Diagnostic tool for issue categorization and capability determination in flexographic printing

Andreas Vidovic

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MASTER THESIS

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Subject: Interaction Design (MAMM01)
Division: Ergonomics and Aerosol Technology
Supervisor: Joakim Eriksson
Co-Supervisors: Robin Karlsson and Joakim Holmgren at Tetra Pak
Examiner: Mattias Wallergård

Abstract

Today communication, promotion and transaction of products are key functions of product packaging. The quality of the package print is therefore of great importance and needs to be consistent for large production quantities. One of the most common technologies for printing on paper or cardboard is flexographic printing. With this technology colors are applied one by one and through their combination new colors arise. However in order to successfully merge the different colors, it is essential that the colors align correctly.

The aim of this master thesis was to design a diagnostic tool for a color-to-color register sensor system based on three sensor cameras. The system is a development project at Tetra Pak with the goal of further improving print quality by combining data from multiple sensors concurrently. The project was initialized with a literature study followed by the implementation of the design process. The design process was based on the user-centric design thinking process and consisted of four distinct phases. The final prototype includes a workflow, developed with Sympathy for Data, to process the raw sensor data. The workflow is combined with a user interface, developed in Power BI, allowing the user to better understand the processed data through interactive visualization. The final prototype serves as a proof of concept for the R2-DiToo development project at Tetra Pak.

Keywords: Color-to-Color Register, Design Process, Data Processing, Data Visualization, Prototyping, Usability

Sammanfattning

Idag är kommunikation, marknadsföring och transaktion av produkter nyckelfunktioner för produktförpackningar. Kvaliteten på det grafiska förpackningstrycket är därför av stor betydelse och måste vara konsekvent för stora produktionskvantiteter. En av de vanligaste tryckteknikerna för tryck på papper eller kartong är flexografiskt tryck. Med denna teknik appliceras färger en efter en och genom deras kombination uppstår nya färger. För att lyckas sammanfoga de olika färgerna är det viktigt att färgerna positioneras korrekt.

Syftet med denna masteruppsats var att designa ett diagnostikverktyg för ett sensorsystem baserat på tre kameror för mätning av färg-till-färg-register. Systemet är ett utvecklingsprojekt hos Tetra Pak, med målet att ytterligare förbättra tryckkvaliteten genom att kombinera data från flera olika sensorer samtidigt. Projektet initierades med en litteraturstudie följt av genomförandet av en designprocess. Designprocessen baserades på den användarcentrerade design-tänkande-processen och bestod av fyra distinkta faser. Den slutliga prototypen består av ett data-processflöde, utvecklat med Sympathy for Data, för att processa sensordata. Processflödet är kombinerat med ett användargränssnitt, utvecklat i Power BI, vilket ger användaren möjlighet till djupare förståelse för den processade datan genom interaktiv visualisering. Den slutliga prototypen är ett *proof of concept* för Tetra Paks utvecklingsprojekt R2-DiToo.

Nyckelord: Färg-till-Färg Register, Designprocess, Dataprocessande, Datavisualizering, Prototypande, Användbarhet

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Lund, November 2021

Andreas Vidovic

Contents

Chapter 1

Introduction

This chapter introduces the context, purpose, and scope of the project.

1.1 Background

Food packaging has been of great importance throughout human history. In Ancient Egypt the discovery of glass blowing led to the molding of glass into food containers. In Ancient China innovations in paper development gave birth to the invention of flexible packaging which during the later centuries was used for packaging of tea and medicine among other items. The wooden barrel was common during medieval times allowing dried food, spirits, and fresh water to travel long distances. However it was not until 1817, post industrial revolution, that the first cardboard box was manufactured. Corrugation was later invented in 1871, followed by the first carton in 1879, and eventually the first cereal box in 1906 by the Kellogg brothers [1]. At this point food packaging had evolved into more than safe storage of food. The packages now had color printed design and were branded to be distinguished from the competition and to create an impact beyond the content of the box [2].

Today communication, promotion and transaction of products are key functions of product packaging [3]. The quality of the package print is therefore of great importance and needs to be consistent for large production quantities. One of the most common technologies for printing on paper or cardboard is flexographic printing. With this technology colors are applied one by one and through their combination new colors arise. However in order to successfully merge the different colors, it is essential that the colors align correctly. Misaligned colors lead to a distorted image. The alignment is controlled by sensors that notice if a color is misaligned and the position of the color application is adjusted accordingly [4]. The process and components of flexographic printing is described in greater detail in chapter 3.

The aim of this master thesis was to design a diagnostic tool for a color-to-color register sensor system based on three sensor cameras. The system is a development project at Tetra Pak with the goal of further improving print quality by combining data from multiple sensors concurrently.

1.2 Tetra Pak

This master thesis was conducted together with Tetra Pak. Tetra Pak has been developing food processing and packaging machines since the 1950s. Today the company provides its products to hundreds of millions of people each day across more than 160 countries [5]. Most of Tetra Pak's research and development is conducted at the Lund site. For example, the processes regarding prepress and printing of the package material [6].

1.2.1 R2DiToo

The thesis project was part of the development project R2-DiToo (Colo**R 2** color register **Di**agnostic **Too**l). The aim of the R2-DiToo project is to develop a portable inline diagnostic tool with three cameras side by side where each camera registers multiple color marks concurrently. The goal of this tool is to provide better capability understanding, reduce analysis time, provide reliable data for improvement of the print process, as well as auto classification of issues to simplify analysis, for example when logging long time data. As part of the diagnostic tool an application is needed. The application will be used by process engineers and development engineers to analyse data trends from the color-to-color register cameras. The R2-DiToo project is described in greater detail in section 3.4.

