TPU 4046 wrinkled. Wrinkling produced shadows that led automated analysis to overestimate contamination, while manual colour-picking sometimes missed faint fibres or subtle damage. Averaging both methods reduced bias but could not guarantee perfect accuracy.

- **Narrow range of materials and substrates:** Only black cotton T-shirts and two TPU granulates were fully tested, since Maegis B failed early screening. This focus ensures the results are relevant for Vistaprint's main production, but means the findings may not transfer to other fabrics or new powders without further testing.

- **Sample size and phase-based filtering:** Out of 81 initial process settings, only a small fraction advanced to the final contamination analysis. Most were filtered out during visual or colour checks. This approach ensures that only operationally relevant cases are studied in detail, but it also leaves a smaller dataset and might miss rare failure modes or subtle effects, making the reported process window stricter than it might be in larger-scale production.

- **Imputation and model artefacts:** To maintain a full-factorial design for contamination, missing data (from samples not reaching phase 3) were filled in with the worst observed value for each granulate. While this is a conservative and safe approach, it removes natural variation and inflates model fit (such as R^2), possibly hiding the true range of outcomes in real production.

Taken together, these points mean that while the recommended process window (170°C, 10 s dwell, either granulate) is reliable and practical for the tested scenario, results should be re-validated if new materials, settings, or larger production runs are introduced. Operators should keep monitoring key quality outputs, especially solid K, and be aware that subjectivity in scoring or edge-case failures may require additional checks.

Considerations for further research:

- Replicate corner points of the process window (e.g., 170°C/10 s, 150°C/15 s, 190°C/10 s) with at least five independent shirts per run, and no imputation.

- Add press pressure and ink-laydown as factors in future DoE, since unexplained variance in solid K suggests hidden effects.

- Extend wash testing to longer cycles for best-performing samples to check for durability and ageing effects. Would be very useful to see whether different degradation patterns lead to different long-term damage.

Chapter 5: Conclusions

This project shows that pressing DTF prints at 170°C for 10 s provides the best combination of colour retention, black-density stability, and minimal contamination across Vistaprint's main TPU-based granulates. Process window optimisation through a phase-based DoE shows that temperature is the main factor for all key quality metrics, while dwell time can be shortened to improve throughput without sacrificing outcome. Granulate selection only becomes important when operating near the limits of the process window, and even then, Maegis A proved more sensitive to lower temperatures than TPU 4046. The main operational implication is clear: Vistaprint can reliably standardise production using a single recipe for most orders, while still maintaining flexibility for granulate changes when needed.

A major methodological insight is that phase filtering, combined with conservative imputation for missing data is good enough for actionable recommendations, but also constrains the analysis by removing natural process variation and potentially hiding some marginal failures. The most significant limitation of the study is the subjectivity in contamination measurement and adhesion scoring, especially in borderline or wrinkled samples, as well as the artificial narrowing of the contamination model due to worst-case imputation. To further improve process control and future-proof DTF production, follow-up work should expand the parameter space to include press pressure and ink lay-down, automate key measurements, validate results on more fabrics and colours, and perform longer-term wash durability studies to ensure quality holds up under real consumer conditions.

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Appendices

A Appendix A: Experimental Design and Methodology

A1. Experimental Design Table

Table 1: Comparison of common experimental designs for process parameter screening and optimization (adapted from Pereira et al. 2021).

Type of Design	Function	Advantages and Disadvantages
Full Factorial	Systematically investigates all combinations of selected factor levels, capturing both main effects and interactions.	**Adv:** Only design that reveals all interactions for a small number of factors (and handles 3+ levels per factor). **Disadv:** Becomes resource-intensive as factor count grows; not used for RSM-based optimization.
Fractional Factorial	Samples only a strategic subset of all possible combinations, studying main effects and some lower-order interactions.	**Adv:** Economical, faster screening. **Disadv:** Risks missing high-order or nonlinear effects; less reliable for processes with strong interactions.
Plackett–Burman	Focuses exclusively on main effects, suitable for rapid screening when many factors exist.	**Adv:** Minimal runs for initial screening. **Disadv:** Does not model interactions; unsuitable if factor interactions are suspected to be important.
Central Composite (CCRD)	Extends factorials by adding axial runs for response surface modeling (RSM). Used in process optimization after screening.	**Adv:** Ideal for detailed optimization, models curvature. **Disadv:** Requires more levels per factor, more complex analysis.
Box–Behnken	Alternative RSM design, avoids extreme settings, suited for safe optimization in known regions.	**Adv:** Efficient for optimization without running edge cases. **Disadv:** Not suitable for initial factor screening or for categorical factors.

A2. Full Factorial Experimental Structure

Table 2: Full-factorial DoE matrix structure for each granulate. Each unique combination of temperature and dwell time was replicated three times, resulting in $3 \times 3 \times 3 = 27$ *samples per granulate and* $N = 81$ *total samples. All runs were performed on black cotton T-shirts under production-matched conditions.*

Granulate	Temperature (°C)	Dwell Time (s)	Replications
Maegis A (current)	150	10	3
	150	15	3
	150	10+5	3
	170	10	3
	170	15	3
	170	10+5	3
	190	10	3
	190	15	3
	190	10+5	3
TPU 4046 (old)	150	10	3
	150	15	3
	150	10+5	3
	170	10	3
	170	15	3
	170	10+5	3
	190	10	3
	190	15	3
	190	10+5	3
Maegis B (low temp)	125	10	3
	125	15	3
	125	10+5	3
	140	10	3
	140	15	3
	140	10+5	3
	155	10	3
	155	15	3
	155	10+5	3

Note: The complete sample tracking table, including all sample IDs, phase status, and pass/fail outcomes, is provided in Appendix C1.

A3. Rubrics and Scoring Sheets

Score (1–5)	Description	Criteria Basis	Photo Placeholder
5	No visible damage. Fully adhered.	No visible issues	
4	Minor edge lifting or cracks affecting <5% of the design.	<5% area affected	
3	Clear defects in 5–25% of the print area. Visible but not critical.	5–25% area affected	
2	Partial delamination (25–50%). Functionally compromised.	25–50% area affected	
1	Major failure with >50% detachment. Adhesion failed entirely.	>50% area affected	

Figure 1: Visual scoring rubric used for adhesion evaluation.

B Appendix B: Data Sheets and Materials

B1. Technical Data Sheets (TDS)

9. PHYSICAL AND CHEMICAL PROPERTIES

Appearance	
Form	solid pellets or powders under room temperature
Color	milky white
Odor	odorless
Safety data	
PH	not applicable
Melting point / range	110- 120 °C (DSC)
Boiling point / range	not applicable
Flash point	not applicable
Ignitiontemperature	>350 C° Method : DIN 51 974
Vapor pressure	not applicable
Density	1 .2 g/cm3 (20°C)
Water solubility	Insoluble
Furtherinformation	The range of values given profiles with the variation range of the product group. The specific physical chemical data can be read in the product information

10. STABILITY AND REACTIVITY

Thermal decomposition	>350° C
Hazardous reactions	No dangerous reactions known

Figure 2: Extract from the technical data sheet of Maegis Granulate B (low-temp).

