CZECH TECHNICAL UNIVERSITY IN PRAGUE
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Influence of manufacturing processes and flatness of input material on black uniformity of LCD displays in automotive industry

Bachelor Thesis

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Affidavid

I declare that I worked out this thesis independently and I quoted all used sources of information in accord with Methodical instructions about ethical principles for writing academic thesis. Moreover I declare that it has not already been accepted for any degree and is also not being concurrently submitted for any other degree.
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Zásady pro vypracování

Při zpracování bakalářské práce se řiďte následujícími pokyny:

- Cílem práce je zanalyzovat vliv jednotlivých výrobních procesů na černou homogenitu displeje
- Ověřte, zda vstupní materiál odpovídá specifikaci
- Analyzujte vztah mezi rovinností vstupních materiálů a černou homogenitou displeje
- Stanovte největšího přispěvatele poklesu černé homogenity z výrobních procesů
- Porovnejte snížení poklesu černé homogenity mezi jednotlivými výrobními cykly
- Analyzujte změny v rovinnosti dílů v průběhu procesu

Rozsah grafických prací: -

Rozsah průvodní zprávy: minimálně 35 stran textu (včetně obrázků, grafů a tabulek, které jsou součástí průvodní zprávy)

Seznam odborné literatury: 100 Statistical tests, Gopal K. Kanji

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jméno a podpis studenta

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Abstract: This thesis deals with the optical performance of LCD displays that are used in cockpits in automotive industry. It focuses specifically on analysis with the help of statistical methods of the possible impacts from the production environment to the black uniformity of the displays. During the experiments, data of black uniformity and flatness of the incoming material as well as semi-products coming from three production cycles are investigated. The work shows that the incoming material is mainly in specification. It also demonstrates that there is no correlation between the black uniformity and flatness of the display. Additionally, it has been confirmed that the first semi-product mainly adapts to the flatness of the cover glass and not the display. As the production consists of several steps, the main contributor along the production processes to the degradation of Black uniformity has been found. Lastly, the improvement program between the production cycles has been marked as partially successful, as there has been possible improvement of optical behavior observed on several production lines. The results of this thesis were used in decision-making in the company of Continental, where the experiments were done, and taken as knowledge learned to the development of the new products.
Keywords: black uniformity, correlation, flatness, hypothesis testing, LCD displays

Abstrakt: Tato práce se zabývá optickým chováním LCD displejů, které se používají v kokpitech v automobilovém průmyslu. Konkrétně se zaměřuje na analýzu možných vlivů výrobního prostředí na rovnoměrnost černé homogenity displejů pomocí statistických metod. Během experimentů jsou zkoumány údaje o černé homogenitě a rovinnosti vstupního materiálu i polotovarů pocházejících ze tří výrobních cyklů. Z práce je patrné, že vstupní materiál je převážně ve specifikaci. Prokazuje také, že neexistuje žádná korelace mezi černou homogenitou a rovinností displeje. Navíc bylo potvrzeno, že první semi-produkt se přizpůsobuje hlavně rovinnosti krycího skla, nikoliv displeje. Jelikož se výroba skládá z několika kroků, byl zjištěn hlavní přispěvatel ke zhoršení černé homogenity mezi výrobními procesy. A konečně, projekt na zlepšování černé homogenity mezi výrobními cykly byl označen za částečně úspěšný, neboť na několika výrobních linkách bylo pozorováno možné zlepšení optického chování. Výsledky této práce byly využity při rozhodování ve společnosti Continental, kde byly experimenty provedeny, a vzaty jako poznatky pro vývoj nových výrobků.
Klíčová slova: černá homogenita, korelace, rovinnost, testování hypotéz, LCD displeje

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List of Acronyms

ADAS	advanced driver-assistance system
DC	Display closing
HB	Hybrid bonding
TFT	thin film transitor
FDC	front driver display
CP	central panel
LCD	liquid crystal display
OLED	organic light-emitting diode
ILMD	image luminescence measurement device

Chapter 1

Introduction

This thesis deals with optical performance of LCD displays which are used for cockpits in automotive industry. Specifically, it focuses on black uniformity of the displays, shortly describes as uniformity of the luminescence around the whole area of the display.
As today the world is facing a digital transformation and displays are important not only for driver as a resource of driving data, but also for co-driver as entertainment during the drive, this topic is for automotive industry very important, since it plays a big role in customer's decision whether to buy a car or not. Therefore, they expect to buy a product of excellent quality. As this task is so important, the goals of the thesis are to analyze the impacts in production to black uniformity of the LCD display in final product as it can be found in next chapters. Goals will be specified in Chapter 3. Specifically, in the rest of Chapter 1, the brief history of Continental company can be found, the main producer of LCD displays for automotive industry on the market and company where author performed the practical part of the thesis. In Chapter 2, the information about the product on which the analysis was performed can be found. In Chapter 3, methodology of the tests is described, followed by Chapter 4, where the description of statistical methods used for evaluation is located. In Chapter 5, the analysis of the experiments is performed and the results are discussed.

1.1 History of the company

Continental is a German company in automotive industry founded in 1871 in Hannover. Firstly the main focus of a production was set on rubber tires. In 1928, major rubber companies in whole Germany merge together into Continental Gummi-Werke AG, making it a leader in tire production around Europe in the 20th century. In late 80's Continental had already around 46 000 employees all around the world. Its logo, shown in Figure 1.1, consists of horse on its 2 back legs, which is encircled by the written name of company and the year of foundation.

Figure 1.1: Continental Logo

The company saw the potential of growth also in other fields of automotive industry. As a result, in 1995 Automotive section was established. During the first 20 years of 21st century company grew into the main supplier in automotive industry, not only in tire production, but also in display and radio technologies and became an innovator in fields of autonomous driving and transition towards new possibilities of using electricity and hydrogen as a fuel instead of petrol. Nowadays, Continental is an important supplier for nearly all of the car brands with more than 250 000 employees in 59 countries. It consists of 3 main areas - ContiTech, which produces main parts for marine, agricultural and railway industry, Automotive, which is responsible for Displays, Radios and advanced driver-assistance system (ADAS) systems, and lastly Tires, producing tires not only for cars, but also for bikes, motorcycles and buses. Each area is then divided into several business units, eg. Automotive Area is divided into Autonomous Mobility, Safety and Motion, Architecture and Networking, User Experience, Services and Technology Trends. For this bachelor thesis this Automotive area is the most important, since the plant, where the experiments were done, is under this area as described in the next chapter. In the Czech Republic there are 5 main plants of Continental company - Brandýs nad Labem, Jičín, Adršpach, Otrokovice and Frenštát pod Radhoštěm and it is one of the biggest employers there with more than 10 600 employees.

1.2 Plant Brandýs nad Labem

As this bachelor thesis is written based on the investigation which was done in Brandýs nad Labem, let the author introduce it. The history of this plant began in the previous century as a state-owned factory of PAL in Prague Kbely. In 1997 PAL decided to build a complete new factory in Brandýs nad Labem where air conditioning and car on-board units production should be done. In early 2000's the production extends of car-radios and printed circuit boards (PCB). In 2007 Continental bought this factory and Continental Automotive Czech Republic s.r.o. was founded. A year after, additional factory to Brandys I was built, which is now called BDY II. There were completely new technologies of display production introduced in 2015 making Brandys I and II one of the most important display production plant in the whole Continental company. Today, together 4 plants are located in Brandys and all of them are part of the Automotive area, concretely the User Experience business unit shown in Figure 1.2.

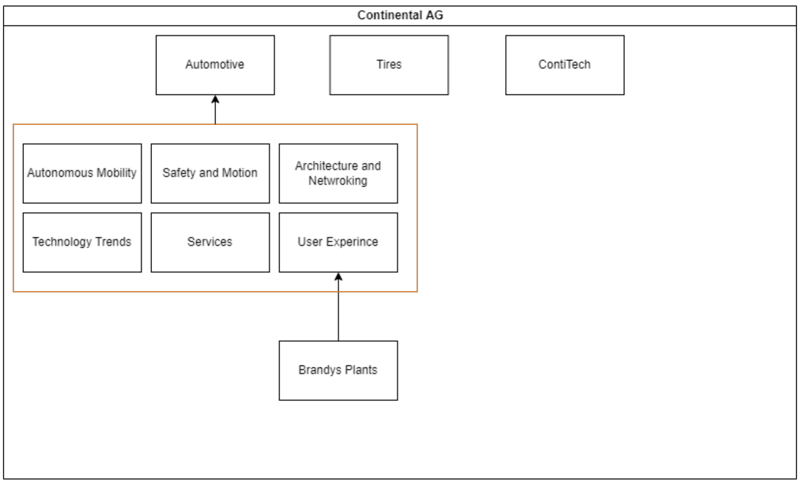

Figure 1.2: Brandys Plants in the Continental company structure, made by author

Chapter 2

Description of production

2.1 Overview of the product

The product is set to be produced as modern multifunctional car dashboard for a reputable European car producer. Design of it is completely new and the production is built on completely new technologies in today Display-technology world. New designs and technologies bring with themselves also new problems for engineers to be solve. One of them is black uniformity of displays which is the topic of this bachelor thesis, as the displays are becoming larger and customers want to have perfectly clear and uniform products.
Black uniformity is a quantity, which is calculated in the testing line of production and should follow the production requirements. That is why the production lined should be introduced in the thesis. In Brandys plant, there are together five production lines to be able to create from input material final dashboard, in four of them displays take part - the first three are assembly lines, the last one is a testing one.
Let the author introduce each of the production lines separately.

2.1.1 Hybrid bonding

Hybrid bonding (HB) is the first assembly line, where thin film transitor (TFT) display panel and cover glass are bonded together using high pressure and silicon as a gluing material. As a result of this process bonded assembly is made and continues in production process. During the process touch panel is pre-bended before gluing with TFT panel, which can lead into stress in material which can lead in low black uniformity. Another aspects of lowering black uniformity are lamination force which is used during gluing process, lamination time, the amount of glue and also pattern in which silicon is applied. These hypothesis are taken into investigation in the practical part of bachelor thesis.