1.3 Project goal

The goal of the thesis project was to develop a prototype of the application for the R2-DiToo project. The design process was to centered around the users, operations engineers and development engineers, in order to provide a user friendly and purposeful tool for issue categorization and capability determination in flexographic printing. Part of the goal of the master thesis was to contribute to the knowledge of how combined color-to-color register data from multiple inline cameras could be processed and visualised through a user interface, with the ultimate goal of further improving print consistency and capability in converting factories. The project would hopefully result in a proof of concept for R2-DiToo and the capability of the sensor system.

1.4 Research questions

The following questions will be addressed and answered in the conclusion of this thesis work.

- Besides color-to-color register data, what other sensor data can be useful for the purposes of R2-DiToo?
- On what software platforms and tools should R2-DiToo be developed?
- How should data be added and managed in the system?
- How and to what extent should R2-DiToo be integrated with existing systems?

- What features are most important for the usability of R2-DiToo?
- How good is the usability of the final prototype?

1.5 Outline of the Thesis

This report will present the different stages of the completed work and the process behind it. The theoretical and technical background will be presented in the next two chapters. The theoretical background covers various concepts and methods of design theory and the technical background will present technical subjects related to the project. In the fourth chapter, the design process will be presented from initial literature study to final prototype. The fifth chapter presents the final prototype, followed by the sixth chapter covering discussion of the project work. The seventh and final chapter concludes the master thesis work.

1.6 Related work

No similar projects or studies were found during the literature study in regard to visualization of color-to-color register data. However, several studies have been conducted investigating new and improved algorithms for register control. One example of such studies is *Theories and control technologies for web handling in the roll-to-roll manufacturing process*. This study was conducted at Texas A&M University in collaboration with Roll-2-Roll Technologies LLC. The objective was to develop a machine direction print registration model for multicolor printing presses. The model factors in various print parameters of the interaction effect between print units [7].

There have also been many studies exploring the visualization of different types of sensor data. The paper *Visualizing sensor data: towards an experiment and validation platform* explores how understanding of sensor data can be improved using interactive sensor data visualization. in the study an extensible visualization and interaction platform is used for the experimentation of multiple types of sensor data visualizations. The platform is illustrated through a medical case study regarding ECG data [8].

1.7 Delimitation

The project scope is limited by a 20 week time frame. In order to successfully achieve the goal of the project within the given time frame the following delimitation was decided:

- Only the most common print issues will be featured in the prototype.
- Sensor data from CDAS (Control and Data Acquisition System) will not be integrated in the prototype.
- The prototype design will not support real time data feed for issue prevention during live production run.

- The final prototype will not be fully implemented to commercial standard, for example in regard to IT security requirements and reliability.
- The prototype will be based exclusively on mock sensor data since the sensor system will not yet be installed during the course of the project.

Chapter 2

Theoretical background

This chapter presents concepts and models of design theory applied throughout the project.

2.1 Design thinking

Design thinking has been around throughout history. The human-centric creative process has been applied by designers and engineers in order to create purposeful products. However it is only in the last few decades that the design process has actually been integrated in the early phases of product-development. Historically design was the last phase of development and mostly focused on the aesthetics of the finished product. The consequence was that products generally had a poor customer satisfaction rate. The term *design thinking* was introduced in 1990 as a unified concept of the user-centered design (UCD) methods and ideas that had been found to increase the success of products. The design thinking ideology states that a user-centric and hands-on approach to problem solving promotes innovation which in turn creates competitive advantage through differentiation [9].

There are three main principles of design thinking: (a) observational research, (b) visual sense-making, and (c) prototyping. Observational research contains methods such as direct observation, contextual inquiry, and interviews. The idea is to define user needs. Visual sense-making helps create deeper understanding of the research data through alignment and visualization of relationships. Empathy maps, journey maps and service blueprints are helpful tools in the process. Prototyping includes methods such as low-fidelity prototyping, wireframing and high fidelity prototyping. The methods help establish an alignment between user and business goals by cost- and time-efficient concept verification [10].

The design thinking process is based on the following six distinct phases [9]:

1. **Empathize**: Create understanding of what the users do, say, think, and feel by conducting user research.

2. **Define**: Specify the user needs by analysing the research and establishing an understanding of the fundamental problem to be solved.

3. **Ideate**: Brainstorm a wide range of ideas that could potentially suffice the specified user needs.
4. **Prototype**: Further develop the most promising ideas to investigate which components of the proposed solutions work and which do not.
5. **Test**: Reintroduce the users and gain feedback on the chosen design direction for the solution.
6. **Implement**: Execute the resulting vision and materialize the solution in a way that truly satisfies the users.

The different phases of the process are iterated, as depicted in figure 2.1, until a satisfactory solution has been reached.

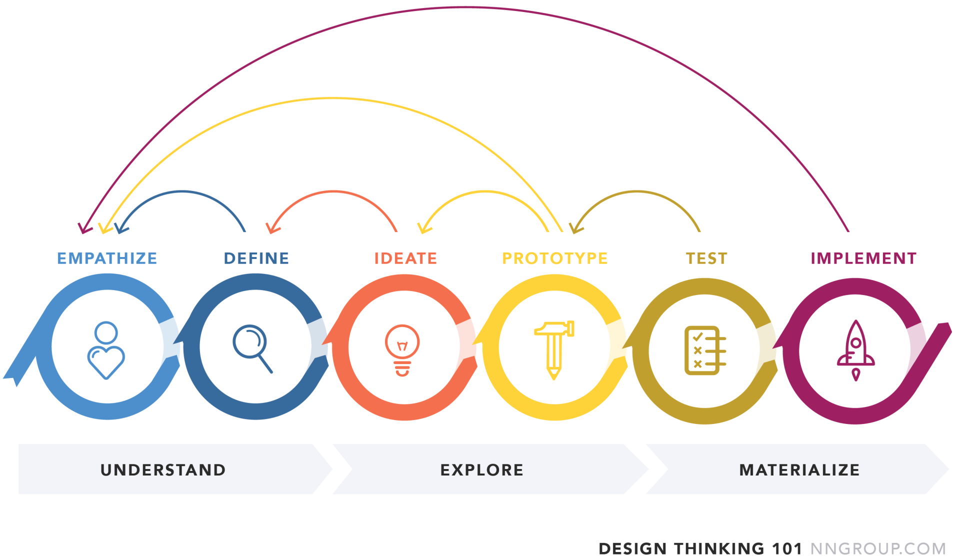


Figure 2.1: The six phases of the design thinking process [9].