C Appendix C: Raw and Processed Data

C1. Master Tracking Table for All Samples

Sample ID	Granulate	Temperature (°C)	Time	Replication	Adhesion Score [1–5]	ΔE* with the reference	value for solid k
1	Maegis A (current)	150	10s	1	reference sample	N/A	N/A
2	Maegis A (current)	150	10s	2	4 - Minor edge lift/cracks	1.5309	2.9750
3	Maegis A (current)	150	10s	3	4 - Minor edge lift/cracks	1.5387	2.7014
4	Maegis A (current)	150	15s	1	reference sample	N/A	N/A
5	Maegis A (current)	150	15s	2	4 - Minor edge lift/cracks	1.4638	2.5354
6	Maegis A (current)	150	15s	3	4 - Minor edge lift/cracks	1.4988	2.8394
7	Maegis A (current)	150	10+5s	1	reference sample	N/A	N/A
8	Maegis A (current)	150	10+5s	2	5 - No visible defects	1.3250	2.9201
9	Maegis A (current)	150	10+5s	3	5 - No visible defects	1.5052	2.9982
10	Maegis A (current)	170	10s	1	reference sample	N/A	N/A
11	Maegis A (current)	170	10s	2	4 - Minor edge lift/cracks	1.1199	1.9619
12	Maegis A (current)	170	10s	3	4 - Minor edge lift/cracks	1.4218	2.4925
13	Maegis A (current)	170	15s	1	reference sample	N/A	N/A
14	Maegis A (current)	170	15s	2	5 - No visible defects	1.4408	2.4697
15	Maegis A (current)	170	15s	3	5 - No visible defects	1.4371	2.5729
16	Maegis A (current)	170	10+5s	1	reference sample	N/A	N/A
17	Maegis A (current)	170	10+5s	2	5 - No visible defects	1.5154	2.8891
18	Maegis A (current)	170	10+5s	3	5 - No visible defects	1.6264	3.2385
19	Maegis A (current)	190	10s	1	reference sample	N/A	N/A
20	Maegis A (current)	190	10s	2	4 - Minor edge lift/cracks	1.5617	3.0721
21	Maegis A (current)	190	10s	3	4 - Minor edge lift/cracks	1.6221	4.1250
22	Maegis A (current)	190	15s	1	reference sample	N/A	N/A
23	Maegis A (current)	190	15s	2	4 - Minor edge lift/cracks	1.5300	2.3803
24	Maegis A (current)	190	15s	3	4 - Minor edge lift/cracks	1.6690	2.8224
25	Maegis A (current)	190	10+5s	1	reference sample	N/A	N/A
26	Maegis A (current)	190	10+5s	2	4 - Minor edge lift/cracks	1.4841	1.5630
27	Maegis A (current)	190	10+5s	3	4 - Minor edge lift/cracks	1.7301	2.3993
28	Maegis B (low temp)	125	10s	1	no adhesion	N/A	N/A
29	Maegis B (low temp)	125	10s	2	no adhesion	N/A	N/A
30	Maegis B (low temp)	125	10s	3	no adhesion	N/A	N/A
31	Maegis B (low temp)	125	15s	1	no adhesion	N/A	N/A
32	Maegis B (low temp)	125	15s	2	no adhesion	N/A	N/A
33	Maegis B (low temp)	125	15s	3	no adhesion	N/A	N/A
34	Maegis B (low temp)	125	10+5s	1	no adhesion	N/A	N/A
35	Maegis B (low temp)	125	10+5s	2	no adhesion	N/A	N/A
36	Maegis B (low temp)	125	10+5s	3	no adhesion	N/A	N/A
37	Maegis B (low temp)	140	10s	1	reference sample	N/A	N/A
38	Maegis B (low temp)	140	10s	2	2 - Significant failure	N/A	N/A
39	Maegis B (low temp)	140	10s	3	2 - Significant failure	N/A	N/A
40	Maegis B (low temp)	140	15s	1	reference sample	N/A	N/A
41	Maegis B (low temp)	140	15s	2	3 - Moderate detachment	N/A	N/A
42	Maegis B (low temp)	140	15s	3	3 - Moderate detachment	N/A	N/A
43	Maegis B (low temp)	140	10+5s	1	reference sample	N/A	N/A
44	Maegis B (low temp)	140	10+5s	2	3 - Moderate detachment	N/A	N/A
45	Maegis B (low temp)	140	10+5s	3	3 - Moderate detachment	N/A	N/A
46	Maegis B (low temp)	155	10s	1	reference sample	N/A	N/A
47	Maegis B (low temp)	155	10s	2	2 - Significant failure	N/A	N/A
48	Maegis B (low temp)	155	10s	3	2 - Significant failure	N/A	N/A
49	Maegis B (low temp)	155	15s	1	reference sample	N/A	N/A
50	Maegis B (low temp)	155	15s	2	3 - Moderate detachment	N/A	N/A
51	Maegis B (low temp)	155	15s	3	3 - Moderate detachment	N/A	N/A
52	Maegis B (low temp)	155	10+5s	1	reference sample	N/A	N/A
53	Maegis B (low temp)	155	10+5s	2	3 - Moderate detachment	N/A	N/A
54	Maegis B (low temp)	155	10+5s	3	3 - Moderate detachment	N/A	N/A
55	TPU 4046 (old)	150	10s	1	reference sample	N/A	N/A
56	TPU 4046 (old)	150	10s	2	4 - Minor edge lift/cracks	1.6445	3.4847
57	TPU 4046 (old)	150	10s	3	4 - Minor edge lift/cracks	1.4194	3.1635
58	TPU 4046 (old)	150	15s	1	reference sample	N/A	N/A
59	TPU 4046 (old)	150	15s	2	4 - Minor edge lift/cracks	1.7027	2.9486
60	TPU 4046 (old)	150	15s	3	4 - Minor edge lift/cracks	1.5121	2.3547
61	TPU 4046 (old)	150	10+5s	1	reference sample	N/A	N/A
62	TPU 4046 (old)	150	10+5s	2	4 - Minor edge lift/cracks	1.5821	3.5397
63	TPU 4046 (old)	150	10+5s	3	4 - Minor edge lift/cracks	1.5230	2.7126
64	TPU 4046 (old)	170	10s	1	reference sample	N/A	N/A
65	TPU 4046 (old)	170	10s	2	4 - Minor edge lift/cracks	1.2798	1.8123
66	TPU 4046 (old)	170	10s	3	4 - Minor edge lift/cracks	1.3877	2.4632
67	TPU 4046 (old)	170	15s	1	reference sample	N/A	N/A
68	TPU 4046 (old)	170	15s	2	4 - Minor edge lift/cracks	1.5316	2.7359
69	TPU 4046 (old)	170	15s	3	4 - Minor edge lift/cracks	1.4893	1.9696
70	TPU 4046 (old)	170	10+5s	1	reference sample	N/A	N/A
71	TPU 4046 (old)	170	10+5s	2	4 - Minor edge lift/cracks	1.3861	1.6387
72	TPU 4046 (old)	170	10+5s	3	4 - Minor edge lift/cracks	1.3529	3.4845
73	TPU 4046 (old)	190	10s	1	reference sample	N/A	N/A
74	TPU 4046 (old)	190	10s	2	4 - Minor edge lift/cracks	1.3255	2.1934
75	TPU 4046 (old)	190	10s	3	4 - Minor edge lift/cracks	1.3383	3.0800
76	TPU 4046 (old)	190	15s	1	reference sample	N/A	N/A
77	TPU 4046 (old)	190	15s	2	4 - Minor edge lift/cracks	1.5398	3.5863
78	TPU 4046 (old)	190	15s	3	4 - Minor edge lift/cracks	1.3120	2.5414
79	TPU 4046 (old)	190	10+5s	1	reference sample	N/A	N/A
80	TPU 4046 (old)	190	10+5s	2	4 - Minor edge lift/cracks	1.3837	2.5474
81	TPU 4046 (old)	190	10+5s	3	4 - Minor edge lift/cracks	1.5869	2.3318

Figure 3: Master tracking table for all samples, showing key experimental parameters, adhesion score, ΔE_{00} results, and filtering status at each phase. Red shading highlights samples excluded at each filtering phase. Complete data (Excel file) is available as a digital supplement or upon request.

Note: The table shows the progression of each sample through the sequential filtering workflow. Samples shaded in red were excluded due to failure at a given phase (e.g., low adhesion score or high color difference). Non-colored cells indicate samples that advanced to further analysis. For confidentiality and size reasons, the full digital file can be accessed upon request.

C2. Full Contamination Database

Sample ID	Granulate	Temperature (°C)	Time	Replication	Washed	# of Cracks (IM-7000)	Edge Damage [%]	Total area measured [µm	tal area contaminated [µ	adjusted area [µm]	mean contamination
4	Maegis A (current)	150	15s	1	No	34	0.0327	81258550	26610	0.0327%	N/A
5	Maegis A (current)	150	15s	2	Yes	470	4.6865	76635990	3591575	4.6865%	4.4291%
6	Maegis A (current)	150	15s	3	Yes	592	4.1718	81514499	3400587	4.1718%	4.4291%
7	Maegis A (current)	150	10+5s	1	No	81	0.1018	83908132	85426	0.1018%	N/A
8	Maegis A (current)	150	10+5s	2	Yes	608	5.8318	82489520	4810585	5.8318%	3.5871%
9	Maegis A (current)	150	10+5s	3	Yes	199	1.3424	77681405	1042781	1.3424%	3.5871%
10	Maegis A (current)	170	10s	1	No	10	0.0063	86797808	5487	0.0063%	N/A
11	Maegis A (current)	170	10s	2	Yes	288	1.3623	83599786	1138906	1.3623%	2.1126%
12	Maegis A (current)	170	10s	3	Yes	532	2.8629	83689931	2395938	2.8629%	2.1126%
13	Maegis A (current)	170	15s	1	No	306	0.516	86118294	444359	0.5160%	N/A
14	Maegis A (current)	170	15s	2	Yes	778	6.6546	84063293	5594069	6.6546%	5.8811%
15	Maegis A (current)	170	15s	3	Yes	425	5.1076	80293349	4101059	5.1076%	5.8811%
64	TPU 4046 (old)	170	10s	1	No	237	0.3579	85842538	307249	0.3579%	N/A
65	TPU 4046 (old)	170	10s	2	Yes	497	3.5278	78114735	2755693	3.5278%	4.0904%
66	TPU 4046 (old)	170	10s	3	Yes	569	4.6531	81595152	3796663	4.6531%	4.0904%
70	TPU 4046 (old)	170	10+5s	1	No	229	0.317	85371295	270598	0.3170%	N/A
71	TPU 4046 (old)	170	10+5s	2	Yes	462	2.6806	81449373	2183332	2.6806%	6.6360%
72	TPU 4046 (old)	170	10+5s	3	Yes	376	12.43	81967088	8681509	10.5915%	6.6360%
73	TPU 4046 (old)	190	10s	1	No	252	0.3354	84694251	284095	0.3354%	N/A
74	TPU 4046 (old)	190	10s	2	Yes	852	6.2175	85571940	5320453	6.2175%	9.9346%
75	TPU 4046 (old)	190	10s	3	Yes	909	13.6516	74159839	10124015	13.6516%	9.9346%
76	TPU 4046 (old)	190	15s	1	No	790	2.1345	85603927	1827253	2.1345%	N/A
77	TPU 4046 (old)	190	15s	2	Yes	834	9.0951	80523896	7323716	9.0951%	8.9572%
78	TPU 4046 (old)	190	15s	3	Yes	948	8.8193	80019569	7057178	8.8193%	8.9572%
79	TPU 4046 (old)	190	10+5s	1	No	824	2.0434	83811294	1712638	2.0434%	N/A
80	TPU 4046 (old)	190	10+5s	2	Yes	884	8.7812	78117149	6859606	8.7812%	8.4531%
81	TPU 4046 (old)	190	10+5s	3	Yes	868	8.1251	77447457	6292676	8.1251%	8.4531%