Together, there are 5 variants of bonded assemblies, each of them use different input material with different characteristics. The first is front driver display (FDC) bonded assembly, which is display that is in the final product located as driver display showing a speedometer, a tachometer or an actual status of gas tank. This assembly is the same for right-hand-side and left-hand-side cars. Besides FDC, there are 2 types of central panel (CP) displays, which are used as a central panel between driver and co-driver in a car. Passengers can set up air-conditioning, radio or navigation here. First CP type is 12" which makes him the biggest one in the production, the second one is 9". Different variants of CP bonded assemblies are used in different cars of the customer. There are also different CP assemblies for left-hand-side and right-hand-side variants of cars. Unlike the FDC, CP bonded assemblies are touch-sensitive which add one extra layer to the CG. To summarize, there are these bonded assemblies produced:

- bonded assembly FDC,
- bonded assembly CP 12" left-hand-side,
- bonded assembly CP 12" right-hand-side,
- bonded assembly CP 9" left–hand-side,
- bonded assembly CP 9" right-hand-side

and the following characteristic of parts and process steps that can affect black uniformity:

- flatness and shape of touch panel,
- flatness and black uniformity of TFT display,
- pressure used during lamination,
- time of lamination,
- pattern of silicon application,

- pre-bending of touch panel,
- material destruction due to high temperature.

2.1.2 Display closing

Display closing (DC) is the second assembly line in the whole process. On this line FDC and CP bonded assemblies are put together into one larger assembly. That means that driver-dashboard and central panel create one unit, making the cockpit of the car compact. This concept is unique in automotive industry, even for Continental it is a first product with this design.
The main construct is made of 2 screwed back-lights, parts made out of aluminum which should furthermore reflect the light behind bonded assemblies. For each bonded assembly, there is a unique back-light. This construct is completed with plastic ornamental frame which border circumference of back-lights. There are some other components included in the construct, but they can not affect black uniformity, so they will not be mentioned. During the process on display closing line FDC and CP bonded assemblies are glued onto the construct with a material that is suited for LED hardening. These parts and process steps can have influence on black uniformity:

- flatness and white uniformity of back-lights,
- flatness and black uniformity of input bonded assemblies,
- type of glue,
- method of glue hardening,
- gravity effect leading into addition of stress,
- temperature deformation.

2.1.3 Final assembly

The third and last assembly line in the process is the final assembly. The main entry component into this line is DC assembly created as described in a previous chapter. Additionally, plastic covers, speaker and ventilators are screwed onto DC assembly during assembly. After this line, product is complete and can be transferred into testing line as described in the next paragraph. These process steps can have influence on black uniformity:

- screwing sequence,
- stress caused by screwing.

2.1.4 Testing line

This line is directly connected with the final assembly line. There are no additional changes in the product, but as the name of the line indicate, several tests are performed on the product. During this process, black uniformity is also calculated and a picture of luminescence is captured by camera for each of bonded assembly - CP and FDC separately. It is the only serial-production process step where the value of black uniformity is known. At this point, black uniformity should not be lower than 45 %. At the end of this line, product is packed into a box and is ready to be shipped to the customer. This line does not have any effect on the black uniformity

2.1.5 Back-light assembly line

Back-light assembly line is the only one, where displays are not included themselves. However as mentioned in Chapter 2.1.2, back-lights are one of the possible impacts. During this process, several foils are glued onto an aluminum construct making perfect reflector of the back-light. Currently, all of the assembly lines and one testing line are located in Brandys. During the data collection, back-light assembly line was located in other plant in Europe, so that it is not able to directly influence the production of back-lights to improve black uniformity.

As now the architecture of the product and manufacturing processes were described, the following chapter focuses on the methodology of the performed experiments.

Chapter 3

Methodology

3.1 Goals of the thesis

As described already in the introduction, this thesis deals with analysis of quantities influencing the black uniformity of the displays. It is expected, that the geometrical characteristics of the input material will have impact on the black uniformity, as the deformation of the input material creates mechanical pressure, which negatively influences the optical characteristics in general, including black uniformity. The impact was shown by internal simulations [1] as well as by academical research at Hefei University of Technology, China [2], and commercial development at BOE company [3, 4].

Goals specified in Chapter 1 are here specified as follows:

- evaluate if received parts from the supplier are within the geometrical limits set in technical drawings:
  - TFT panels,
  - cover glasses,
- evaluate if the black uniformity of TFT panels from the supplier is equal to or higher than the minimum set,
- evaluate if there is a correlation between flatness and black uniformity of TFT panels,
- evaluate how flatness and shape of cover glass and TFT panel affect the final flatness of HB assembly,

- evaluate the biggest contributors to black uniformity loss out of production processes,
- evaluate if there are improvements between production cycles.

3.2 Method of the experiments

Experiments were done in 3 separate production cycles called internally LOOPs. Each LOOP is done with the same batch of material and usually also same settings are applied during the production of samples within one LOOP. After each of the LOOPs, measured data are statistically evaluated and several settings changes are done on the production lines.

As this is one of the first projects of this range in Continental, no knowledge learned from previous projects cannot be applied. Firstly, input material is measured as follows:

- TFT displays - flatness and black uniformity,
- cover glasses - flatness,
- backlights - flatness.

After the measurement, HB assemblies from TFT displays and cover glasses are produced and flatness and black uniformity of it are measured. Same concept is applied on DC assembly line and Final assembly line. Simply, after each of the production steps, black uniformity and flatness are measured to see the difference. First LOOP was done with input material of:

- 32 L4 CP TFT displays and cover glasses,
- 32 L3 CP TFT displays and cover glasses,
- 64 FDC TFT displays and cover glasses.

For the first LOOP, the scrap rate of 20 % was predicted meaning that during the process steps 20 % of input material will be lost due to incorrect gluing, scratches, air-bubbles in assemblies etc.

For the second LOOP these amounts of input material were planned:

- 16 L4 CP TFT displays and cover glasses,

- 16 L3 CP TFT displays and cover glasses,
- 32 FDC TFT displays and cover glasses

and the third LOOP was done with the same amount of input material as the first one. Material used for all LOOPs came from the same supplier's batch creating only low diversity of characteristics of material.
As these experiments run together with normal serial production, some measurements were forced to be skipped to save time and human resources which lead in the end to less data for evaluation.

3.3 Black uniformity measurements

The internal Continental measurement procedure follows two main sources

- VESA Flat Panel Display Measurements Standard,
- Uniformity Measurement Standard for Displays, Deutsches Flachdisplay Forum [5].

However, algorithms used in these standards were simplified for time reduction. For all measured values defined in Continental standard the evaluation of the measurement uncertainty according to the "Guide to the expression of uncertainty in measurement" [6] is required.
There are several necessary requirements concerning the display properties as described below:

- liquid crystal display (LCD) technology is used, not suitable for organic light-emitting diode (OLED) technology,
- no pixel defects in active area of LCD display,
- size of active area $\Delta x_D, \Delta y_D$ is typically $< 300 \cdot 150\, mm$,
- number of active pixels $M_D, ND < 4096 \cdot 2048$,
- luminescence (white) $> 300 \frac{cd}{m^2}$.

These variables will be explained below. Furthermore, the measurements should be performed in stable and repeatable working conditions and at normal room temperature, measured perpendicular. In case of back-light usage, when measuring Display Closing and Final assembly, back-light shall be driven at maximum capacity.

As a measurement device, a luminescence camera, also referred as image luminescence measurement device (ILMD), with maximum resolution greater than the measured display should be used. It is important that the angle of measurement is selected in a way that inside this angle the light distribution of the display does not change significantly, since the optical behavior of display varies over viewing direction. The measurement distance is set in a way that image of the display is as large as possible, it employs the maximum number of pixels for sensor. As the position of the display in the measuring machine is not exactly the same every time, it is recommended to have at least 10 pixels at each side free.

The size of the measured rectangle at display side should be M_D, N_D pixels and size of the rectangle in the camera image M_L, N_L. When taken into account the condition that resolution of the camera is bigger than the display, horizontal reproduction scale is described as $\beta_{H,LD}$ as [1]

$$\beta_{H,LD} = \frac{M_L}{M_D} > 1 \tag{3.1}$$

and vertical reproduction scale $\beta_{V,LD}$ as [1]

$$\beta_{V,LD} = \frac{N_L}{N_D} > 1. \tag{3.2}$$

These β coefficients are important when defining the pattern of measurement, especially blurring, to avoid Moire effect which lead into non-valid measurement. During measurement luminance image defined as [1]

$$Y(i,j), i = 0...N_L, j = 0...M_L \tag{3.3}$$

is taken and from it the average luminance and the black uniformity shall be calculated as described in the following paragraphs.

Let's define horizontal pixel pitch as [1]

$$p = \frac{\Delta x_D}{M_D}, \tag{3.4}$$

vertical pixel pitch as [1]

$$q = \frac{\Delta y_D}{N_D}, \tag{3.5}$$

legacy pixel pitch as $p_L = 0.204 \; \frac{mm}{Pixel}$ and legacy display pixels for averaging $N_{DEL} = 11 \; Pixels$.

Using formulas (3.4) and (3.5), let's define display pixels for averaging (used then in black uniformity calculation) as [1]

$$M_{DE} = \frac{N_{DEL} \cdot p_L}{p}, \tag{3.6}$$

$$N_{DE} = \frac{N_{DEL} \cdot p_L}{q}. \tag{3.7}$$

Furthermore, let a display area describe as DA, which is equal to the image of the display on the camera sensor, and reduced display area for evaluation DA1, which is equal [1]

$$DA1 = DA - N_{LE} \tag{3.8}$$

on every border, where N_{LE} is number of camera pixels for averaging described as [1]

$$N_{LE} = M_{DE} \cdot \beta_{H,LD} = N_{DE} \cdot \beta_{V,LD}. \tag{3.9}$$

Finally, the equation for black uniformity calculation can be described as [1]

$$u = \frac{\min(Y_{box}(i,j))}{\max\left(Y_{box}(k,l)\right)}, \; (i,j),(k,l) \in DA1, \tag{3.10}$$

where $Y_{box}(i,j)$ and $Y_{box}(k,l)$ are the boxes of filtered luminance in the image.

Chapter 4

Statistical methods

To achieve the goals of the thesis and to evaluate the impact of production lines to Black uniformity, statistical tests of hypothesis for one, two or three samples will be used. They are divided between parametric and non-parametric tests. Parametric tests assume that the data values have the normal distribution. That is why firstly it is necessary to test the normality assumption of the data. This can be done with the help of different tests of normality as listed below [7]:

- Anderson-Darling test,
- Shapiro-Wilk test,
- Kolmogorov-Smirnov test,
- Jarque-Bera test,
- Fisher's cumulant test for normality,
- The w/s-test for normality.

As described in [8] and [9] Shapiro-Wilk test followed by Anderson-Darling test are the most powerful ones with number of data samples between 50 - 500, which is the typical amount of samples in this bachelor thesis. Author decided to use Anderson-Darling test of normality to evaluate if the data come from normal distribution.