2.2 User experience

The term *user experience* (UX) was coined by professor Don Norman. To explain the meaning of the term Norman states the following [11]:

> *"No product is an island. A product is more than the product. It is a cohesive, integrated set of experiences. Think through all of the stages of a product or service - from initial intentions through final reflections, from first usage to help, service and maintenance. Make them all work together seamlessly."*

Great products provide great UX. In order to create great UX, designers consider not only the use of the product but also how it will be acquired, owned and how troubleshooting will be handled. UX design goes beyond essential functionality and integrates aspects such as efficiency and pleasure when interacting with the product. The design should be based on the particular needs of the user in the specific context in which the product will be used [12]. As quoted by world-renowned architect Eliel Saarinen: "Always design a thing by considering it in its next larger context - a chair in a room, a room in a house, a house in an environment, an environment in a city plan." Successful UX is about considering the broader context and designing the entire user journey centered around a digital product or service [13].

2.3 Service design

In contrast to UX, service design addresses how the UX is internally supported. Service design considers the *how* of the UX by focusing on the planning and structure of the underlying resources of the system and business. For example, when interacting with a user interface the data displayed needs to be stored and retrieved in an efficient manner to support a smooth UX. Certain user requests might need to be handled by support personnel before the user can proceed with the ongoing task. A well-thought-out service design helps companies fill the gap between what they intend to deliver and what is actually delivered. It also minimizes duplication of processes within siloed business units to reduce redundancies and wasted resources. UX and service design are co-dependent and therefore need to developed in parallel. A service blueprint is a diagram presenting a structured overview of the relationship between touch points in the UX and the different underlying service components (see Figure 2.2) [14].

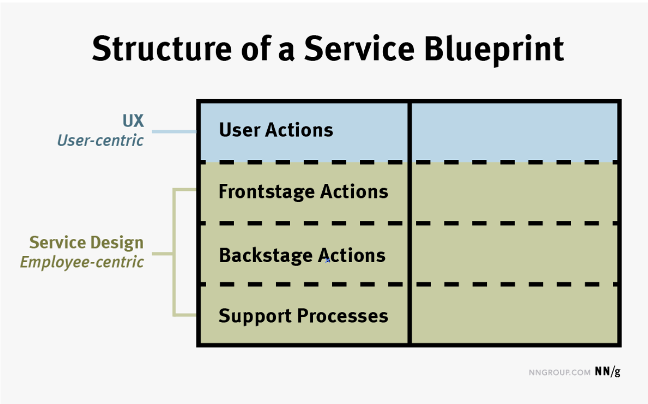


Figure 2.2: Structure of a service blueprint [14].

2.4 User interface

The communication between a product and a user relies on the user interface (UI). The UI essentially acts as the language between user and product, enabling the product to perform tasks to achieve the goals of the user. Therefor it is of great importance for a product to have a UI that communicates effectively in a way that corresponds to the natural intuition of the user [15].

2.5 Observational research

2.5.1 Interviews

Interviews are a commonly used method within UCD. Interviews can be useful in order to better understand the user, tasks and workflows related to the context of the product. The method can also be used for moderating usability studies and for developing scenarios and use cases, among other things. There are several different approaches when conducting interviews. One approach is the semi-structured interview. Semi-structured interviews are based on an introduction to the main topic followed by a list of questions and related topics to discuss, suggestions of problems and promises, and finally closing comments. The idea of this interview structure is to enable discussions and insight regarding new related topics while gathering information about the predefined topics. The method is a suitable substitute when direct observation of behavior is not an option. A semi-structured interview can lead to better understanding of user goals, uncover previously unknown issues and possibilities as well as insight about the context in which the product will be used [16].

2.5.2 Contextual inquire

Contextual inquire is a design method that improves the understanding of how and for what purpose a product will be used. By understanding which aspects are most important requirements can be defined and prioritized in order to improve usability of a product. Contextual inquiry is an observational research method based on four principles [17]:

1. **Focus**: Create a plan for the inquiry based on a well defined purpose.
2. **Context**: Observe the user in the context in which the product will be used.
3. **Partnership**: Engage in conversation with the user in order to gain insight about the less articulate aspects of the context.
4. **Interpretation**: Discuss the findings with the user and establish a common understanding as to which aspects matter the most.

2.6 Visual sense-making

2.6.1 Personas

Personas is a useful method to define clear target users for the design process. Based on user research a fictive person representing a typical user can be created. The persona should represent the most important aspects of the target user group. It is a helpful method to establish a common idea among the design team about who the user is. Without a persona there is a risk of communicating an elastic user that conveniently adapts to each designer's liking along the design process and ultimately leading to a poor product-user fit in reality. Some of the most useful characteristics of a persona is their general computer knowledge, their domain knowledge, their goals and tasks, the frequency in which the will use the product, their vocabulary, their level of motivation, the physical context in which they will use the product, their age, physical abilities and access preferences [15].