Figure 4: Full database of contamination results for all tested process settings and replications, including the output of IM-7000 image analysis, measured and adjusted contamination, and mean contamination (%). Green shading indicates samples that advanced to microscopic analysis.

This table was used as the primary source for all subsequent phase filtering and analysis. For replications that did not reach phase 3, the "mean contamination" field is marked N/A. The detailed digital dataset is available on request.

C3. Minitab-Processed Contamination Table

# Sample ID	Tт Granulate	# Temperature (°C)	Tт Time	# Replication	ΔE* with the reference	solid K value	contamination for DoE
2	Maegis A (current)	150	10s	2	1.5309	2.975004809	9.93%
8	Maegis A (current)	150	10+5s	2	1.3250	2.920053207	3.59%
5	Maegis A (current)	150	15s	2	1.4638	2.535419491	4.43%
56	TPU 4046 (old)	150	10s	2	1.6445	3.484743924	9.93%
62	TPU 4046 (old)	150	10+5s	2	1.5821	3.539653634	9.93%
59	TPU 4046 (old)	150	15s	2	1.7027	2.948613546	9.93%
3	Maegis A (current)	150	10s	3	1.5387	2.701449124	9.93%
9	Maegis A (current)	150	10+5s	3	1.5052	2.998249565	3.59%
6	Maegis A (current)	150	15s	3	1.4988	2.839430788	4.43%
57	TPU 4046 (old)	150	10s	3	1.4194	3.163547806	9.93%
63	TPU 4046 (old)	150	10+5s	3	1.5230	2.712603261	9.93%
60	TPU 4046 (old)	150	15s	3	1.5121	2.354702528	9.93%
11	Maegis A (current)	170	10s	2	1.1199	1.961925038	2.11%
17	Maegis A (current)	170	10+5s	2	1.5154	2.889080734	9.93%
14	Maegis A (current)	170	15s	2	1.4408	2.46965968	5.88%
65	TPU 4046 (old)	170	10s	2	1.2798	1.8123429	4.09%
71	TPU 4046 (old)	170	10+5s	2	1.3861	1.638736985	6.64%
68	TPU 4046 (old)	170	15s	2	1.5316	2.735888381	9.93%
12	Maegis A (current)	170	10s	3	1.4218	2.492519123	2.11%
18	Maegis A (current)	170	10+5s	3	1.6264	3.238496116	9.93%
15	Maegis A (current)	170	15s	3	1.4371	2.572907638	5.88%
66	TPU 4046 (old)	170	10s	3	1.3877	2.463239586	4.09%
72	TPU 4046 (old)	170	10+5s	3	1.3529	3.484546731	6.64%
69	TPU 4046 (old)	170	15s	3	1.4893	1.969554379	9.93%
20	Maegis A (current)	190	10s	2	1.5617	3.072109565	9.93%
26	Maegis A (current)	190	10+5s	2	1.4841	1.562954515	9.93%
23	Maegis A (current)	190	15s	2	1.5300	2.380318796	9.93%
74	TPU 4046 (old)	190	10s	2	1.3255	2.19338977	9.93%
80	TPU 4046 (old)	190	10+5s	2	1.3837	2.54744473	8.45%
77	TPU 4046 (old)	190	15s	2	1.5398	3.586321154	8.96%
21	Maegis A (current)	190	10s	3	1.6221	4.124982089	9.93%
27	Maegis A (current)	190	10+5s	3	1.7301	2.3993165	9.93%
24	Maegis A (current)	190	15s	3	1.6690	2.822359005	9.93%
75	TPU 4046 (old)	190	10s	3	1.3383	3.080020846	9.93%
81	TPU 4046 (old)	190	10+5s	3	1.5869	2.331795501	8.45%
78	TPU 4046 (old)	190	15s	3	1.3120	2.541357459	8.96%

Figure 5: Database table showing the contamination values used for the Minitab GLM/ANOVA analysis. Cells with measured values correspond to successful phase 3 measurements; empty or N/A entries were conservatively populated with the maximum observed contamination for each granulate (9.93%) to maintain a balanced factorial design, as described in Section 3.4 and discussed in Section 5.

Note: The imputation of missing contamination values allowed statistical models to run without excluding process settings. This conservative approach, as discussed in the report, preserves the DoE structure but may inflate apparent process stability and understate true variance. All such cells are visually indicated in the table and described in the Limitations section.

C4. Data Availability

Raw experimental data, phase-filtered tables, and Minitab-ready files are available as digital supplements or upon request to facilitate replication or further analysis.

D Appendix D: Statistical Outputs

General Factorial Regression: DeltaE versus Sorted Granulate, Sorted TEMPERATURE, Sorted TIME

Factor Information

Factor	Levels	Values
Sorted Granulate	2	Maegis A, TPU 4046
Sorted TEMPERATURE	3	150, 170, 190
Sorted TIME	3	10, 10+5, 15

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	**17**	**0.37490**	**0.022053**	**1.89**	**0.094**
Linear	**5**	**0.13553**	**0.027106**	**2.33**	**0.085**
Sorted Granulate	1	0.01454	0.014536	1.25	0.279
Sorted TEMPERATURE	2	0.07793	0.038963	3.35	0.058
Sorted TIME	2	0.04307	0.021533	1.85	0.186
2-Way Interactions	**8**	**0.17983**	**0.022479**	**1.93**	**0.117**
Sorted Granulate*Sorted TEMPERATURE	2	0.11244	0.056219	4.83	0.021
Sorted Granulate*Sorted TIME	2	0.01048	0.005242	0.45	0.644
Sorted TEMPERATURE*Sorted TIME	4	0.05691	0.014227	1.22	0.336
3-Way Interactions	**4**	**0.05955**	**0.014887**	**1.28**	**0.315**
Sorted Granulate*Sorted TEMPERATURE*Sorted TIME	4	0.05955	0.014887	1.28	0.315
Error	**18**	**0.20955**	**0.011641**		
Total	**35**	**0.58445**			