Anderson-Darling test

As already described, Anderson-Darling test is used to evaluate if the set of data come from normal distribution. This test defined by Theodore Wilbur Anderson and Donald Allan Darling in 1954 uses test statistic A as [10]:

$$A^2 = -n - \sum_{i=1}^{n} \frac{2i-1}{n} [ln(F(X_i)) + ln(1 - F(X_{n+1-i}))], \tag{4.1}$$

where $X_1 < ... < X_n$ are the ordered sample observations and n is the number of observations in the sample. Then the test statistic must be compared with critical value.
After test of normality author used following tests of hypothesis to compare the data.

4.1 Comparison tests

Comparison tests are used to compare the differences in characteristics of sample(s) (variance, mean/median). These tests can be separated into three sections based on how many samples are tested:

- tests for one sample,
- tests for two samples,
- tests for three and more samples.

In this thesis, all three categories of comparison tests are used. Firstly, let the author describe the one sample tests, which are later used in the thesis.

4.1.1 T-test for population mean

T-test for population mean (one-sample t-test) is a statistical test used for testing if there is a significant difference between mean of selected sample and hypothesized mean. In can be used only if the sample is normally distributed and variance of it is unknown. The null-hypothesis states that the mean of sample $\overline{x}$ does not significantly differs (i.e., it is equal or higher or smaller) from hypothesized mean x_0 [7]:

$$H_0 : \overline{x} = x_0. \tag{4.2}$$

The test statistics t uses the mean of the sample $\overline{x}$, hypothesized mean x_0, standard deviation of the sample s and number of sample observations n as [7]:

$$t = \frac{\overline{x} - x_0}{s/\sqrt[2]{n}}. \tag{4.3}$$

The test can be one-sided in case of testing if the mean of sample is lower or higher than the hypothesized mean x_0. If the sample is not normally distributed, following test can be used.

4.1.2 One-sample Wilcoxon signed rank test

One-sample Wilcoxon signed rank test is used for testing if there is a significant difference between median of the not normally distributed sample and hypothesized median. The null-hypothesis states that the median of the sample η is equal (or higher or smaller) to the hypothesized median η_0 [11]:

$$H_0 : \eta = \eta_0. \tag{4.4}$$

This test works on ranking the observations of the sample based on the distance to the hypothesized median. The test starts with rank of 1 to the observation, that is the closest to the median, and continues until all observations are ranked. After the the sum of positives rankings [1] and sum of negative rankings is calculated. The test statistics W is the sum of the ranks of positive differences between the observations and the hypothesized median value, which must be then compared to the critical value.

After describing the one sample tests, let us have a look at two samples tests.

[1] These are the ranks of the observations that are higher than hypothesized median

4.1.3 T-test for two population means

T-test for two population means (two-sample t-test) is used for comparison of means of two not-paired and normally-distributed samples. Except of normality, variances of both samples should be equal for the test. Normally, the null-hypothesis states that means of samples $\overline{x_1}$, $\overline{x_2}$ are equal (higher or smaller) [7]:

$$H_0 : \overline{x_1} = \overline{x_2}. \tag{4.5}$$

For test statistics t it takes then the two sample means $\overline{x_1}$, $\overline{x_2}$, the amount of observations for both samples n_1, n_2 and pooled standard deviation s, which can be calculated as [7]:

$$s = \sqrt{\frac{(n_1 - 1){s_1}^2 + (n_2 - 1){s_2}^2}{n_1 + n_2 - 2}}, \tag{4.6}$$

where s_1, s_2 are standard deviations of samples one and two. Finally, the formula for the test statistics t can be described as [7]:

$$t = \frac{\overline{x_1} - \overline{x_2}}{s\sqrt{1/n_1 + 1/n_2}}. \tag{4.7}$$

4.1.4 Mann-Whitney U test

Mann-Whitney U test is used when comparing the distribution of two samples not coming from normal distribution. In this thesis the test is used to compare medians of two samples. The null-hypothesis states that the two distributions are equal or that the medians are not significantly different (i.e., equal, smaller or higher) [12]:

$$H_0 : \eta_1 = \eta_2. \tag{4.8}$$

As other non-parametric tests, Mann-Whitney test uses ranking system. It orders the observations from both samples combined from lowest to highest and gives the rank based on the numeric index of the ordering. After test statistics U_1 and U_2 are calculated as [12]:

$$U_1 = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1, \tag{4.9}$$

$$U_2 = n_1 n_2 + \frac{n_2(n_2+1)}{2} - R_2, \tag{4.10}$$

where n_1 and n_2 are numbers of observations in sample one and two, R_1 and R_2 are the sums of ranks for all observations in each sample separately as described above. For evaluating the result of the test lower from U_1, U_2 is taken and compared to the critical value in reference table for this test.

When comparing more than two data-sets, there are special group of tests for doing it. In these thesis, only Kruskal-Wallis test was used.

4.1.5 Kruskal-Wallis test

Kruskal-Wallis test is used for comparing distribution of 3 or more not normally distributed sample. In this thesis the test is used for comparing the median of the samples. The null-hypothesis states that all the samples come from the same distribution [7]:

$$H_0 : \eta_1 = ... = \eta_x. \tag{4.11}$$

As non-parametric test it uses the ranking instead of the numeric values. The test takes all the observations from all samples and order it from smallest to largest. Ranking is then taken as numeric index of this ordering and for each of the sample the sum of the rankings is made. This is then used for calculating the test statistics t as [7]:

$$t = \frac{12}{n(n+1)} \sum_{i=1}^{C} \frac{{R_i}^2}{n_i} - 3(n+1), \tag{4.12}$$

where n is sum of number of observations from all samples, R_i is the rank sum of i-th sample, C is number of samples and n_i is the number of observations from i-th sample.

In case of rejecting the null-hypothesis, further analysis using Bonferroni test is done to find which samples differs to which samples. This test is explained below.

Bonferroni test

In this thesis, Bonferroni test is used for analyzing which of the sample medians differs from the others. This test runs with all of the possible pairs of the samples from the Kruskall-Wallis test. The null hypothesis states that the medians of both samples are equal [13].

$$H_0 : \eta_1 = \eta_2 \tag{4.13}$$

As the result of this test, the user knows which sample medians differs from each other.

Besides comparison tests, there are two main tests used for testing if paired samples are correlated between each other. Let the author describe them in the next section.

4.2 Correlation tests

As already mentioned, correlation tests are used when evaluation of relationship between two or more samples is needed. For normally distributed data-sets, Pearson's correlation test can be used, otherwise Spearman's correlation test is needed. Functionality of both tests is described below.

4.2.1 Pearson correlation coefficient test

The Pearson correlation coefficient ρ can be applied between two samples in case that both samples are normally distributed. The formula for calculation of ρ is [14]:

$$\rho = \frac{cov(x_1, x_2)}{s_1 s_2}, \tag{4.14}$$

where cov is covariance between samples,s_1, s_2 are standard deviations of the samples. The coefficient describes the linear relationship between the samples in range from -1 to 1 [14]. When the coefficient is negative, it means, that when numerical values from sample one increase, then in sample two decrease. When the coefficient is positive, it means, that when numerical values from sample one increase, then in sample two increase as well.

After the correlation coefficient is calculated, it it important to test if it is significant. For these purposes, the hypothesis test for the population correlation coefficient is used. The null-hypothesis states the following [7]:

$$H_0 : \rho = 0. \tag{4.15}$$

To test the hypothesis, the following test statistic t is calculated [7]:

$$t = \frac{\rho\sqrt{(n-2)}}{\sqrt{(1-\rho^2)}}, \tag{4.16}$$

where n is a number of observation pairs. Lastly the test statistic is compared to the critical value.

For easier description, in the thesis, the whole process of calculating the Pearson correlation coefficient and testing the significance is referred as Pearson's correlation test.

The next test is being used for evaluating the correlation in case the samples do not come from normal distribution.

4.2.2 Spearman correlation coefficient test

Spearman correlation coefficient test[2] is used for investigation the significance of the correlation between two not normally-distributed samples of observations obtained in pairs [7]. The null-hypothesis states that the samples are not significantly correlated. Using the test, firstly observations in both samples are ranked 1, 2,..., n in order from smallest to highest separately. After that, the difference d_i between the ranks in each pair of observations is calculated. To get the test statistic Z the quantity $R = \sum_{i=1}^{n} {d_i}^2$ is calculated [7]. For samples of more than 10 observations the test statistic Z is then [7]

$$Z = \frac{6R - n(n^2-1)}{n(n+1)\sqrt{(n-1)}} \tag{4.17}$$

and needs to be compared with critical values. In case, the test statistic lies in the critical region, the null-hypothesis is rejected.

[2]In thesis called Sperman's correlation test

Ending with this test, all of the tests used in the thesis are now described. In this thesis, for (not) rejecting the null-hypothesis, p-value is used, which is always compared with level of significance.

4.3 Classification methods

In addition to statistical tests, to reach the goals of the experiments, there is a need for classification of shape of cover glass and TFT panel based on the geometrical measurement. For this purpose, as classifier, K-nearest neighbors algorithm [15] is used in this thesis.

4.3.1 K-nearest neighbors

K-nearest neighbors algorithm, further KNN, is a non-parametric supervised learning classifier in machine learning, which is used when there is a need to classify data into categories [15]. As the algorithm is labeled as supervised, as input, the user must provide the training data-set, where the classification has been already done, and then the testing data-set, where the classification should be done. The training data-set is simply saved into a memory as reference, the algorithm does not calculate any model using mathematical formulas. After that, as described in [15], for each observation x_0 in the testing set, given the positive integer K, the KNN identifies K observations from the training set that are closest to the x_0 and takes their category label. The observation x_0 is then classified with the category that occurs in the previous step most of the time.

With the description of all statistical methods used in the thesis, all the needed pre-requirements for the practical part were introduced to the reader. Therefore, let the author describe the performed experiments and the obtained results in the next chapter.

Chapter 5

Experiments

For evaluation of the data in this chapter, softwares MATLAB [10] and Minitab [16] were used.

5.1 Received parts within the geometrical limits

In this section, there are two main tasks - evaluate if the calculated flatness of material is in specification and also each of the columns of data measured in laboratory is within the set limits. For this evaluation, there are together three different TFT displays as well as cover glasses - FDC, CP L3, CP L4.