2.6.2 Storyboards

In addition to personas, storyboards can offer further insight about user scenarios. The method helps illustrate the context in which the user will adapt the product and how the product will solve the user's problem. A storyboard is a story based on sequential drawings depicting a typical use case. The tool helps designers visualize the user experience and explore how the user might interact with the product. Storyboarding creates engagement and empathy by capturing attention and depicting a story that users can relate to [18].

2.7 Prototyping

Prototyping is a way of communicating design ideas efficiently and at low cost. By creating a simple test model of the proposed product concept, user testing can be conducted at an early stage of the design process. This enables a solid foundation for the design project where the different stakeholder are provided insight about the direction of the design. Early stage prototyping allows for early stage changes and minimizes the risk of choosing a sub optimal design direction from the start leading to expensive corrections later in the process [19]. *The 1-10-100 Rule* states that the cost of product changes increase as the product moves further along the production system. If the cost of product error prevention is 1 dollar, for example by conducting early stage usability testing of prototypes, then the equivalent cost of error correction is 10 dollars. The cost of failure, for example due to lost revenue caused by design related product error, is then equivalent to 100 dollars [20].

2.7.1 Low-fidelity prototypes

The fastest and cheapest prototyping is low-fidelity. These prototypes are commonly made with paper and pencil and allows the exploration of many different design approaches. The main point is the focus on design thinking rather than the visual appeal of the various design elements. However, the method is limited in regard to the lack of realism and therefore users might find it hard to give feedback about the user experience [19].

2.7.2 High-fidelity prototypes

High-fidelity prototyping engages users in the experience by moving closer to the actual product design. Digital prototypes are commonly created using vector based design tools. The advantages of this method is the improved concept visualization granting a greater understanding of the user interaction and how well the product matches the needs of the user. The disadvantages compared to low-fidelity prototyping is the increased cost and time, as well as the risk of users focusing too much on the aesthetic design impression rather than the underlying functionality and design concept [19].

2.8 Brainstorming

Brainstorming is a common method of design thinking. The method is primarily applied in the idea generation process, however, it might be useful during later design phases as well. Starting from a well defined problem description the design team collectively comes up with a variety of potential solutions. The goal is to produce as many ideas as possible in a set amount of time. Up to an hour is usually well enough. The method requires a open and inviting communication, where the team members feel comfortable sharing ideas off the top of their head. Outside the box thinking is necessary for the method to work efficiently providing a wide base of ideas for future stages of iteration [21].

2.9 Usability testing

The International Organization for Standardization (ISO) defines usability as "extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (ISO 9241-210) [22]. There are many different testing methods to measure and evaluate usability. These methods can be applied at any stage of the design process to evaluate potential design decisions.

2.9.1 Think aloud

Think aloud is a test method where a group of representative users will be given a set of tasks to perform using a product in development. During the course of the test, uses will be encouraged to freely express any thoughts that comes to mind regarding the process. The idea is to generate unfiltered and honest feedback. The major advantages of this testing method is the low cost, low risk of facilitating a bias study, applicability during any stage in the development life cycle, convincing result from direct user opinions, and the simplicity of facilitating the study in a basic form. There are however a few downsides to the method as well. Users are generally uncomfortable freely expressing themselves without first filtering their thoughts. This issue is usually apparent in the beginning of the test and after some time the participants become more comfortable upholding the monologue. There is also a risk of the test leader clarifying more than necessary, affecting the decision making in a bias way [23].

2.9.2 System Usability Scale

The System Usablity Scale (SUS) is a low-cost and reliable usability assessment tool. The tool consists of a questionnaire based on the following 10 statements [24]:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.

4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

The user is asked to respond to each statement according to a 5-point agreement scale ranging from *Strongly agree* to *Strongly disagree*. The scores are converted according to a scoring table and multiplied by 2.5, resulting in a final score between 0 and 100. The final score serves as a general measurement of the system usability. [24].

2.10 Design guidelines and principles

2.10.1 10 usability heuristics

In the 90's, human-computer interaction researcher Jakob Nielsen defined a well known list of 10 general principles of interaction design [25]:

1. **Visibility of system status**: A system should clearly inform the user about the current state in order to create trust in the product through the predictability of interactions.
2. **Match between system and the real world**: The system design language should be familiar to users by presenting information in a natural and logical order. An understanding of the users' language and terminology should be established through user research.
3. **User control and freedom**: Mistakes made in the system should be easily revoked through the support of *undo* and *redo* features, and by presenting a clear way of exiting the ongoing process.
4. **Consistency and standards**: The design should be based on current conventions of the platform and industry. The system should also be consistent in it's design to improve learnability and reduce cognitive load.
5. **Error prevention**: Preventing errors is preferable compared to informing of errors after they have already occurred. Unconscious errors, known as slips, and mistakes based on design unfit for the user can be avoided by providing helpful constraints and informative defaults for user input.
6. **Recognition rather than recall**: The memory load of the user should be minimized by presenting elements, actions and options across user interfaces. Information that is not directly visible should be easily retrievable.

7. **Flexibility and efficiency of use**: The system should allow the tailoring of frequent actions. Utilizing shortcuts enables experienced users to operate more efficiently while novice users can have the full support of the system's design to reduce cognitive load and ease learnability.

8. **Aesthetic and minimalist design**: Information should be prioritized in the user interface. Irrelevant information clutters the view and reduces the relative visibility of essential information.

9. **Help users recognize, diagnose, and recover from errors**: Error messages should inform the user of what went wrong in a easily interpreted and recognizable format.

10. **Help and documentation**: If necessary the user should be provided documentation to ensure tasks can be completed to satisfaction. The documentation of the system should be easy to search and task instructions should be presented step by step.

2.10.2 Design principles

In his classic book *The design of everyday things*, professor Donald Norman describes the following four principles of interaction design [12]:

1. **Affordance**: The relationship between an object and a user determining what the user can do with the object. For example, a heavy box of magazines can only be lifted by a strong person, ergo the object only afford lifting for a strong person. The affordance is a relationship. It is not solely a property of the object since it depends on both the object and the user.