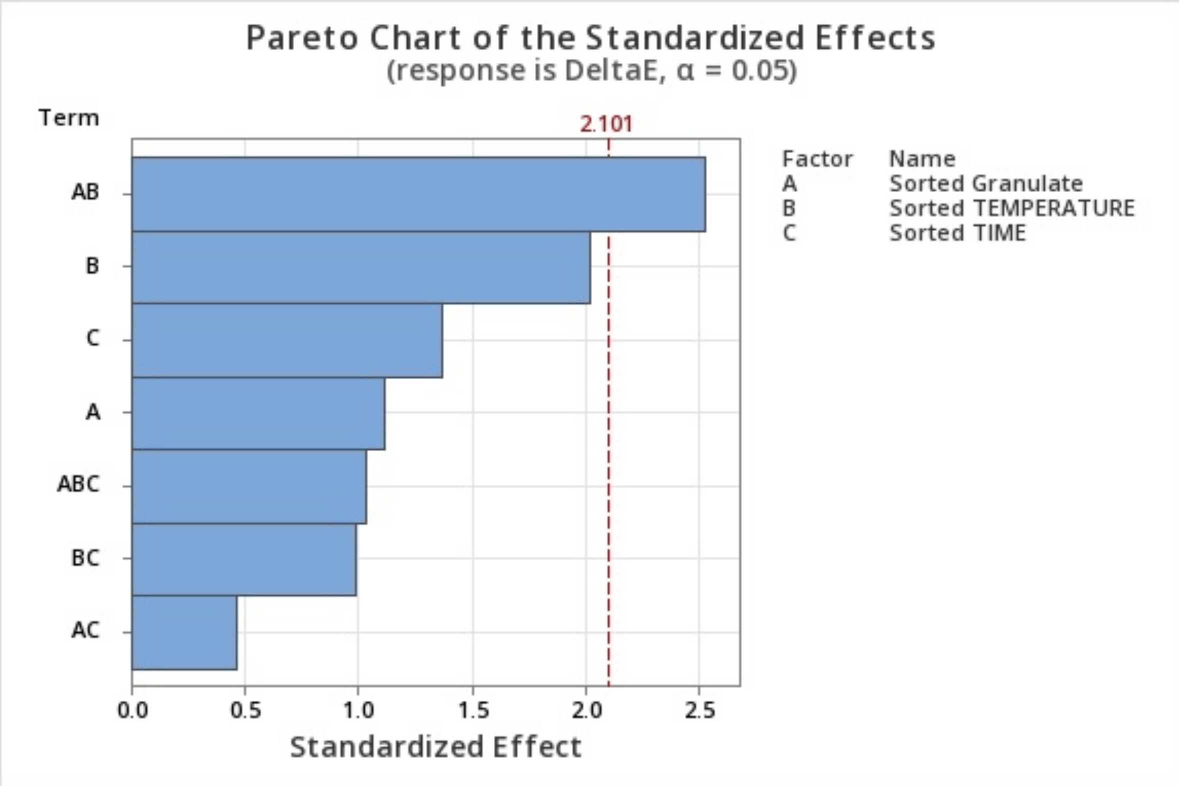
Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.107896	64.15%	30.28%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	**1.4811**	**0.0180**	**82.36**	**0.000**	
Sorted Granulate					
Maegis A	0.0201	0.0180	1.12	0.279	1.00
Sorted TEMPERATURE					
150	0.0395	0.0254	1.55	0.138	1.33
170	-0.0653	0.0254	-2.57	0.019	1.33
Sorted TIME					
10	-0.0485	0.0254	-1.91	0.072	1.33
10+5	0.0190	0.0254	0.75	0.464	1.33
Sorted Granulate*Sorted TEMPERATURE					
Maegis A 150	-0.0635	0.0254	-2.50	0.022	1.33
Maegis A 170	-0.0089	0.0254	-0.35	0.730	1.33
Sorted Granulate*Sorted TIME					
Maegis A 10	0.0132	0.0254	0.52	0.609	1.33
Maegis A 10+5	0.0109	0.0254	0.43	0.674	1.33
Sorted TEMPERATURE*Sorted TIME					
150 10	0.0614	0.0360	1.71	0.105	1.78
150 10+5	-0.0557	0.0360	-1.55	0.139	1.78
170 10	-0.0649	0.0360	-1.80	0.088	1.78
170 10+5	0.0355	0.0360	0.99	0.337	1.78
Sorted Granulate*Sorted TEMPERATURE*Sorted TIME					
Maegis A 150 10	0.0316	0.0360	0.88	0.391	1.78
Maegis A 150 10+5	-0.0361	0.0360	-1.00	0.328	1.78
Maegis A 170 10	-0.0558	0.0360	-1.55	0.138	1.78

Term	Coef	SE Coef	T-Value	P-Value	VIF
Maegis A 170 10+5	0.0787	0.0360	2.19	0.042	1.78



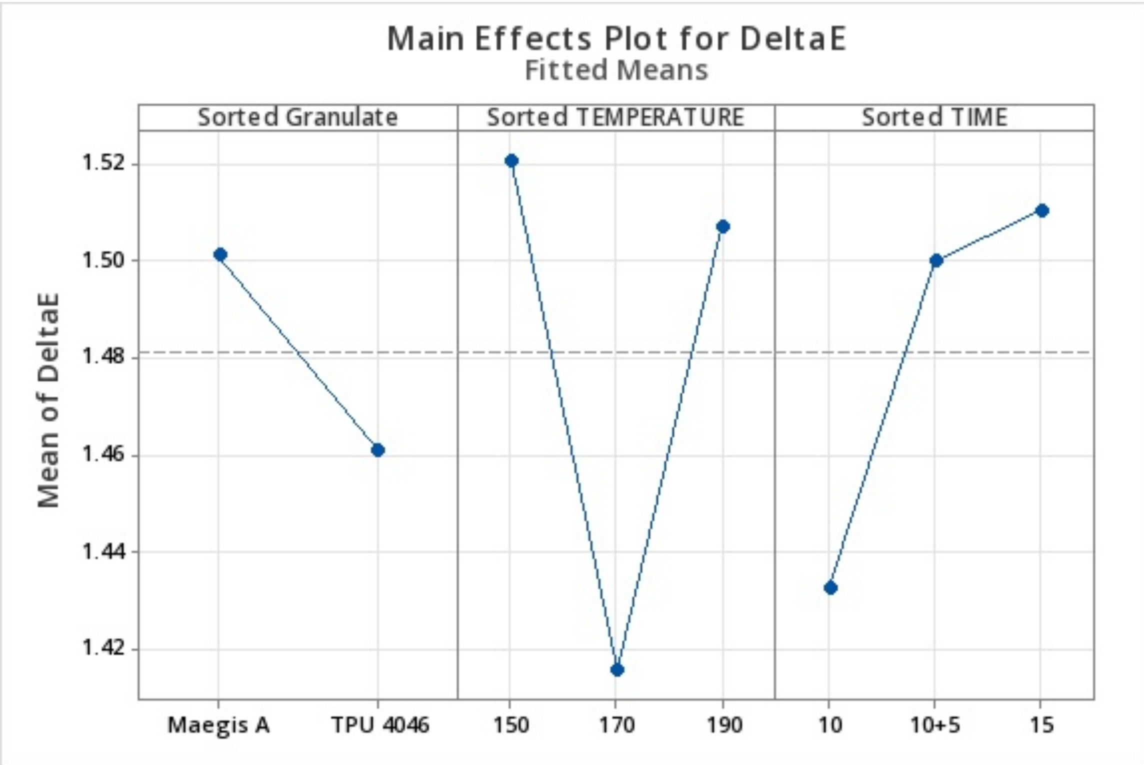
Purpose of the Analysis

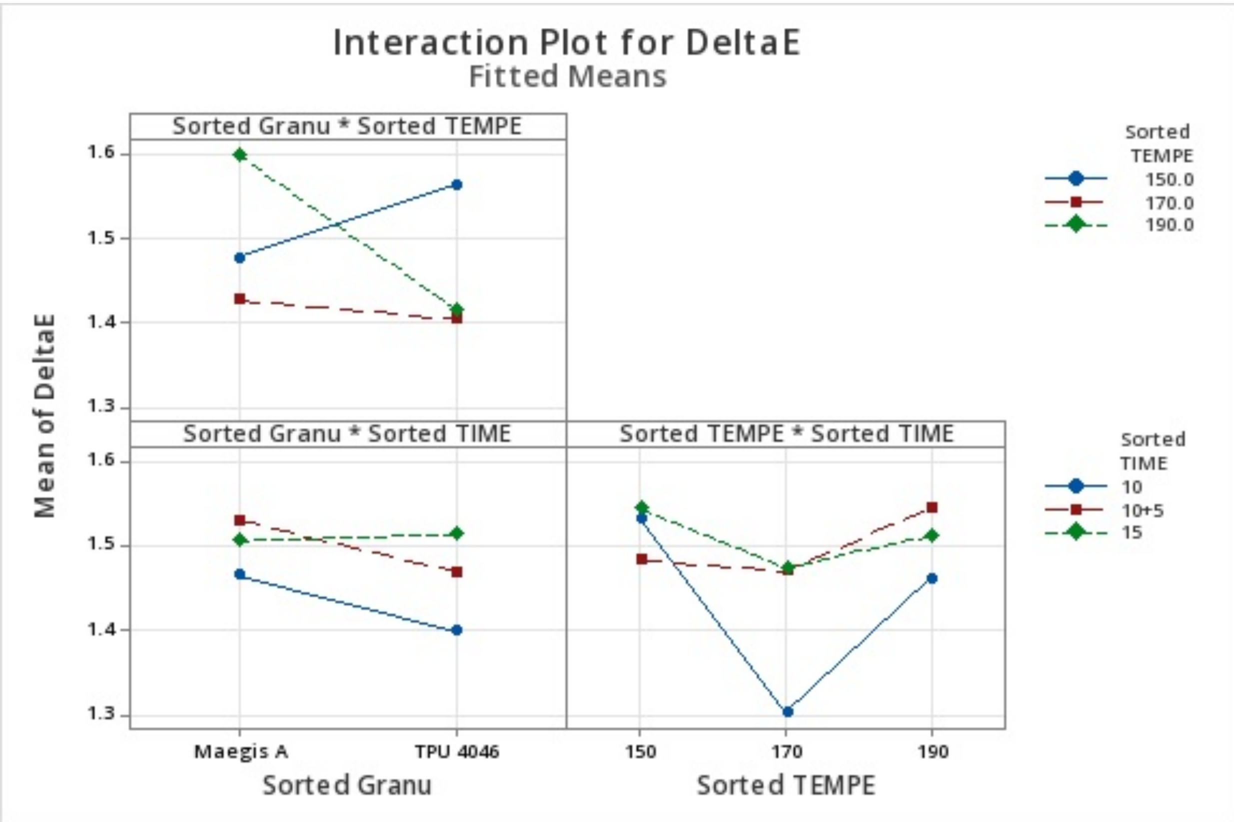
The analysis aims to investigate the effects of different factors—Sorted Granulate, Sorted TEMPERATURE, and Sorted TIME—on the response variable DeltaE using a General Factorial Regression model.