5.1.1 FDC

Cover glass

For FDC cover glasses together 220 measurements were available for evaluation. Firstly, test of normality was used on dataset. As the p-value of the test is 0.0005, the null hypothesis of the Anderson-Darling test is rejected, the data do not come from normal distribution. This observation leads to usage of non-parametric tests for further evaluation. Test if the flatness on significance level of 0.05 is equal or lower than 0.2 is wanted to be performed. As usage of non-parametric tests is needed, one-sample Wilcoxon signed rank

test was used. The principle of this test is described in theoretical part. It is needed to use right-sided variant of this test, means that the alternate hypothesis states that data come from distribution with median higher than 0.2. As the p-value is 1, the null hypothesis is not rejected, resulting in statement that data come from the distribution with median lower 0.2.
The similar way is used when looking at the columns themselves. Together, 25 columns named P1, P2 and so on are available. Firstly, normality is tested. As seen from Table 7.1, none of the columns have normally distributed data, in all cases the null hypothesis of Anderson-Darling test is rejected, means, that data do not come from normal distribution. Afterwards, the two one-sided Wilcoxon tests were performed for each of the column with the significance level of 0.05. For the lower limit left-sided test was used as an alternative hypothesis, for the upper limit right-sided one. In Table 7.2 there are results for all the columns, not rejecting the null hypothesis.
That means that all of the columns in general are within the limits set by Continental to the supplier.

The evaluation of FDC cover glasses is finished. The same approach is needed to be used in the other input material for FDC side - the TFT panels.

TFT panels

For FDC TFT panels evaluation, results of 160 measurements were available.
As first, test of normality was used on the data set, resulting in p-value of 0.005 which is leading to rejection of null-hypothesis of Anderson-Darling test, data do not come from normal distribution.
Afterwards, non-parametric one-sample Wilcoxon signed rank test as in Chapter 5.1.1 was used, right-sided, to test, if the data come from distribution of median lower than 0.2 mm. As result of p-value 1, null hypothesis is not rejected, data come from distribution with median lower than 0.2 mm.

There are 36 columns available for evaluation. From the results of normality test, shown in Table 7.3, for some datasesets (P2, P8, P12, P19, P20, P21 and P30), the null hypothesis of Anderson-Darling test is not rejected, meaning that they can come from normal distribution. For the rest of the columns, the null hypothesis is rejected, they do not come from normal distribution.

For columns following normal distribution, t-test is used, once evaluating if mean is higher than 0.1 mm as alternative hypothesis, second time if mean is lower than -0.1 mm as alternative hypothesis. From results seen in Table 7.5, null-hypothesis for all columns for both test is not rejected, leading to the statement that the mean is between -0.1 mm and 0.1 mm.

For columns not following the normal distribution, two one-tailed Wilcoxon tests are used for evaluating that median lies between -0.1 mm and 0.1 mm. Shown in 7.4, null-hypothesis for all the columns for both test is not rejected, median of the columns is located between -0.1 mm and 0.1 mm.

In conclusion, both parts of FDC [1] are proven to be in specification based on the results of performed tests. This result was expected, as the supplier should control the quality of their production before sending them to Continental company. On the other side, it is surprising, that the data in general do not follow normal distribution, which is expected in stable massive production, leading to hypothesis, that supplier's production could be unstable.

5.1.2 CP L3

The same approach as was used with FDC parts is needed to be applied also on CP L3 parts.

Cover glass

For evaluation of the CP L3 cover glasses, 64 samples are available. Firstly, normality of the flatness of cover glasses is tested. As the p-value result is 0.0005, null hypothesis of Anderson-Darling testis rejected, data do not come from normal distribution. For further testing of median below 0.2 mm, non-parametric right-sided Wilcoxon test is used, resulting in p-value of 1, which does not reject the null hypothesis. As the result, median

[1] TFT panel, cover glass

of flatnesses lies below 0.2 mm.

Additionally, data from 20 columns are available for testing. As done with flatness, firstly normality test on each of 20 column is performed. As seen from Table 7.6, some of the columns follow the normal distribution, most of them not.

For columns following normality, two one-sided t-tests are used, to evaluate if mean lies in the range of -0.1 and 0.1 mm, same as in Chapter 5.1.1. P-values of both tests for each data column in Table 7.7 show, that the mean is in the set limits as null hypothesis is not rejected in all cases.

For data not following normality, two one-tailed Wilcoxon tests are used, to evaluate if median lies in the range of -0.1 and 0.1 mm. As seen in Table 7.8, null hypothesis is not rejected in all cases, median lies in the range of -0.1 and 0.1 mm.

TFT panel

For the evaluation of TFT panels, there are 32 samples available, the least out of all types of input material. Firstly, flatness of panels is tested, starting with normality test. As p-value is 0.11, null hypothesis is not rejected, which leads to right-tailed t-test for testing of mean value below 0.2 mm. This test results in p-value of 1 which means not rejecting null-hypothesis, mean of flatness is below 0.2.

For deeper evaluation there are 20 columns available, similar to the cover glass. In Table 7.9 is shown the result of normality test for all of them. There is difference from other products visible, most of the columns follow the normal distribution.

Approach from other variants is repeated resulting in Tables 7.10 and 7.11. In case of column P16, the null-hypothesis of right-tailed Wilcoxon test is rejected, which means that median does not lay in the specification set for the supplier. The rest of the columns is in specification as both null-hypothesis are not rejected.

As conclusion, CP L3 cover glasses behave in similar way as the FDC parts. In case of CP L3 TFT panels, more of the columns follow the normality, together with the final flatness, on the other side, data from one column seems to be out of the specification.

5.1.3 CP L4

The last parts under investigation belong to the CP L4 variant. Specification remains the same as with other two variants.

Cover glass

For the CP L4 evaluation, measurements of 140 samples are available. Firstly, normality of flatness is tested, resulting in p-value of 0.0016, which leads to rejection of null-hypothesis. Flatness does not follow the normal distribution. Additionally, right-tailed Wilcoxon test is used for testing, with alternative hypothesis that median is above 0.2 mm. As the p-value is 1, null hypothesis is not rejected. Median is below 0.2 mm.

For the concrete columns, the position of each column is shown Figure 5.1, firstly normality is tested. As seen from Table 7.12 most of the columns rejects the null hypothesis, meaning, that they do not come from normal distribution. Additionally, columns following normality are tested by two one-tailed t-tests and columns not following normality are tested by two one-tailed Wilcoxon tests. As seen from results in Tables 7.13 and 7.14, for all of the columns null hypothesis is not rejected in both cases. That means, means/medians lay in specification.

TFT panels

For evaluation of the CP L4 TFT panels, 96 samples are available. Firstly, normality of flatness is tested, resulting in p-value of 0.0005 which leads to the rejection of the null-hypothesis. Flatness data do not come from normal distribution and for further testing, usage of non-parametric right-tailed Wilcoxon test is needed. The out-coming p-value is 0.0001, which means rejecting the null-hypothesis, median of flatness does not lay in specification. Additionally, data from 20 columns are available to be tested. As seen from Table 7.15 only data column P3 follows the normal distribution, the rest not. For the column P3, two one-tailed t-tests are used, for the rest of the columns, two one-tailed Wilcoxon tests are used. Out-coming p-values are shown in Tables 7.13 and 7.17. For

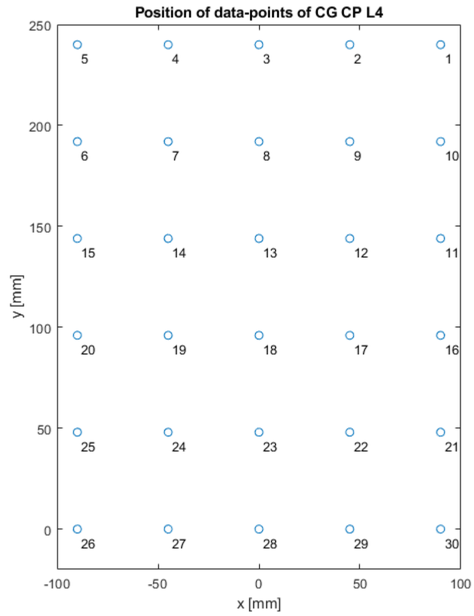

Figure 5.1: Position of the data-points CG CP L4

column P18, null-hypothesis is rejected, there the data is not in specification. For the rest, null-hypothesis is not rejected, all other columns are in specification.

5.1.4 Discussion

It is seen that all of the variants[2] and materials[3] are generally in specification. The only exception are the TFT panels of CP L4 variant. What is surprising is the non-normality of the data which is expected from the stable production. This potential instability of the supplier processes can lead to fluctuating quality of the incoming material.

5.2 Black uniformity of TFT panels

In this section, evaluation of black uniformity of received TFT panels is performed. As described, together 3 types of TFT panels are available - CP L3, CP L4 and FDC. For all of the types, the limit defined by the specification for the supplier is the same - 55 %.

[2]FDC, CP L4, CP L3
[3]TFT panel, cover glass

5.2.1 FDC TFT Panels

For evaluation, black uniformity calculations for samples is available. Firstly, the normality is tested, resulting in p-value 0.7895, which leads to not rejecting the null-hypothesis. Data come from normal distribution. Additionally, the test of if mean is above 55 % is performed. As data come from normal distribution, left-tailed t-test is used for this purposes, resulting in p-value of 1, which leads to not rejecting the null-hypothesis. The mean of the data set is higher than 55 %, samples are in specification.

5.2.2 CP L4 Panels

For evaluation of black uniformity of CP L4 Panels, there are 88 calculations available. Firstly, normality is tested, resulting in p-value of 0.14, therefore, the null-hypothesis is not rejected, data come from the normal distribution. T-test is used for further evaluation of mean. It performs test with the same parameters as in case of FDC. As the p-value of the test is 1, null hypothesis is not rejected, mean is above 55 %. Samples are in specification.

5.2.3 CP L3 Panels

For evaluation of last set of panels, there are 95 calculations to be evaluated. As the test of normality results in p-value of 0.17, null-hypothesis is not rejected, data come from normal distribution. Additionally, left-tailed t-test is performed. Result of the test is p-value of 1, null-hypothesis is not rejected. Even this set of panels is with the mean greater than 55 % and in specification.

5.2.4 Discussion

In conclusion, mean of all variants [4] is greater than 55 %. The positive aspect is also that the normal distribution was found in all of the data sets. This shows stable process on the supplier side.

[4] FDC, CP L3, CP L4

5.3 Correlation between flatness and black uniformity of TFT panels

In this section, the evaluation if there is a correlation between the flatness and the black uniformity is performed. In general, both attributes of paired data must be tested for normality. In case that both attributes follow the normality, Pearson correlation test can be applied to see if there is correlation between two attributes. In case only one of attributes or none follows the normal distribution, Spearman's correlation test must be applied. Together, there are three sets of paired data - flatness and black uniformity, one set for each variant. All sets contain the same samples that were evaluated in the parts above.