2. **Signifier**: The purpose of signifiers is to convey to the user where the actions, determined by the affordances, should take place. Signifiers work like clues in guiding the user through the various interactive functions of the product.

3. **Mapping**: Mapping is the relationship between action and reaction when interacting with an object. A room with multiple light sources typically has one switch for each light. The location and correspondence between the different switches and associated light sources determine how easy it is to understand which switch goes to which light. Usability can be improved by arranging the switches in the same pattern as the light sources to create a natural mapping.

4. **Feedback**: When a user interacts with a product it is essential that the product notifies the user that the interaction has in fact been registered. This is called feedback. Feedback has to be immediate and informative. Examples of feedback is the start sound when turning on a computer, or the load bar in a web browser indicating that the request for a web page is in progress.

2.10.3 Fitts' Law

Through his studies during the 50's psychologist Paul Fitts discovered that the time it takes a person to move a pointer, for example a mouse cursor, to a target area is a function of the distance to the target divided by the target size. Fitts' law is commonly applied in UI and UX design where rapid pointing movements are involved [26].

2.10.4 Hick's Law

Hick's Law, also known as the Hick-Hyman Law, defines how long it takes a person to make a choice in a given situation depending on the number of alternatives to choose from. The law defines the following function: $RT = a + b\log_2(n)$. RT is the reaction time, (n) is the number of alternatives to chose from, and a and b are constants depending on the specific task for which a choice is to be made. In combination with other design principles this law is a prime resource when balancing functionality against complexity [26].

2.11 Gestalt principles

In order to visually organize design elements and information in a comprehensive manner, the gestalt principles can be of great use. These principles are concerned with the way our minds process visual input by organizing patterns, objects and shapes into unified forms. The following are three of the most essential gestalt principles [27]:

1. **Similarity**: Our mind creates relationships between elements of similar design. For example, elements of similar color, shape, orientation, and size appear to be more strongly connected then elements lacking visual similarity. By applying this principle information can be visually organized, making it easier for the user to navigate a user interface (see Figure 2.3).

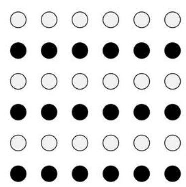


Figure 2.3: The principle of similarity [28].

2. **Proximity**: Elements that are more closely positioned then the surrounding elements of a group appear to have a stronger relationship. Proximity is the most efficient way to communicate connection between elements. For example, the use of white space is a common approach in visual design to create a clear separation between non related elements (see Figure 2.4).

3. **Figure-ground**: When observing an image the eye tries to register solid objects. The elements of the image are perceived as either *figures* in the foreground or as *ground*, elements discarded in the focus of the eye. By utilizing contrast, for example by placing light text on a dark background, the focus of the user can be targeted to specific elements (see Figure 2.5).

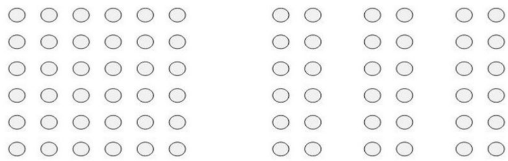


Figure 2.4: The principle of proximity [29].

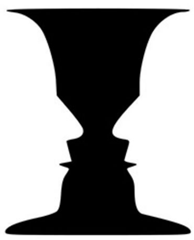


Figure 2.5: The principle of figure-ground [30].

Chapter 3

Technical background

This chapter presents technology related to the project and software tools utilized in the development of the prototype.

3.1 Overview of flexographic printing

There are three main types of flexographic printing technology: central impression, stack, and inline. Tetra Pak's flexographic production is purely based on the inline technology. Inline flexographic printing is conducted by unwinding a roll of thin cardboard material, known as substrate, and feeding it through a row of print units (see Figure 3.1). The typical ink system for printing is CMYK. CMYK includes the following four colors: cyan, magenta, yellow, and black. Additional spot colors can be added to expand the range of different colors that can be reproduced, known as the color gamut. Each print unit applies one color with varying density for different positions of the package design. This is conducted by pressing flexible relief plates bearing color onto the web. By combining different densities of the different colors the final package design is produced (see Figure 3.2). After each application of a color the substrate needs to be dried by applying forced hot air convection, before adding the next color [4]. At Tetra Pak packages are printed at speeds of up to 600 meter per minute and there can be many webs of packages printed side by side, each with its own plate for each color. The printed substrate is finally rewound into a spool and ready for the next process of the aseptic package material production [4].

3.2 Job specific print variables

In order to obtain a consistent high quality print for a specific design, print variables need to be optimized and standardized for the specific print job. The job specific print variables consists of (a) substrates, (b) inks, (c) coatings, (d) ink metering system, and (e) plate package [32].

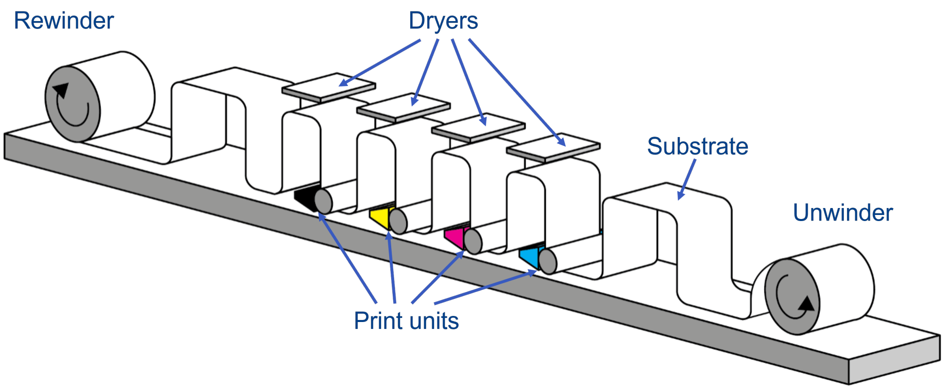


Figure 3.1: The flexographic printing press.