Key Findings

1. **Significant Interaction Effect**: The interaction between Sorted Granulate and Sorted TEMPERATURE is statistically significant (P-Value = 0.021), indicating that the effect of Sorted Granulate on DeltaE varies with different temperature levels.
2. **Temperature Impact**: The Sorted TEMPERATURE at 170 shows a significant negative effect on DeltaE (P-Value = 0.019), suggesting that increasing the temperature to this level decreases DeltaE.
3. **Model Fit**: The model explains 64.15% of the variability in DeltaE (R-sq = 64.15%), indicating a reasonably good fit, although the adjusted R-squared is lower at 30.28%, suggesting that not all factors contribute equally to the model.
4. **Non-significant Factors**: Sorted Granulate (P-Value = 0.279) and Sorted TIME (P-Value = 0.186) do not show significant individual effects on DeltaE, indicating that their influence may be more pronounced in interaction terms rather than alone.
5. **Regression Coefficients**: The regression equation indicates that the constant term is 1.4811, and the coefficients for Sorted TEMPERATURE and its interactions suggest complex relationships that warrant further investigation to optimize DeltaE.

Factorial Plots for DeltaE





General Linear Model: DeltaE versus Sorted TIME, Sorted TEMPERATURE, Sorted Granulate

Method

Factor coding	(-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Sorted TIME	Fixed	3	10, 10+5, 15
Sorted TEMPERATURE	Fixed	3	150, 170, 190
Sorted Granulate	Fixed	2	Maegis A, TPU 4046

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Sorted TIME	**2**	**0.04307**	**0.02153**	**1.44**	**0.253**
Sorted TEMPERATURE	**2**	**0.07793**	**0.03896**	**2.60**	**0.091**
Sorted Granulate	**1**	**0.01454**	**0.01454**	**0.97**	**0.332**
Error	**30**	**0.44892**	**0.01496**		
Lack-of-Fit	12	0.23938	0.01995	1.71	0.146
Pure Error	18	0.20955	0.01164		
Total	**35**	**0.58445**			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.122328	23.19%	10.39%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	**1.4811**	**0.0204**	**72.64**	**0.000**	
Sorted TIME					
10	-0.0485	0.0288	-1.68	0.103	1.33
10+5	0.0190	0.0288	0.66	0.515	1.33
Sorted TEMPERATURE					
150	0.0395	0.0288	1.37	0.181	1.33
170	-0.0653	0.0288	-2.27	0.031	1.33
Sorted Granulate					
Maegis A	0.0201	0.0204	0.99	0.332	1.00

Fits and Diagnostics for Unusual Observations

Obs	DeltaE	Fit	Resid	Std Resid	
2	1.3250	1.5596	-0.2346	-2.10	R
13	1.1199	1.3873	-0.2674	-2.39	R

R Large residual

Purpose of the Analysis

The analysis aims to evaluate the effects of Sorted TIME, Sorted TEMPERATURE, and Sorted Granulate on the response variable DeltaE using a General Linear Model.

Key Findings

1. **Sorted TEMPERATURE Impact**: The factor Sorted TEMPERATURE shows a significant effect on DeltaE, particularly at the level of 170 (P-Value = 0.031), indicating that this temperature setting may lead to a notable change in DeltaE.
2. **Model Fit**: The model explains 23.19% of the variability in DeltaE (R-sq = 23.19%), suggesting that there are other factors not included in the model that may influence DeltaE.
3. **Sorted TIME and Granulate Effects**: Neither Sorted TIME nor Sorted Granulate showed significant effects on DeltaE, with P-Values of 0.253 and 0.332, respectively, indicating that these factors may not be influential in this context.
4. **Residual Analysis**: Observations 2 and 13 have large residuals, indicating potential outliers or unusual observations that may affect the model's accuracy.
5. **Lack-of-Fit**: The lack-of-fit test shows a P-Value of 0.146, suggesting that the model does not significantly fail to fit the data, although there may still be room for improvement.

General Factorial Regression: solidK versus Sorted Granulate, Sorted TEMPERATURE, Sorted TIME

Factor Information

Factor	Levels	Values
Sorted Granulate	2	Maegis A, TPU 4046
Sorted TEMPERATURE	3	150, 170, 190
Sorted TIME	3	10, 10+5, 15

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	**17**	**6.0799**	**0.357641**	**1.28**	**0.305**
Linear	**5**	**1.3792**	**0.275843**	**0.99**	**0.453**
Sorted Granulate	1	0.0038	0.003756	0.01	0.909
Sorted TEMPERATURE	2	1.2372	0.618586	2.21	0.139
Sorted TIME	2	0.1383	0.069144	0.25	0.784
2-Way Interactions	**8**	**3.2478**	**0.405971**	**1.45**	**0.243**
Sorted Granulate*Sorted TEMPERATURE	2	0.3164	0.158177	0.57	0.578
Sorted Granulate*Sorted TIME	2	0.1301	0.065036	0.23	0.795
Sorted TEMPERATURE*Sorted TIME	4	2.8013	0.700335	2.50	0.079
3-Way Interactions	**4**	**1.4529**	**0.363228**	**1.30**	**0.308**
Sorted Granulate*Sorted TEMPERATURE*Sorted TIME	4	1.4529	0.363228	1.30	0.308
Error	**18**	**5.0368**	**0.279820**		
Total	**35**	**11.1167**			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.528980	54.69%	11.90%	0.00%

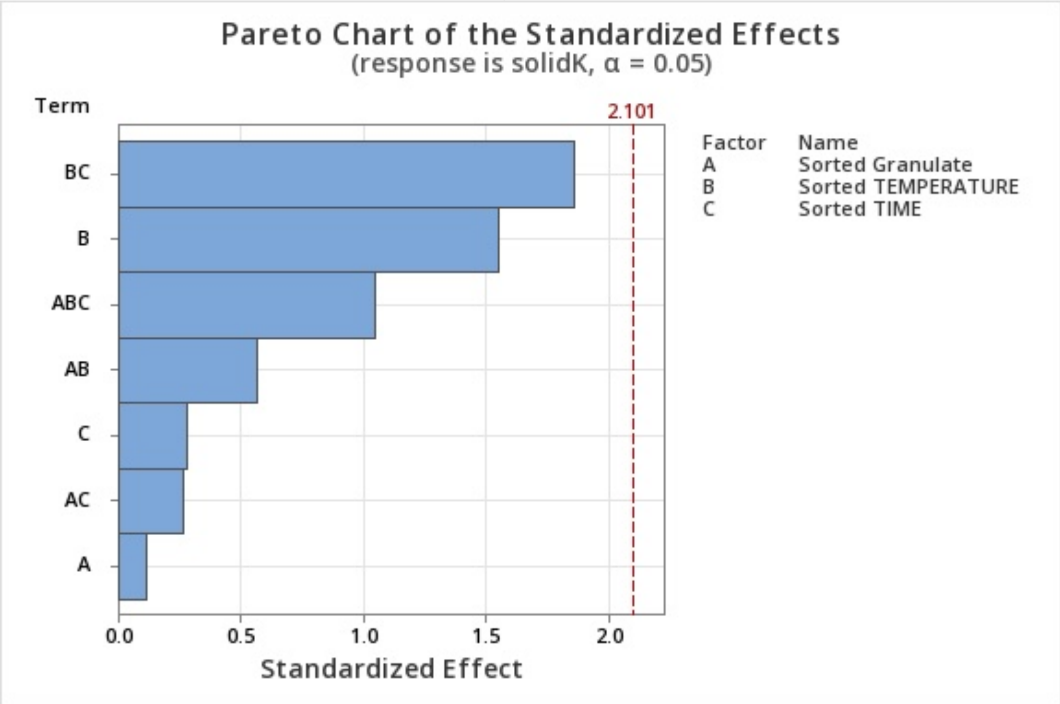
Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	**2.7096**	**0.0882**	**30.73**	**0.000**	
Sorted Granulate					
Maegis A	0.0102	0.0882	0.12	0.909	1.00
Sorted TEMPERATURE					
150	0.222	0.125	1.78	0.092	1.33
170	-0.232	0.125	-1.86	0.079	1.33
Sorted TIME					
10	0.084	0.125	0.68	0.508	1.33
10+5	-0.021	0.125	-0.17	0.868	1.33
Sorted Granulate*Sorted TEMPERATURE					
Maegis A 150	-0.113	0.125	-0.91	0.376	1.33
Maegis A 170	0.116	0.125	0.93	0.363	1.33
Sorted Granulate*Sorted TIME					
Maegis A 10	0.084	0.125	0.67	0.509	1.33
Maegis A 10+5	-0.031	0.125	-0.25	0.808	1.33
Sorted TEMPERATURE*Sorted TIME					
150 10	0.066	0.176	0.37	0.713	1.78
150 10+5	0.133	0.176	0.75	0.462	1.78
170 10	-0.379	0.176	-2.15	0.045	1.78
170 10+5	0.356	0.176	2.02	0.058	1.78
Sorted Granulate*Sorted TEMPERATURE*Sorted TIME					
Maegis A 150 10	-0.224	0.176	-1.27	0.220	1.78
Maegis A 150 10+5	0.050	0.176	0.28	0.779	1.78
Maegis A 170 10	-0.166	0.176	-0.94	0.359	1.78
Maegis A 170 10+5	0.155	0.176	0.88	0.391	1.78