5.3.1 FDC panels

For evaluation of FDC panels, together, there are 156 paired values flatness - black uniformity. Firstly, normality of both attributes is tested. Test of normality of flatness results in p-value lower than 0.0005 and in case of black uniformity the p-value is 0.8678. In case of flatness, null-hypothesis is rejected, data do not follow the normal distribution. As one of the data-sets does not follow the normal distribution, Spearman's correlation test must be used for further evaluation. Described in 4.2.2, the null-hypothesis states that paired data-sets are independent. In this case, p-value of the test is 0.0085, which leads to the rejection of the null-hypothesis. Flatness and black uniformity of FDC panels are not independent, there is a correlation between the data-sets. However, as the correlation coefficient ρ = -0.2, the correlation is not strong.

5.3.2 CP L4 panels

For evalution of CP L4 panels, there are 64 paired values flatness - black uniformity available. Both attributes are fistly tested with normality test with resulting p-values of 0.0005 for flatness and 0.36 for black uniformity. Based on the results, the null-hypothesis of normality test for flatness is rejected, data do not come from normal distribution. As one of the data-sets does not follow the normal distribution, Spearman's correlation test is used in further evaluation, resulting in p-value of 0.68. Null-hypothesis is not rejected, there is no correlation found between black uniformity and flatness of CP L4 panels.

5.3.3 CP L3 panels

Same procedure as with other two variants is proceeded with CP L3 panels. Together there are 48 paired values flatness - black uniformity available. Normality is tested for both of the attributes, resulting in p-values of 0.0006 for flatness and 0.38 for black uniformity. Null-hypothesis is rejected in case of flatness, data there do not come from the normal distribution. As in other cases, data of one of the attributes do not come from the normal distribution. Therefore, Spearman's correlation test is used. Resulting p-value is 0.52, the null-hypothesis is not rejected, there is no correlation between flatness and black uniformity found.

5.3.4 Discussion

In general, there is from insufficient to weak correlation between flatness and black uniformity observed in the data. However, in this investigation, the most simple method was used for possible correlation findings, using just one value for geometrical characteristic[5] and one value for optical characteristic[6] of the panel. There is possibility to use more advanced methods for evaluation, looking at the whole area of the panel and using gradient of luminescence loss and gradient of deformation around the whole active area of the panel [1]. For the advanced evaluation, however, more information as data output of both measurements[7] is needed, which requires large data storage and more resources of the workers in the laboratories. As the investigation was performed under time and resource shortage, this approach was not selected.

[5] flatness
[6] black uniformity
[7] dimensional for flatness, optical for black uniformity

5.4 Correlation between flatness and shape of TFT panel and cover glass to the flatness of bonded assembly

In this part, the goal is to investigate possible influence of flatness and shape of incoming material to the flatness of the first semi-product from the production chain - bonded assembly. For each bonded assembly in the data set, there is a list of used material in it. It is then clear which cover glass goes with which TFT panel. For performing the correlation investigation, firstly the classification of the shape is needed to be performed. For easier classification, the algorithm will decide only between convex and concave shape. As the parts are not labeled initially, firstly reconstruction of some samples from measurements needs to be done, to be qualified by the author and then used as precedent for the algorithm.

Reverse engineering

For the reconstruction, Matlab script [10] has been used. It takes all the measurement points $P_1 - P_n$ from sample available, structured as P[x,y,z], and using interpolation, mesh is created in area of the TFT panel/cover glass, with distance of 5 mm between the points. After that mesh is plotted using surface function and the view is set to be from above. Examples are shown in Figures 5.2 and 5.3. Based on the color scaling [8], the shape can be identified. The reconstruction procedure was proceeded with 120 FDC cover glasses, 64 FDC TFT panels, and 32 CP L3 and CP L4 TFT panels and cover glasses. In case of all variants of TFT panels and CP L4 cover glasses, only one shape was identified and therefore, it makes no sense to use parameter "shape" for further evaluation in these cases. For the rest of the variants the remaining samples can be classified by algorithm based on the author's input from this chapter.

[8]units in mm

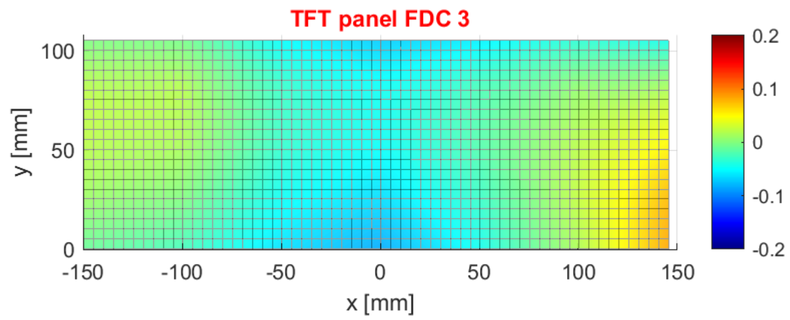

Figure 5.2: Reconstructed measurement of FDC TFT panel

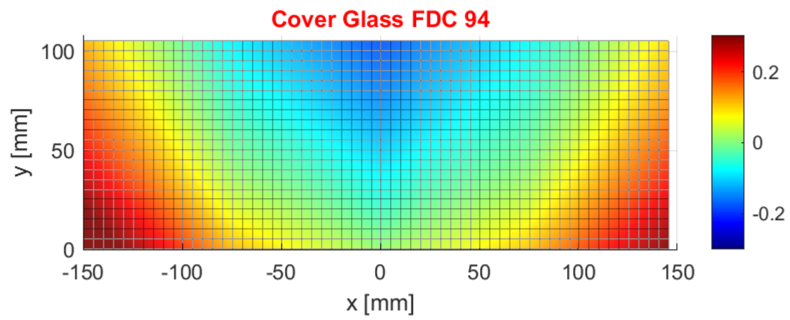

Figure 5.3: Reconstructed measurement of FDC cover glass

5.4.1 Shape recognition model

The algorithm used to classify the rest of the samples is K-nearest neighbors (KNN). The functionality of the algorithm is described in Chapter 4.3.1. For KNN, firstly data must be split into train and test set. The commonly-used 80/20 split ratio [15] is used in this thesis. For prediction, amount of neighbors for evaluation is set to be 5. As KNN is referred as memory-based algorithm [15], the train-set is then saved into memory and used to make prediction with test-set. After the prediction for test-set are made, it is important to validate it. In this thesis, confusion matrix is used. If the result of precision is satisfactory, the remaining data can be classified using the KNN algorithm. Let the author describe the process with concrete numbers for each of the 2 variants.

FDC cover glass

In case of FDC cover glass, there are 120 samples classified by author and additional 100 samples to be classified[9]. The 120 samples are split into train-set (100 samples) and test-set (20 samples). Based on the test-set confusion matrix the error rate is 0 %.

CP L3 cover glass

In case of CP L3 cover glass, there are 32 samples classified by author and additional 16 samples to be classified by algorithm. The 32 samples are split into train-set (24 samples) and test-set (6 samples). Based on the test-set confusion matrix the error rate is 0 %.

As the shapes are now classified, the next part is investigating possible correlations between input material and Bonded assy, on each of the variants separately starting with FDC.

5.4.2 FDC

For FDC, there are together 110 samples with measurements available. Additionally, each of the cover glass is labeled either as convex of concave. These two groups are evaluated separately. After split, there 55 samples with convex cover glass and 55 samples with concave cover glass.

Convex cover glass

As data-set for flatness of Bonded Assy does not follow the normality, Spearman's test is used to evaluate possible correlation between flatness of TFT panel and Bonded and flatness of cover glass and Bonded. In case of test with TFT panel, p-value of the test is 0.15 and in case of test with cover glass, the p-value is 0.77. In both cases, the is no significant correlation observed.

[9]To have higher amount of samples for better accuracy of prediction, even measurements out of this experiment were used. These extra parts will not be used for anything else.

Concave cover glass

Even in case of concave cover glass, the data-set for flatness of Bonded Assy does not follow the normality, Spearman's test is used as previously, resulting in p-values of 0.004 in case of TFT panel and 0.0001 in case of cover glass. In this case, both flatnesses have significant correlation with flatness of Bonded Assy. Additionally, it is clear that the cover glass shape has significant influence as well.

5.4.3 CP L4

As for CP L4 parameter "shape" is not used, there is no need for distinguish into several groups. In total, there are 32 samples with flatness of TFT panel, cover glass and Bonded Assy. As the data-set for Bonded Assy does not follow normality, Spearman's test is used resulting in p-values of 0.59 in case of test with Bonded assy and TFT panel and 0.006 with Bonded assy and cover glass. That means, that there is a significant correlation between flatness of cover glass and Bonded assy found.

5.4.4 CP L3

For CP L3, there are together 32 samples with measurements available. Additionally as in case of FDC, each of the cover glass is labeled either as convex of concave. After split, there 25 samples with concave cover glass and only 7 samples with convex cover glass. As the convex data-set is too small, author decided not to use parameter "shape" into consideration. All 32 samples are evaluated as one data-set. As the flatness of Bonded assy does not follow the normality, Spearman's test is used for further evaluation, resulting in p-values of 0.12 in case of test with flatness of TFT panel, and p-value of 0.005 in case of test with flatness with cover glass. In this case, flatness of cover glass is significantly correlated with flatness of Bonded assy.

5.4.5 Discussion

In all three variants, correlation between the flatness of cover glass and flatness of TFT panel was found. This results is not surprising, as the stiffness of the cover glass is higher than of TFT panel. During the Hybrid Bonding process, the TFT panel is adapting to the shape of the cover glass. Additionally, in case of FDC, there was a difference in results between the shapes found. Unfortunately, for other variants parameter "shape" could not be included in the evaluation either for having just one shape or not enough of data.

5.5 Biggest contributor of black uniformity loss along the processes

In this section, the goal is to evaluate the biggest contributor of black uniformity loss along the processes. As described in Chapter 2.1, there are together three main processes where the TFT panel is included - Hybrid Bonding, Display Closing and Final Assembly in the order they are named. The biggest contributor is evaluated based on data from the first LOOP. As the initial value of black uniformity is not the same for every TFT panel/sub-assembly, relative loss of black uniformity between the steps is calculated for further evaluation as follows:

- relative loss of black uniformity from TFT panel to HB assembly,
- relative loss of black uniformity from HB assembly to DC assembly,
- relative loss of black uniformity from DC assembly to Final assembly.

As described above, there are three data-sets available for each of the product variant. Let's have a look at each of the variants separately.

5.5.1 FDC

For evaluation of the FDC, there are 38 samples in all three data-sets available. In Figure 5.4 the box-plots of the data-sets with highlighted means of each can be seen.