Figure 3.2: Printing with CMYK colors [31].

3.2.1 Substrates

Flexographic printing supports many different substrates. There are two major categories of substrate: (a) wood-based products and (b) petroleum or mineral-based products. The wood-based category generally consists of paper, paperboard, linerboard, tissue, newsprint and currugated. Substrate from petroleum or mineral include film, foil and laminated structure. Each subgroup of substrates consists of several different specifications of material structure. The choice of substrate for a specific print job is typically determinded by the requirements of the finished package. Three of the most important requirements are strength, flexibility, and protection. In terms of print quality, the most essential substrate characteristic is consistency. A reproducible print result relies on the consistency of the substrate properties. These properties can be divided into three groups: (a) structural properties, (b) surface properties, and (c) chemical properties. Examples of structural properties influencing print quality are substrate thickness, flatness, clarity, and dimensional stability. Surface properties include brightness, coefficient of friction, gloss, and surface tension, to name a few. The last group, chemical properties include Sizing, moisture, and aging. There are many standardized test methods available for the assessment of the various substrate properties [32].

3.2.2 Inks

Inks are compositions of the chemical components pigment and vehicle. In order to achieve a reproducible print, a proper ink balance is crucial. The balance between the chemical components determines color, drying, trapping, transfer, and lay characteristics of the ink. Consistency in print result requires careful monitoring and control of ink balance during production. The main print variables to control during production are the viscosity, pH, temperature, and ink foaming [32].

The first ink component, pigments, define the visual identity, more generally referred to as the color of the ink. These insoluble colorants are responsible for the fade resistance, transparency, and product resistance. The second ink component, vehicle, is composed of resins, solvents, and additives. The vehicle carries the pigment to the substrate using its components. The resin binds the pigment to the substrate and the solvent converts the pigment, resin and additives from solid form to a printable fluid form. There are three different types of ink systems for printing: (a) solvent ink, (b) water ink, and (c) UV or EB ink. The main difference between the three systems is the chemical component that constitutes the function of the solvent. For example, the solvent functionality of water ink systems is composed of water and ammonia, or water, ammonia and organic amines [32].

3.2.3 Coatings

Coating applications and speciality inks are used to create distinguishable print elements. There are four categories of coatings: (a) promotional branding, (b) interactives, (c) brand security, and (d) track and trace. Promotional branding includes inks such as: metallic inks, fluorescent inks, and inks that change with temperature, called thermochromics. Examples of interactive inks include phosphorescents, inks that glow in the dark. Part of the brand security category is the photochromic inks, inks that alter color based on UV exposure. The final category, track and trace, include conductive inks for the printing of *radio frequency identification devices* (RFID), an electrical tag scanning technology based on radio waves [32].

Coatings present additional print challenges compared to the typical flexographic inks. The particle size of the speciality inks are often larger and the pigment shape is different. The viscosity and specific gravity are in many cases also higher [32].

3.2.4 Ink metering system

The ink metering system controls the ink transfer to the printing plate. The system has three essential parts: (a) the anilox roll, carrying ink to the printing plate; (b) the doctor blade, removing excess ink from the anilox roll; and (c) the doctor blade chamber, that is the ink reservoir (see Figure 3.3). A consistant print result relies on the correct ink volume being transferred to the anilox roll at high speeds, despite the presence of immense turbulence in the doctor blade chamber [32].

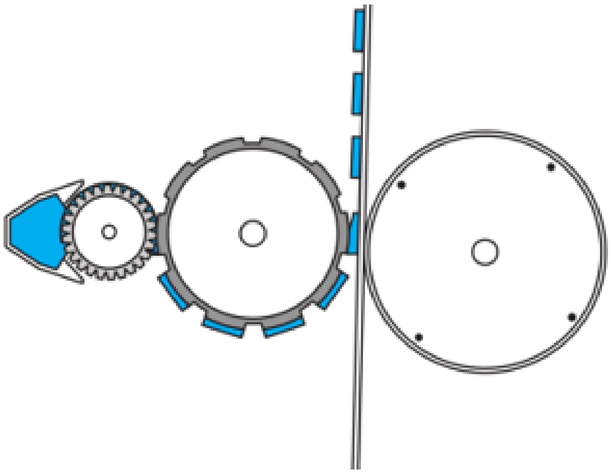


Figure 3.3: The ink metering system.

3.2.5 Plate package

The plate package is comprised of the plate, sleeve, and mounting material (see Figure 3.4). The interaction between these components is made consistant through the standardization of optimal component combination.

Plate

The plate contains the design pattern for the specific print job. The main consideration when optimizing choice of plate type is the ink release characteristics. Print quality is primarily determined by the following plate variables: (a) material, rubber or photopolymer based; (b) plate durometer, affecting dot gain, plate durability, impression pressure, and effectiveness of mounting material; (c) caliper, affecting the imaging traits and tonal range; (d) uniformity, necessary to evade over impressing; (e) image relief, influencing image distortion and minimum dot size on plate; and (f) processing method, determining the quality of the plate [32].

Sleeve and mounting

Sleeves are cylindrical tubes that the plate is mounted onto. There are generally two types of sleeves: (a) nickel sleeves, made of thin metal; and (b) composite sleeves, fiber reinforced polymer. A plate is mounted onto a sleeve using hard tapes or compressible backings. The main difference between these two types of mounting material is that hard tape does not cushion the plate to substrate impression. The combined hardness of the plate and mounting material influences the print quality primarily in regard to solid ink density and uniformity, dot gain and dot structure, and slur and banding. The mounting of a sleeve onto a print cylinder is conducted using compressed air to create a tight coupling. The accuracy of plate and sleeve mounting is crucial to ensure minimal registration inaccuracies [32].