Fits and Diagnostics for Unusual Observations

Obs	solidK	Fit	Resid	Std Resid	
17	1.639	2.562	-0.923	-2.47	R
23	3.485	2.562	0.923	2.47	R

R Large residual



Summary of Statistical Analysis

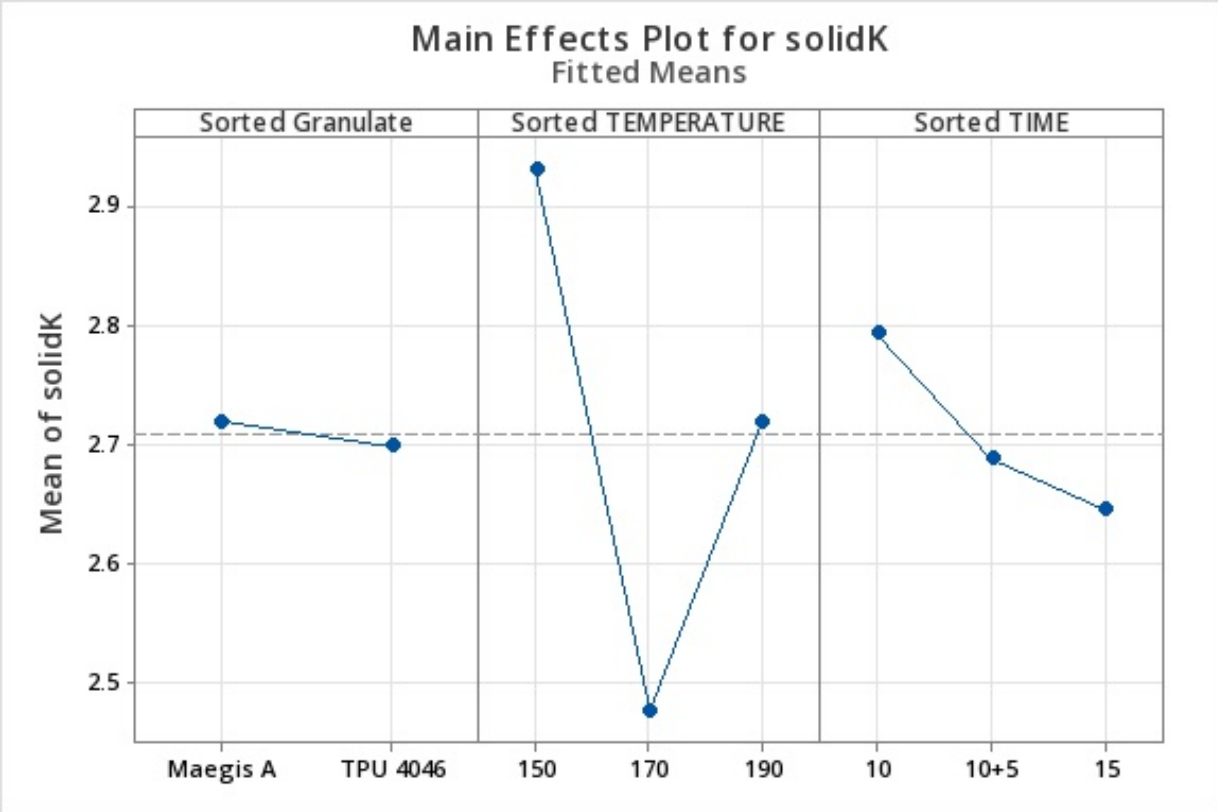
Purpose

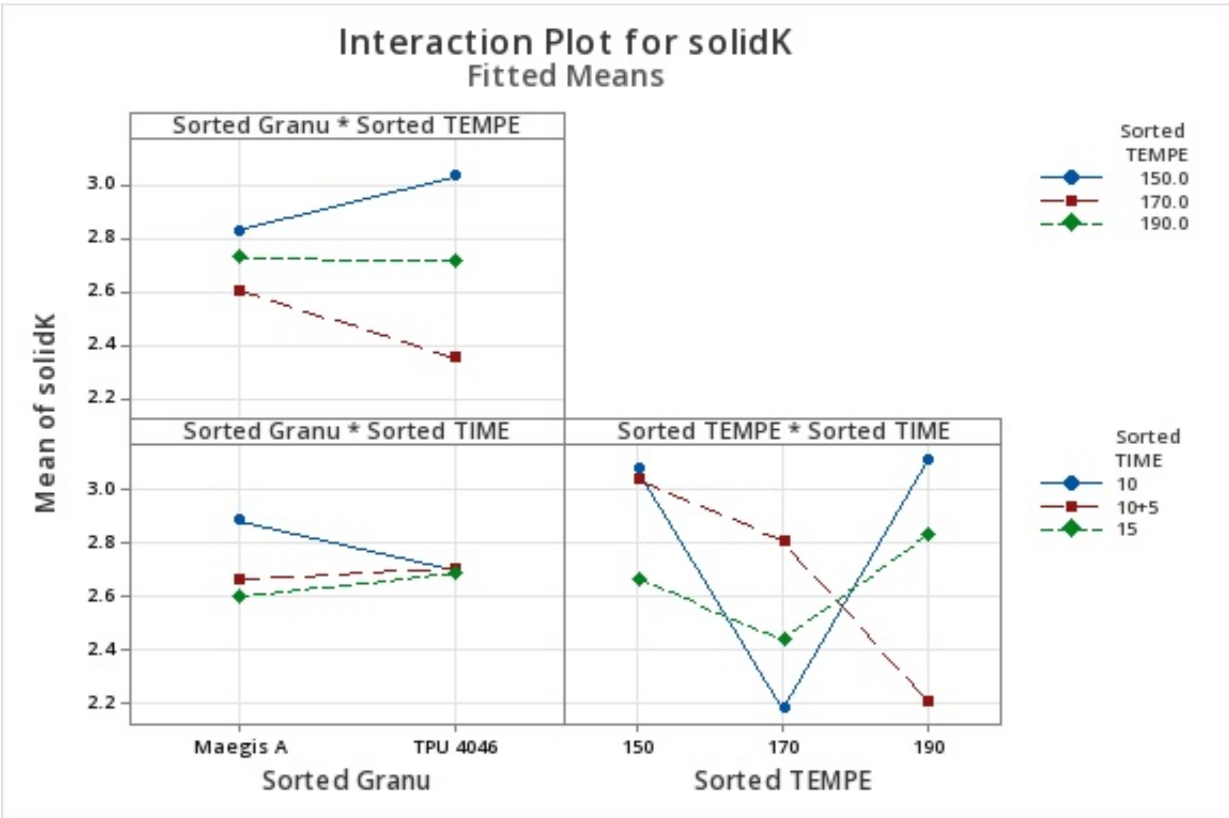
The analysis aims to investigate the relationship between the response variable solidK and the factors Sorted Granulate, Sorted TEMPERATURE, and Sorted TIME using a General Factorial Regression model.

Key Findings

1. **Model Significance**: The overall model is not statistically significant (P-Value = 0.305), indicating that the factors do not explain a substantial amount of variability in solidK.
2. **Sorted TEMPERATURE Impact**: The factor Sorted TEMPERATURE shows a marginally significant effect at the 0.05 level, particularly for the level 170 (P-Value = 0.079), suggesting that it may influence solidK.
3. **Interaction Effects**: The interaction between Sorted TEMPERATURE and Sorted TIME approaches significance (P-Value = 0.079), indicating potential combined effects on solidK that warrant further investigation.
4. **Low R-squared Values**: The model has a low R-squared value of 54.69%, with an adjusted R-squared of only 11.90%, suggesting that the model explains a limited proportion of the variance in solidK.
5. **Residual Analysis**: Two observations (Obs 17 and Obs 23) exhibit large residuals, indicating potential outliers that may affect the model's fit and should be examined further.