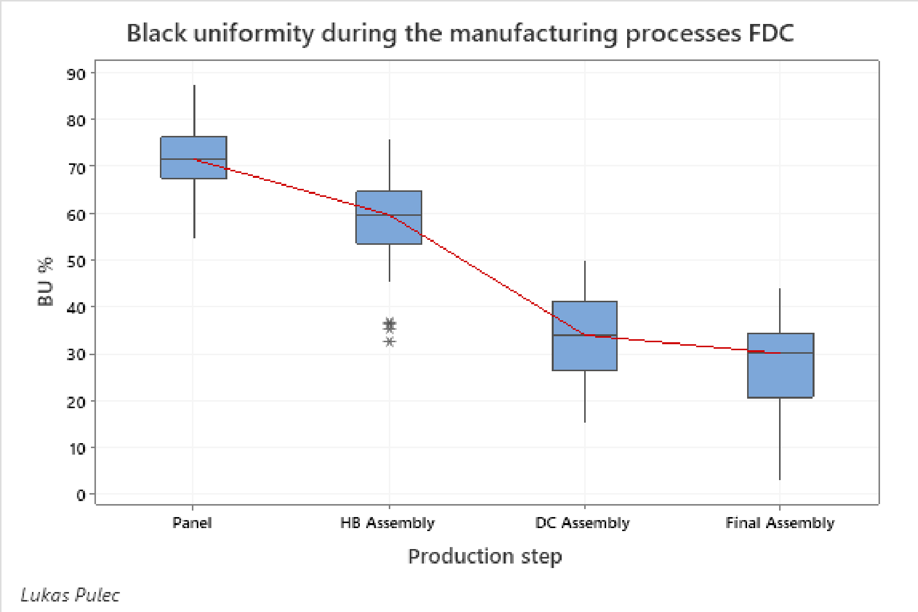

Figure 5.4: Black uniformity performance over production processes of FDC

From these values the relative loss of the black uniformity was calculated and its distribution with mean and standard deviation is shown in Figure 5.5.

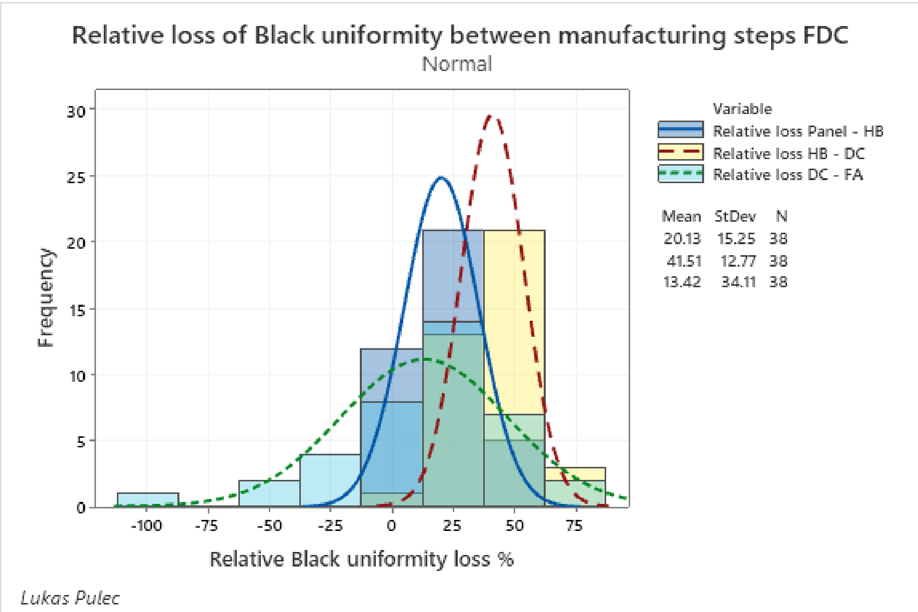

Figure 5.5: Relative loss of black uniformity over production processes of FDC

Already from the histogram, it is obvious, that the contribution of processes differs. However, let author to confirm it using the statistical tests.

Firstly, normality of each of the data-set is tested. As the p-values of Anderson-Darling test are 0.28, 0.34 and 0.06, null-hypothesis are not rejected in any cases, data come from normal distribution. Another requirement except of normality for ANOVA test is that data-sets must have equal variance. For this purpose, Levene-test for homogeneity of variances is used, resulting in p-value lower than 0.05. Variances are significantly different, ANOVA test cannot be used. For further evaluation, Kruskal-Wallis test must be applied. As described in Chapter 4.1.5, the null-hypothesis states that all medians are equal. In this case, the p-value of the test is 0.001, at least one median is different. As the null hypothesis is rejected, post-analysis using Bonferroni test is needed to be performed to see, which median/medians differs. As seen from p-values in Table 5.1, the median of relative drop HB - DC is different from the two others.

Sample A	Sample B	P-value of Bonferroni test
Relative loss panel - HB	Relative loss HB - DC	1.33E-06
Relative loss panel - HB	Relative loss DC - FA	1
Relative loss HB - DC	Relative loss DC - FA	1.48E-06

Table 5.1: P-values of Bonferroni test of relative loss of black uniformity on FDC

In Figure 5.6, using boxplots there are displayed all three data-sets with highlighted median. Using it, it is obvious that median of data-set of relative drop HB-DC is higher than the other two, making then the Display Closing process the biggest contributor of black uniformity loss along the processes. The next variant to be evaluated is CP L4.

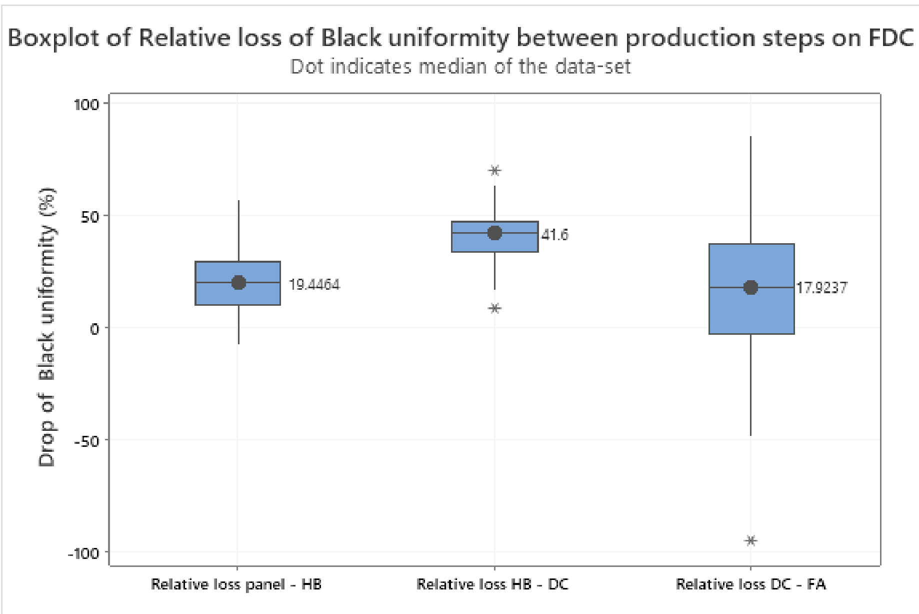

Figure 5.6: Boxplots of relative loss of black uniformity between production steps on FDC

5.5.2 CP L4

For evaluation of the CP L4, there are only 16 samples in 3 data-sets available. This amount of samples lowers the power of the tests performed quite significantly [17]. In the Figure 5.7 the box-plots of the data-sets with highlighted means of each can be seen and in Figure 5.8 there is displayed the distribution of the relative loss of black uniformity between each production step. From the histogram it can be seen that the distribution of data-sets is similar to each other, only in case of relative loss Panel - HB it is a bit wider and with lower mean.

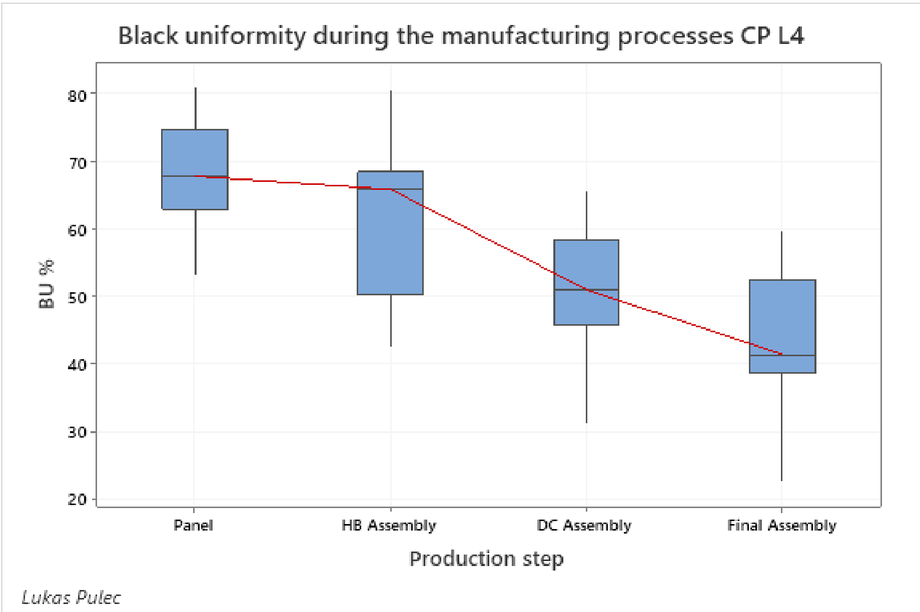

Figure 5.7: Black uniformity performance over production processes of CP L4

Firstly, normality of all 3 data-sets is tested, resulting in p-values of 0.005, 0.08, 0.39. Null-hypothesis of Anderson-Darling test is rejected in case of first data set, data do not come there from normal distribution, non-parametric test is needed to be used. For further analysis of the medians, Kruskall-Wallis test is applied, resulting in p-value of 0.71. It means, that all of the data-set have the similar median. In case of CP L4, the biggest contributor was not identified, all of the processes contribute similarly.

The last variant to be evaluated is CP L3.