Figure 3.4: Plate mounting onto a sleeve [33].

3.3 Press component print variables

The press component print variables consist of all the mechanical parts of the printing press. The category consists of the following four print variables: (a) dryers, (b) registration control, (c) tension control, and (d) press mechanics. The state of the press components dictates if the press is able to evenly deliver and properly dry ink, in addition to mechanically holding impression settings and register. Optimization and routine measurements in comparison with original performance specification is therefore of great importance to ensure a satisfactory print quality [32].

3.3.1 Dryers

Dryers are used to remove elusive ink from the substrate after printing. The drying is performed using forced hot air convection making the ink solvents evaporate. Two types of dryers are utilized in flexographic printing. The first type, interstation dryer, dries the substrate between each printing unit to achieve a dry trap for the next color to be applied. The second type, overhead dryer, is positioned at the end of the print line to remove the excess ink from the last color and applying the final drying of the all the inks. the ink drying depends on the velocity, volume, and temperature of the air, as well as the dwell time. The correct settings is vital to achieve successful evaporation of excess ink and avoid damage to the substrate [32].

3.3.2 Registration control

Color-to-color and print-to-substrate registration need to be maintained during the production run. If color-to-color registration is misaligned the image of the package design can appear distorted and blurry, since the colors are not correctly printed on top of each other (see Figure 3.5. The print register is dependent on several different print variables, for example: web tension, gear condition, web movement, plate and sleeve mounting, and overall condition of the press. Successful print registration relies on (a) side and circumferential registration, (b) web guiding, and (c) web viewing [32].

Figure 3.5: Comparison between correctly aligned and misaligned colors. (Image from forum, URL: https://graphicdesign.stackexchange.com/questions/13557/giving-a-light-brown-fazed-grained-effect-to-images-in-ai-cs5-disorting-pixeliz).

Side and circumferential registration

Side and circumferential registration uses mechanical, hydraulic, or electric equipment to control the deck positioning in lateral and longitudinal direction in order to maintain register. Hydraulic and electric register equipment can be automatic while also allowing operators to remotely fine tune registration by incrementally moving the web [32].

Web guiding

The web maintains the correct position using web guiding to move the web sideways, as well as backwards and forwards. The web guiding is generally applied during unwinding of the substrate, before the first print station, and lastly during rewinding of the printed substrate. The system is a closed control loop consisting of the web, sensor, controller, and hydraulic actuating cylinder. There are four typical tactics of sensor positioning: (a) edge guiding, web edge position is detected and maintained; (b) fixed sensor center guiding, centerline is maintained by one sensor at each edge; (c) moving sensor center guiding, sensors maintain centerline by continuous repositioning side to side; and (d) line or pattern guiding, a printed line or pattern is detected and laterally maintained independently from the edge position [32].

Web viewing

Web viewing is conducted by the operator to evaluate the printed web during production. There are four main technologies used to observe the web at high speeds during production: (a) stroboscope, (b) oscillating mirrors, (c) rotating drum mirrors, and (d) video scanning. A stroboscope uses a lamp and voltage pulse source to create a frequency synchronous flash according to the print repeat length. The method offers limited image definition at a relatively low cost. The second technology, oscillating mirrors, enable increased visual dwell time for improved print detail evaluation. However, the speed capability and the web repeat length is limited by the method. Rotating drum mirrors is a more suitable technology for high speed evaluation. The technology is suitable for speeds over 600 meter per second with print magnification between 5X and 10X. However, the most common web viewing technology is video scanning. The advantages of this method are the absent of distortion, high magnifying capability, and superior evaluation of print details [32].

3.3.3 Tension control

Flexographic presses rely on tension control to enable printing at high speeds while maintaining high print quality. The tension control is typically applied in the unwind tension zone, intermediate tension zone, and finally in the rewind tension zone. The correct web tension is essential to avoid (a) stretching and width reduction during unwinding, (b) shortened print length and curling during the press run, and (c) to ensure a high quality finish in the rewind. The tension control often compensates for web handling issues, such as loss of color-to-color registration and web shifts side-to-side [32].

3.3.4 Press mechanics

Press mechanics include components such as gears, bearings, cylinders, rollers, and drive trains. The print quality during production is determinded by the condition of the mechanical components. For example, the various cylinders along the press have to be properly parallel and maintain correct mass distribution to eliminate vibration at the bearings [32].

3.4 R2-DiToo

R2-DiToo is a development project conducted at the Tetra Pak site in Lund. The goal of the diagnostic tool is to provide better capability understanding, reduce analysis time, provide reliable data for improvement of the print process, as well as auto classification of issues to simplify analysis, for example when logging long time data. R2-DiToo will provide additional information of register movements compared to current systems, allowing for future implementation of extended control and monitoring during production by detecting currently undetectable register deviations.
The current register control in Tetra Pak's converting factories does not provide complete information regarding the capability of the printing presses. Therefore there is no official packaging material specification available as a basis when consolidating costumers regarding the expectations of the print finish. Today the expectations of production quality are based on an unofficial specification. The current sensor system consists of one camera positioned above the middle web after each print unit. The sensor measures the lateral and longitudinal position of the print unit's color

mark in relation to the reference mark of the first print unit. It does not detect the distance between the different color marks or deviations between webs. Register maintaining is therefore solely based on the print quality of the middle web. Only measuring the middle web and only one color at a time makes it hard to detect the relationship between the different colors as more than one color might be misaligned concurrently. Issues such as shrinking of outer webs caused by overheating and plate mounting errors might also be overlooked by the current setup. This could result in faulty print, waste or even customer claims.