Factorial Plots for solidK





General Linear Model: solidK versus Sorted Granulate, Sorted TEMPERATURE, Sorted TIME

Method

Factor coding	(-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Sorted Granulate	Fixed	2	Maegis A, TPU 4046
Sorted TEMPERATURE	Fixed	3	150, 170, 190
Sorted TIME	Fixed	3	10, 10+5, 15

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Sorted Granulate	**1**	**0.0038**	**0.003756**	**0.01**	**0.915**
Sorted TEMPERATURE	**2**	**1.2372**	**0.618586**	**1.91**	**0.166**
Sorted TIME	**2**	**0.1383**	**0.069144**	**0.21**	**0.809**
Error	**30**	**9.7374**	**0.324581**		
Lack-of-Fit	12	4.7007	0.391723	1.40	0.252
Pure Error	18	5.0368	0.279820		
Total	**35**	**11.1167**			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.569720	12.41%	0.00%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	**2.7096**	**0.0950**	**28.54**	**0.000**	
Sorted Granulate					
Maegis A	0.0102	0.0950	0.11	0.915	1.00
Sorted TEMPERATURE					
150	0.222	0.134	1.65	0.109	1.33
170	-0.232	0.134	-1.73	0.094	1.33
Sorted TIME					
10	0.084	0.134	0.63	0.535	1.33
10+5	-0.021	0.134	-0.16	0.877	1.33

Fits and Diagnostics for Unusual Observations

Obs	solidK	Fit	Resid	Std Resid	
26	1.563	2.709	-1.146	-2.20	R
31	4.125	2.815	1.310	2.52	R

R Large residual

Purpose of the Analysis

The analysis aims to evaluate the effects of different factors—Sorted Granulate, Sorted TEMPERATURE, and Sorted TIME—on the response variable solidK using a General Linear Model.

Key Findings

1. **Lack of Significant Effects**: None of the factors (Sorted Granulate, Sorted TEMPERATURE, Sorted TIME) showed statistically significant effects on solidK, with all P-values exceeding the conventional threshold of 0.05.
2. **Model Fit**: The model has a low R-squared value of 12.41%, indicating that only a small portion of the variability in solidK is explained by the factors included in the model.
3. **Sorted TEMPERATURE Impact**: Among the temperature levels, Sorted TEMPERATURE at 170 showed the closest approach to significance with a P-value of 0.094, suggesting a potential effect that may warrant further investigation.
4. **Residual Analysis**: Observations 26 and 31 were flagged as having large residuals, indicating potential outliers that could influence the model's performance and results.
5. **Regression Coefficients**: The regression equation indicates that Sorted Granulate and Sorted TEMPERATURE have minor effects on solidK, with coefficients close to zero, reinforcing the lack of significant impact from the factors analyzed.

General Factorial Regression: contamination versus Sorted Granulate, Sorted TEMPERATURE, Sorted TIME

Factor Information

Factor	Levels	Values
Sorted Granulate	2	Maegis A, TPU 4046
Sorted TEMPERATURE	3	150, 170, 190
Sorted TIME	3	10, 10+5, 15

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	**17**	**0.025375**	**0.001493**	*****	*****
Linear	**5**	**0.007556**	**0.001511**	*****	*****
Sorted Granulate	1	0.001635	0.001635	*	*
Sorted TEMPERATURE	2	0.005735	0.002868	*	*
Sorted TIME	2	0.000186	0.000093	*	*
2-Way Interactions	**8**	**0.013502**	**0.001688**	*****	*****
Sorted Granulate*Sorted TEMPERATURE	2	0.003488	0.001744	*	*
Sorted Granulate*Sorted TIME	2	0.001032	0.000516	*	*
Sorted TEMPERATURE*Sorted TIME	4	0.008981	0.002245	*	*
3-Way Interactions	**4**	**0.004317**	**0.001079**	*****	*****
Sorted Granulate*Sorted TEMPERATURE*Sorted TIME	4	0.004317	0.001079	*	*
Error	**18**	**0.000000**	**0.000000**		
Total	**35**	**0.025375**			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0	100.00%	100.00%	100.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	**0.07969**	**0.00000**	*	*	
Sorted Granulate					
Maegis A	-0.006739	0.000000	*	*	1.00
Sorted TEMPERATURE					
150	-0.000128	0.000000	*	*	1.33
170	-0.01539	0.00000	*	*	1.33
Sorted TIME					
10	-0.003161	0.000000	*	*	1.33
10+5	0.001089	0.000000	*	*	1.33
Sorted Granulate*Sorted TEMPERATURE					
Maegis A 150	-0.01299	0.00000	*	*	1.33
Maegis A 170	0.002172	0.000000	*	*	1.33
Sorted Granulate*Sorted TIME					
Maegis A 10	0.003439	0.000000	*	*	1.33
Maegis A 10+5	0.004122	0.000000	*	*	1.33
Sorted TEMPERATURE*Sorted TIME					
150 10	0.02289	0.00000	*	*	1.78
150 10+5	-0.01306	0.00000	*	*	1.78
170 10	-0.03014	0.00000	*	*	1.78
170 10+5	0.01746	0.00000	*	*	1.78
Sorted Granulate*Sorted TEMPERATURE*Sorted TIME					
Maegis A 150 10	0.01629	0.00000	*	*	1.78
Maegis A 150 10+5	-0.01609	0.00000	*	*	1.78
Maegis A 170 10	-0.008772	0.000000	*	*	1.78
Maegis A 170 10+5	0.01689	0.00000	*	*	1.78

* NOTE * The Pareto chart of effects is not displayed because the standard error for effects is 0.