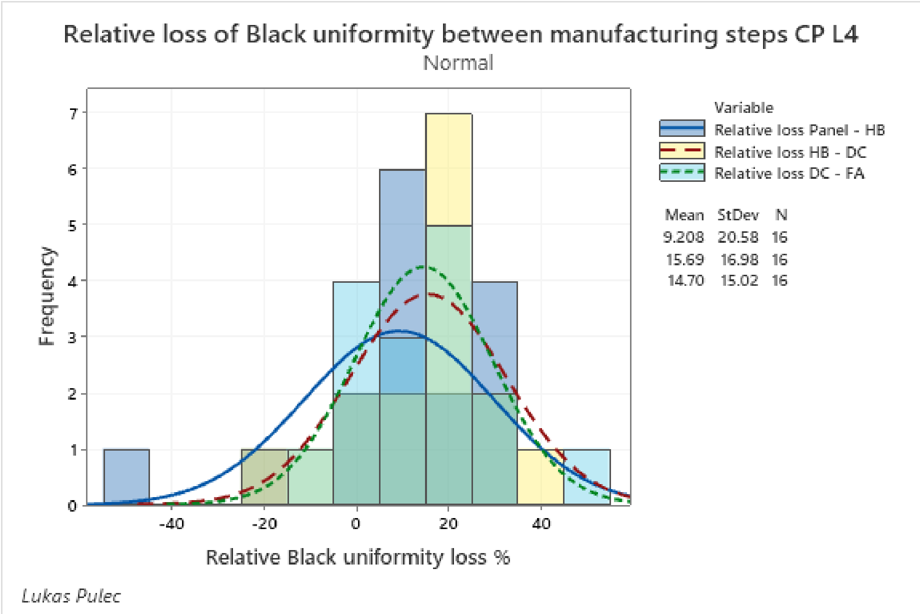

Figure 5.8: Relative loss of black uniformity over production processes of CP L4

5.5.3 CP L3

For evaluation of CP L3, there are 24 samples in 3 data-sets available. In the Figure 5.9 there can be seen the box-plots of original values of black uniformity after each production step and in Figure 5.10 relative loss of black uniformity is displayed. Surprising is that that in case of relative loss DC - FA, the mean of loss is negative, means that black uniformity performance got better after the Final Assembly process. The other 2 data-sets seem to have in average similar impact on the black uniformity. Let's investigate it using statistical tests.

Firstly, normality of each of the data-set is tested, resulting in p-values of 0.11, 0.0005 and 0.32. In case of one data-set, the data do not come from normal distribution, non-parametric Kruskall-Wallis test is used for further evaluation. This test results in p-value of 0.000007, which rejects the null-hypothesis. Medians of the data-set are not equal. As post-analysis, Bonferroni test is performed, its results are displayed in Table 5.2. It is visible, that median of relative loss DC - FA differs from the other two. As already mentioned in the beginning of this chapter, the relative loss DC - FA is even negative. It means, that the biggest contributes are together Hybrid Bonding and Display Closing.

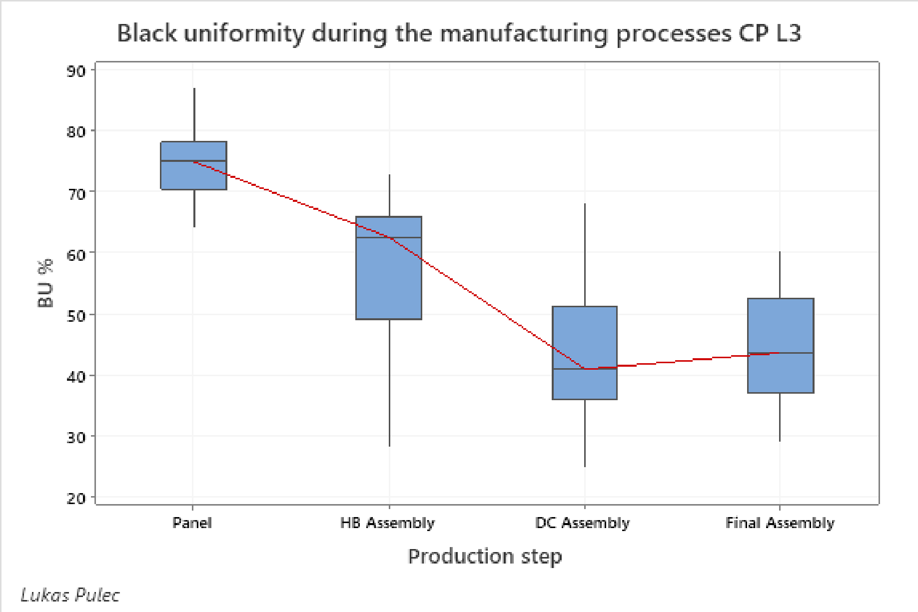

Figure 5.9: Black uniformity performance over production processes of CP L3

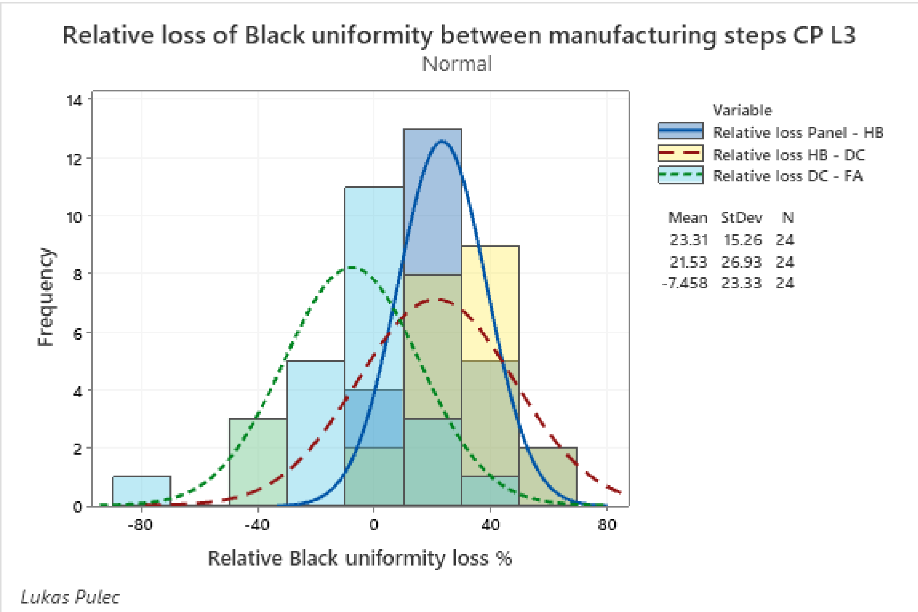

Figure 5.10: Relative loss of black uniformity over production processes of CP L3

5.5.4 Discussion

Based on the results, there is a high difference in contribution of production lines on black uniformity loss based on different variants of the product. The difference can result from low amount of samples available for the evaluation, but also from different mechanical architecture of each of the variant, which affects distribution of the stress in the product. Additionally, for each of the variant, there are different tools used for gluing and holding

Sample A	Sample B	P-value of Bonferroni test
Relative loss panel - HB	Relative loss HB - DC	1.00
Relative loss panel - HB	Relative loss DC - FA	0.000133457
Relative loss HB - DC	Relative loss DC - FA	4.31E-05

Table 5.2: P-values of Bonferroni test of relative loss of black uniformity on CP L3

the product, which can have high impact as well. Surprising is the result, that in case of CP L3 variant, there is an increase of black uniformity values during the process, which is not often spotted [1].

5.6 Improvement between the Loops

The goal of this chapter is to evaluate if there is an improvement of behavior - lower loss of black uniformity, during the production steps between initial LOOP 1 and last LOOP 3. Possible improvement is evaluated separately for every variant of the product and every production line.

Unfortunately, as mentioned already in Chapter 3, due to management decisions, the experiments were closed sooner. During LOOP 3 not a single sample was produced into its final status. It means, there are no data for performance after Final assembly. Evaluation consists then only of Hybrid bonding and Display closing.

For analysis, the relative drop of black uniformity is used, similarly as in previous chapter.

5.6.1 FDC

For evaluation of the potential improvement on FDC, there are 38 samples available for LOOP 1 and 50 samples for LOOP 3 for both relative loss data-sets [10]. In case of relative loss panel - HB, firstly normality of both data-sets is tested. Data-set for LOOP 1 follows normality, as it was already tested in Chapter 5.5.1. Data-set for LOOP 3 follows the normality as well, as p-value of the Anderson-Darling test is 0.2. Parametric two-sample t-test can be performed, against alternative mean of data-set of the LOOP 1 is lower than mean of data-set of the LOOP 3. As the p-value of this test is 1, null-hypothesis is not rejected, mean of relative loss from LOOP 1 is higher than from LOOP 3. Here, improvement of performance is confirmed.

In case of relative loss HB - DC, normality is firstly tested as well. Data-set for LOOP 1 follows the normality as tested in Chapter 5.5.1. Data-set for LOOP 3 does not follow the normality, as the p-value of Anderson-Darling test is 0.047, which rejects the null-hypothesis. For further evaluation, Mann-Whitney test is used with alternative hypothesis, that median of data-set from LOOP 1 is lower than from LOOP 3. As the test results in p-value of 0.0001, null-hypothesis is rejected, the improvement has been not achieved.

To conclude this part, in case of Hybrid bonding, improvement is observed, in case of

[10] relative loss panel - HB, relative loss HB - DC

Display Closing not.

5.6.2 CP L4

For evaluation of the potential improvement on CP L4, there are 16 samples available for both LOOPs. In case of relative loss panel - HB, non-parametric Mann-Whitney test must be used, as data-set for LOOP 1 was already tested as non-normally distributed in Chapter 5.5.2. Same as in part above, the test is performed against alternative hypothesis that median of relative loss of LOOP 1 is lower than of LOOP 3. As the p-value of the test is 0.0001, null-hypothesis is rejected, there is no performance improvement observed. In case of relative loss HB - DC, the data-set for LOOP 1 follows normality, as tested in Chapter 5.5.2. Data-set for LOOP 3 is tested by Anderson-Darling test, resulting in p-value of 0.053, null-hypothesis is not rejected, data comes from the normal distribution. As both data-sets follow normality, parametric two-sample t-test can be used for further evaluation. Test is performed against alternative hypothesis that mean of relative loss from LOOP 1 is lower than from LOOP 3 and results in p-value of 0.36. The null hypothesis is not rejected, there has been performance improvement observed.
In conclusion, in case of CP L4 variant, there can be improvement observed on DC production lines.

5.6.3 CP L3

For evaluation of the potential improvement on CP L3, there are 24 samples available for both LOOPs. In case of relative loss panel - HB, data-set for LOOP 1 follows normality as already discussed in Chapter 5.5.3, data-set for LOOP 3 is tested by Anderson-Darling normality test, resulting in p-value of 0.276, data-set follows the normality as well. For further evaluation, parametric two-sample t-test is used against alternative hypothesis that mean of relative loss from LOOP 1 is lower than from LOOP 3. As the test results in p-value 0.09, the null-hypothesis is not rejected, there can be improvement observed. In case of relative loss HB - DC, non-parametric Mann-Whithey test must be used, as the data-set for LOOP 1 was already tested as not-following the normality. The test is performed against alternative hypothesis that the median of data-set from LOOP 1 is lower than from LOOP 3. As the p-value of the test is 0.92, the null-hypothesis is not rejected, improvement can be observed in this case.