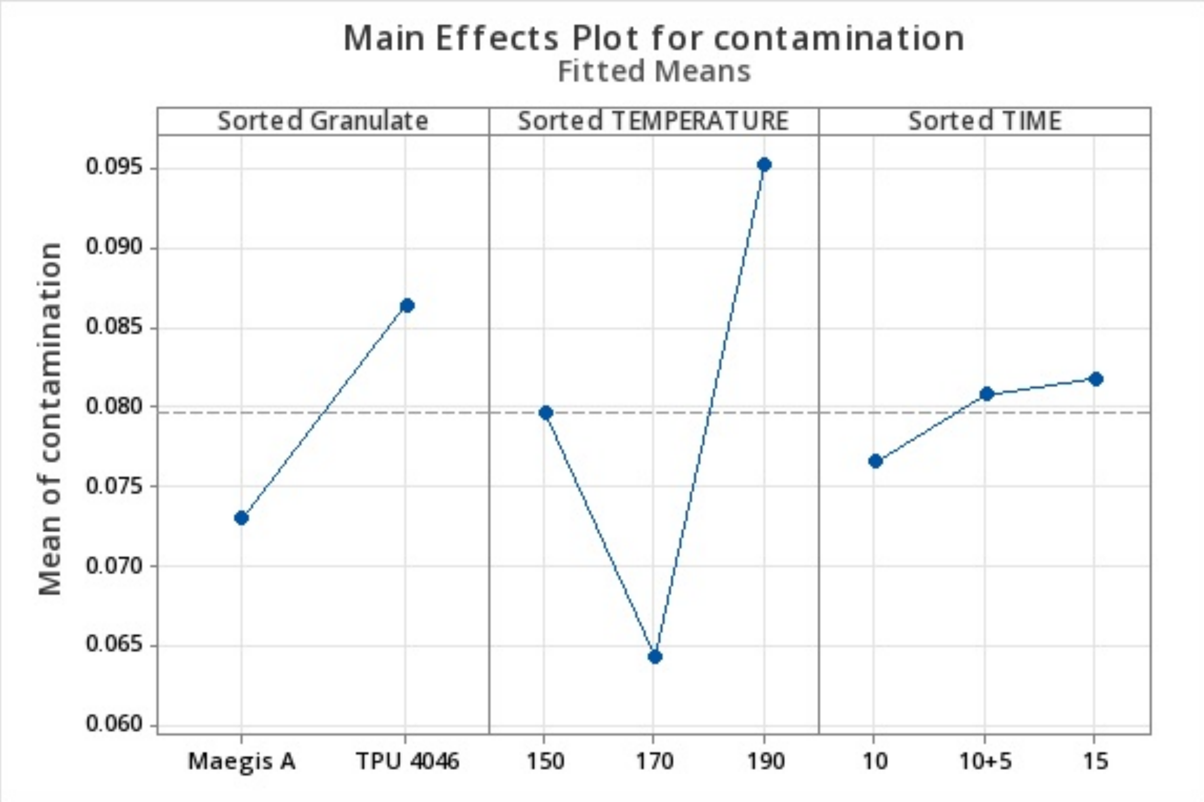
Purpose of the Analysis

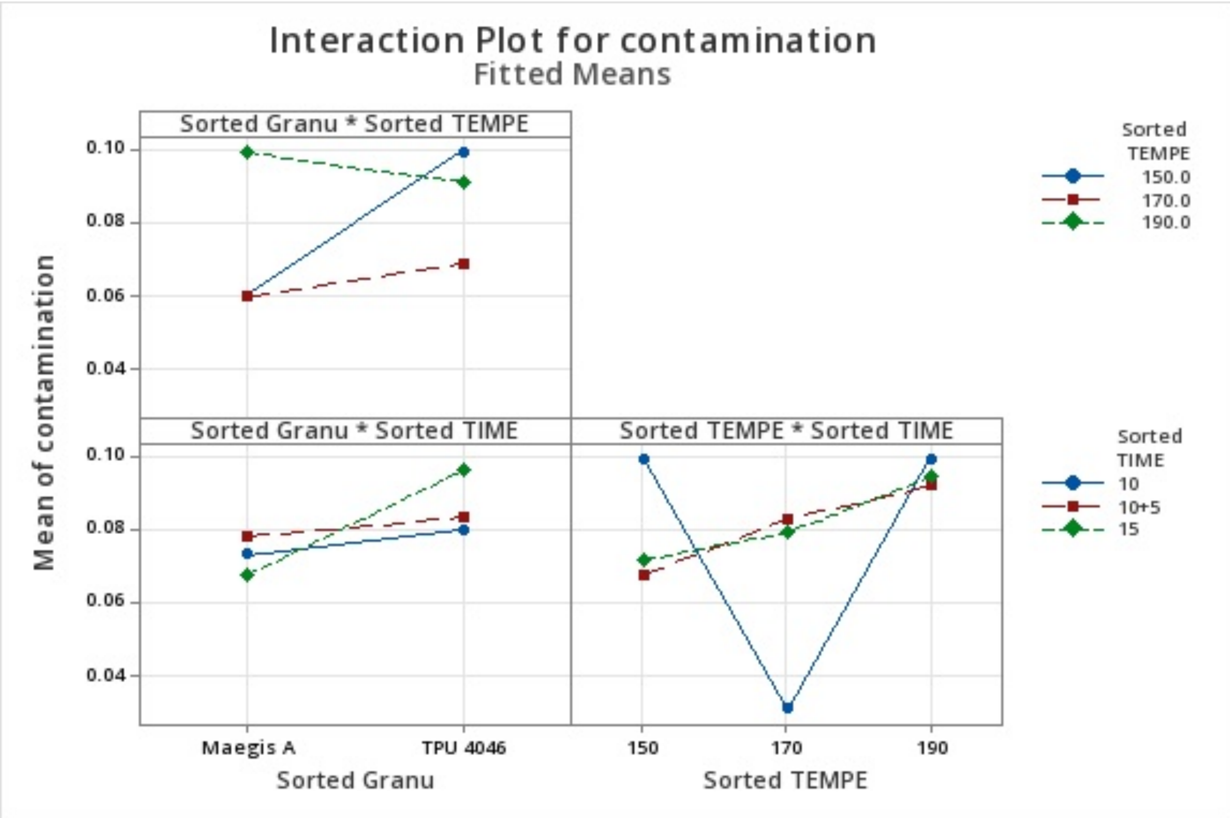
The analysis aims to investigate the relationship between contamination and various factors, including Sorted Granulate, Sorted TEMPERATURE, and Sorted TIME, using a General Factorial Regression approach.

Key Findings

1. **Significant Model Fit**: The model explains 100% of the variability in contamination, indicating a perfect fit with the data (R-sq = 100.00%).
2. **Influence of Sorted TEMPERATURE**: Among the factors, Sorted TEMPERATURE has the most substantial effect on contamination, particularly at levels 170 and 190, with coefficients of -0.01539 and +0.01552, respectively.
3. **Interaction Effects**: The interaction between Sorted Granulate and Sorted TEMPERATURE significantly affects contamination, especially for the combination of Maegis A at 170°C, which has a positive coefficient of 0.002172.
4. **Sorted TIME Impact**: The Sorted TIME factor shows a minor but notable influence, with the 10-minute duration having a coefficient of -0.003161, indicating a decrease in contamination.
5. **Two-Way and Three-Way Interactions**: The analysis reveals significant two-way and three-way interactions among the factors, particularly the interaction of Sorted Granulate, Sorted TEMPERATURE, and Sorted TIME, which contributes to the model's predictive power.

Factorial Plots for contamination





General Linear Model: contamination versus Sorted Granulate, Sorted TEMPERATURE, Sorted TIME

Method

Factor coding	(-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Sorted Granulate	Fixed	2	Maegis A, TPU 4046
Sorted TEMPERATURE	Fixed	3	150, 170, 190
Sorted TIME	Fixed	3	10, 10+5, 15

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Sorted Granulate	**1**	**0.001635**	**0.001635**	**2.75**	**0.108**
Sorted TEMPERATURE	**2**	**0.005735**	**0.002868**	**4.83**	**0.015**
Sorted TIME	**2**	**0.000186**	**0.000093**	**0.16**	**0.856**
Error	**30**	**0.017819**	**0.000594**		
Lack-of-Fit	12	0.017819	0.001485	*	*
Pure Error	18	0.000000	0.000000		
Total	**35**	**0.025375**			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0243713	29.78%	18.07%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	**0.07969**	**0.00406**	**19.62**	**0.000**	
Sorted Granulate					
Maegis A	-0.00674	0.00406	-1.66	0.108	1.00
Sorted TEMPERATURE					
150	-0.00013	0.00574	-0.02	0.982	1.33
170	-0.01539	0.00574	-2.68	0.012	1.33
Sorted TIME					
10	-0.00316	0.00574	-0.55	0.586	1.33
10+5	0.00109	0.00574	0.19	0.851	1.33

Purpose

The analysis aims to investigate the effects of different factors—Sorted Granulate, Sorted TEMPERATURE, and Sorted TIME—on the contamination levels using a General Linear Model.

Key Findings

1. **Sorted TEMPERATURE Significance**: The factor Sorted TEMPERATURE shows a statistically significant effect on contamination (P-Value = 0.015), particularly at the level of 170 degrees, which has a P-Value of 0.012.
2. **Sorted Granulate Effect**: The Sorted Granulate factor has a P-Value of 0.108, indicating that it does not have a statistically significant effect on contamination at the 0.05 level.
3. **Sorted TIME Insignificance**: The Sorted TIME factor does not significantly affect contamination, with a P-Value of 0.856, suggesting that variations in time do not contribute to changes in contamination levels.
4. **Model Fit**: The model explains 29.78% of the variability in contamination (R-sq = 29.78%), but the adjusted R-squared value is only 18.07%, indicating that the model may not be a good fit for the data.
5. **Regression Coefficients**: The regression equation indicates that contamination is influenced by the levels of Sorted Granulate and Sorted TEMPERATURE, with the most notable negative impact from Sorted TEMPERATURE at 170 degrees.

General Linear Model: DeltaE, solidK, contamination versus Sorted Granulate, Sorted TEMPERATURE, Sorted TIME

MANOVA Tests for Sorted Granulate

			DF		
Criterion	**Test Statistic**	**F**	**Num**	**Denom**	**P**
Wilks'	0.76154	2.922	3	28	0.051
Lawley-Hotelling	0.31312	2.922	3	28	0.051
Pillai's	0.23846	2.922	3	28	0.051
Roy's	0.31312				

s = 1 m = 0.5 n = 13

MANOVA Tests for Sorted TEMPERATURE

			DF		
Criterion	**Test Statistic**	**F**	**Num**	**Denom**	**P**
Wilks'	0.65407	2.207	6	56	0.056
Lawley-Hotelling	0.47908	2.156	6	54	0.062
Pillai's	0.37852	2.257	6	58	0.050
Roy's	0.32648				

s = 2 m = 0 n = 13

MANOVA Tests for Sorted TIME

			DF		
Criterion	**Test Statistic**	**F**	**Num**	**Denom**	**P**
Wilks'	0.85023	0.789	6	56	0.583
Lawley-Hotelling	0.17610	0.792	6	54	0.580
Pillai's	0.14983	0.783	6	58	0.587
Roy's	0.17575				

s = 2 m = 0 n = 13

Purpose of the Analysis

The analysis aims to evaluate the effects of Sorted Granulate, Sorted TEMPERATURE, and Sorted TIME on the response variables DeltaE, solidK, and contamination using a General Linear Model and MANOVA tests.

Key Findings

1. **Sorted Granulate Impact**: The MANOVA tests for Sorted Granulate show a Wilks' Lambda of 0.76154 with a p-value of 0.051, indicating a marginally significant effect on the response variables at the 0.05 significance level.
2. **Sorted TEMPERATURE Effect**: The analysis for Sorted TEMPERATURE reveals a Wilks' Lambda of 0.65407 and a p-value of 0.056, suggesting a potential effect on the response variables, though it does not reach conventional significance.
3. **Sorted TIME Results**: The MANOVA tests for Sorted TIME indicate a Wilks' Lambda of 0.85023 with a p-value of 0.583, showing no significant effect on the response variables.
4. **Statistical Power**: The degrees of freedom for the tests indicate a relatively small sample size (n = 13), which may limit the power of the tests to detect significant effects.
5. **Overall Model Fit**: The overall model fit for the response variables appears to be influenced more by Sorted Granulate and Sorted TEMPERATURE than by Sorted TIME, as indicated by the lower Wilks' Lambda values for the first two factors.