5.6.4 Discussion

In conclusion, the improvement program can be described as mostly successful. In case of FDC, there can be improvement observed on HB line. In case of CP L4, there is improvement observed on DC line, and in case of CP L3 on both lines. For the two remaining lines, there are several possible reasons for not reaching the improvement. Firstly, the amount of samples in LOOPs is relatively low, the real distribution can be still hidden. Secondly, as the settings of the production lines is complex, there is a possibility that in just 3 LOOPs, the best-performing settings was not found. And lastly, some parts of the product were redesigned in between the LOOPs which can have possible effect as well.

Chapter 6

Conclusion

This thesis deals with the optical performance of LCD displays that are used in cockpits in automotive industry. It focuses specifically on analysis with the help of statistical methods of the possible impacts from the production environment to the black uniformity of the displays.

In the theoretical part, firstly the company of Continental, where the analysis is performed, is introduced. After that, the investigated product is delineated, together with its mechanical architecture and all three production processes and their chain. Furthermore, the methodology of the experiments is explained and the specific goals of the thesis are defined as below:

- evaluate if received parts from the supplier are within the geometrical limits set in technical drawings,
  - TFT panels,
  - cover glasses,
- evaluate if the black uniformity of TFT panels from the supplier is equal to or higher than the minimum set,
- evaluate if there is a correlation between flatness and black uniformity of TFT panels,
- evaluate how flatness and shape of cover glass and TFT panel affect the final flatness of Hybrid Bonding assembly,
- evaluate the biggest contributors to black uniformity loss out of production processes,

- evaluate if there are improvements between production cycles.

Lastly, all statistical methods that are used in the practical part are described.

In the practical part, together 6 experiments are performed to achieve the goals of the thesis. It starts with the evaluation of quality of the incoming material in terms of optical performance - black uniformity and geometrical characteristics -flatness. In general, both aspects are found to be in specification, even though there are some dimensions that tend to be outside of it. In additional to that, analysis of dependence between both parameters - black uniformity and flatness on display panels is performed. It results into the finding that there is mostly no correlation between these two attributes. After that, the investigation of influence of flatness on input material to the first semi-product flatness is performed. In the beginning, the goal here was also to include the shape of the incoming material. Unfortunately, due to lack of data or having just one shape it it performed only in two cases from six possible. As the result it has been found that the first semi-product is taking the flatness of the cover glass in nearly all of the variants of the product. As the experiments were performed on several production lines, the next part focuses on finding the biggest contributor from them to the degradation of the black uniformity. Lastly, it has been found out, that the improvement program of the production lines, which was running parallel to the experiments, was partially successful, as there was the improvement in the optical performance observed in several cases. With all of these experiments, all goals of the thesis have been achieved.

In general, the weakest point of the experiments was the low amount and quality of the data available from the production. Nevertheless, the obtained results look mostly promising and were used in the decision-making and taken as lessons learned to the development of the new products.

As the follow-up to these experiments, the author sees the possibility to use the luminescence pictures instead of black uniformity value, and to use more detailed geometrical measurement of displays and then to try to perform the analysis of dependence again.

Chapter 7

Appendix

Column	P-value of normality test
P1	0.0005
P2	0.0005
P3	0.0005
P4	0.0005
P5	0.0005
P6	0.0005
P7	0.0005
P8	0.0005
P9	0.0005
P10	0.0005
P11	0.0005
P12	0.0005
P13	0.0010
P14	0.0011
P15	0.0005
P16	0.0005
P17	0.0005
P18	0.0005
P19	0.0005
P20	0.0005
P21	0.0005
P22	0.0005
P23	0.0169
P24	0.0005
P25	0.0005

Table 7.1: P-values of normality test for FDC CG data columns

Column	P-value of right-tailed Wilcoxon test	P-value of left-tailed Wilcoxon test
P1	1	1
P2	1	1
P3	1	1
P4	1	1
P5	1	1
P6	1	1
P7	1	1
P8	1	1
P9	1	1
P10	1	1
P11	1	1
P12	1	1
P13	1	1
P14	1	1
P15	1	1
P16	1	1
P17	1	1
P18	1	1
P19	1	1
P20	1	1
P21	1	1
P22	1	1
P23	1	1
P24	1	1
P25	1	1

Table 7.2: P-values of Wilcoxon test for FDC cover glass data columns

Column	P-value of normality test
P1	0.0005
P2	0.9599
P3	0.0005
P4	0.0005
P5	0.0005
P6	0.0005
P7	0.0005
P8	0.4340
P9	0.0005
P10	0.0353
P11	0.0005
P12	0.1634
P13	0.0005
P14	0.0005
P15	0.0007
P16	0.0206
P17	0.0144
P18	0.0005
P19	0.1328
P20	0.1030
P21	0.1658
P22	0.0417
P23	0.0105
P24	0.0024
P25	0.0005
P26	0.0005
P27	0.0005
P28	0.0307
P29	0.0005
P30	0.7963
P31	0.0005
P32	0.0005
P33	0.0005
P34	0.0005
P35	0.0121

Table 7.3: P-values of normality test for FDC TFT displays data columns

Column	P-value of right-tailed Wilcoxon test	P-value of left-tailed Wilcoxon test
P1	1	1
P3	1	1
P4	1	1
P5	1	1
P6	1	1
P7	1	1
P9	1	1
P10	1	1
P11	1	1
P13	1	1
P14	1	1
P15	1	1
P16	1	1
P17	1	1
P18	1	1
P22	1	1
P23	1	1
P24	1	1
P25	1	1
P26	1	1
P27	1	1
P28	1	1
P29	1	1
P31	1	1
P32	1	1
P33	1	1
P34	1	1
P35	1	1

Table 7.4: P-values of Wilcoxon test of FDC TFT panels

Column	P-value of right-tailed T-test	P-value of left-tailed T-test
P2	1	1
P8	1	1
P12	1	1
P19	1	1
P20	1	1
P21	1	1
P30	1	1

Table 7.5: P-values of t-test of FDC TFT panel

Column	P-value of normality test
P1	0.2285
P2	0.1266
P3	0.0957
P4	0.0557
P5	0.0006
P6	0.0265
P7	0.0005
P8	0.0005
P9	0.0005
P10	0.0005
P11	0.1950
P12	0.0005
P13	0.0005
P14	0.0005
P15	0.0706
P16	0.0005
P17	0.2459
P18	0.0190
P19	0.1734
P20	0.0005

Table 7.6: P-values of normality test for CP L3 cover glass data columns

Column	P-value of right-tailed t-test	P-value of left-tailed t-test
P1	1	1
P2	1	1
P3	1	1
P4	1	1
P11	1	1
P15	1	1
P17	1	1
P19	1	1

Table 7.7: P-values of t-test of CP L3 Cover Glass

Column	P-value of right-tailed Wilcoxon test	P-value of left-tailed Wilcoxon test
P5	1	1
P6	1	1
P7	1	1
P8	1	1
P9	1	1
P10	1	1
P12	1	1
P13	1	1
P14	1	1
P16	1	1
P18	1	1
P20	1	1

Table 7.8: P-values of Wilcoxon test of CP L3 cover glass

Column	P-value of normality test
P1	0.971
P2	0.002
P3	0.033
P4	0.202
P5	0.428
P6	0.590
P7	0.392
P8	0.514
P9	0.398
P10	0.156
P11	0.385
P12	0.061
P13	0.200
P14	0.136
P15	0.561
P16	0.005
P17	0.377
P18	0.352
P19	0.123
P20	0.025

Table 7.9: P-values of normality test of CP L3 TFT panels

Column	P-value of right-tailed t-test	P-value of left-tailed t-test
P1	1	1
P4	1	1
P5	1	1
P6	1	1
P7	1	1
P8	1	1
P9	1	1
P10	1	1
P11	1	1
P12	1	1
P13	1	1
P14	1	1
P15	0.87	1
P17	1	1
P18	1	1
P19	1	1

Table 7.10: P-values of t-test of CP L3 TFT panels

Column	P-value of right-tailed Wilcoxon test	P-value of left-tailed Wilcoxon test
P2	1	1
P3	1	1
P16	0.001	1
P20	1	1

Table 7.11: P-values of Wilcoxon tests of CP L3 TFT panels

Column	P-value of normality test
P1	0.0005
P2	0.1347
P3	0.0785
P4	0.0072
P5	0.0162
P6	0.0356
P7	0.0076
P8	0.0047
P9	0.0665
P10	0.0692
P11	0.0005
P12	0.0005
P13	0.0005
P14	0.0005
P15	0.0798
P16	0.0005
P17	0.0005
P18	0.0005
P19	0.0005
P20	0.0235

Table 7.12: P-values of normality test of CP L4 cover glasses

Column	P-value of right-tailed Wilcoxon test	P-value of left-tailed Wilcoxon test
P1	1	1
P4	1	1
P5	1	1
P6	1	1
P7	1	1
P8	1	1
P11	1	1
P12	1	1
P13	1	1
P14	1	1
P16	1	1
P17	1	1
P18	1	1
P19	1	1
P20	1	1

Table 7.13: P-values of Wilcoxon test of CP L4 cover glasses

Column	P-value of right-tailed t-test	P-value of left-tailed t-test
P2	1	1
P3	1	1
P9	1	1
P10	1	1
P15	1	1

Table 7.14: P-values of t-test of CP L4 cover glasses

Column	P-value of normality test
P1	0.0017
P2	0.0171
P3	0.2516
P4	0.0005
P5	0.0005
P6	0.0005
P7	0.0005
P8	0.0005
P9	0.0005
P10	0.0269
P11	0.0005
P12	0.0005
P13	0.0005
P14	0.0005
P15	0.0005
P16	0.0005
P17	0.0005
P18	0.0005
P19	0.0005
P20	0.0005

Table 7.15: P-values of normality test of CP L4 TFT panels

Column	P-value of right-tailed Wilcoxon test	P-value of left-tailed Wilcoxon test
P1	1	1
P2	1	1
P4	1	1
P5	1	1
P6	1	1
P7	1	1
P8	1	1
P9	1	1
P10	1	1
P11	1	1
P12	0.45	1
P13	0.13	1
P14	0.65	1
P15	1	1
P16	0.86	1
P17	0.08	1
P18	0.04	1
P19	0.86	1
P20	0.1	1

Table 7.16: P-values of Wilcoxon test of CP L4 TFT panels

Column	P-value of right-tailed t-test	P-value of left-tailed t-test
P3	1	1

Table 7.17: P-values of t-test test of CP L4 TFT panels

Chapter 8

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