R2-DiToo addresses the current limitations by using three inline cameras registering color marks on the middle web as well as two additional webs, one on each side. The system will be positioned after the last print unit. Additional print issues can be detected by concurrently measuring and comparing deviations between the color marks of the different webs. The new cameras will also be able to detect color marks on every single package at the full production speed of 600 meters per minute. The current cameras only register once every second, which equals six times every 10 meters. In Figure 3.6 the difference between the current sensor system and R2-DiToo is illustrated.

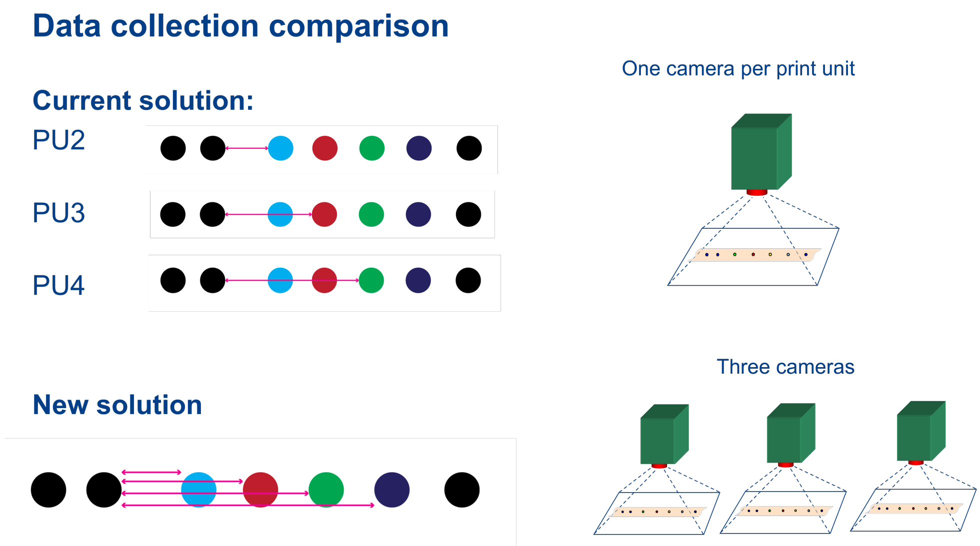


Figure 3.6: The current register control sensor system (top) compared with the R2-DiToo (bottom) sensor system.

The diagnostic tool will be used in Tetra Pak's converting factories across the world. The mobility of the system allows it to be transported between factories and installed when there is a need for more extensive research in order to detect print issues and improve print capability. R2-DiToo consists of a bracket with three register cameras that can be adjusted by hand. The cameras are connected to a power station where the sensor data is collected. The power station consists of a small mobile cabinet with a monitor to display the register positions during production. Data collection equipment is provided by the camera manufacturer. However, a data processing and analysis tool needs to be developed by Tetra Pak. The analysis tool will be used by operations engineers and development engineers to analyse data trends from the color-to-color register cameras.

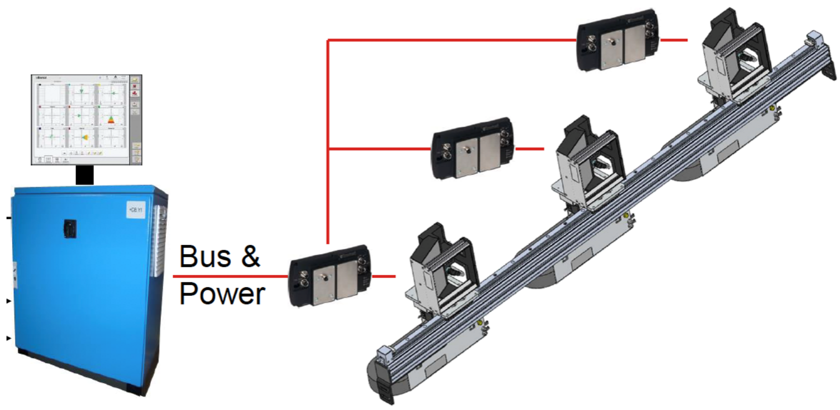


Figure 3.7: The R2-DiToo sensor system.

3.5 Software tools

3.5.1 Power BI

Power BI is a scalable platform for self-service and enterprise business intelligence (BI). The platform enables visualization of large quantities of data in order to gain a deeper insight in support of data driven decision making. Power BI enables the creation of interactive data reports, cloud based collaborations and several security solutions for the protection of sensitive organizational data [34, 35].

3.5.2 Sympathy for data

Sympathy for Data is an open-source python based framework built for data analytics and data science applications. The purpose of the framework is to enable automation of data processing in regard to data accessing, merging, transformation, analysis and visualization. The tool is essentially developed to combat repetitive and challenging data analysis. The Sympathy for Data platform allows for standalone application deployment as well as server integration in connection with other enterprise solutions. The user interface consists of a grid and a library of modular components. Each component has ports for data input and data output. A data process workflow can be designed by placing different types of modules on the grid and connecting them through the output and input ports. Subflows can be linked together allowing for high complexity workflows. [36, 37].

Chapter 4

The design process

This chapter covers the design process from preliminary literature study to implementation of the final prototype.

4.1 Process overview

The project was initialized with a literature study followed by the implementation of the design process. The design process was based on the user-centric design thinking process, as described in section 2.1, and consisted of the following four distinct phases: (a) Create understanding, (b) Ideate, (d) Design solutions, and (e) Evaluate. The result from each phase was the basis for the next phase in line. Tasks related to different phases were partly conducted in parallel to enable an efficient work process and collaboration with the stakeholders. An overview of the design process is presented in Figure 4.1.

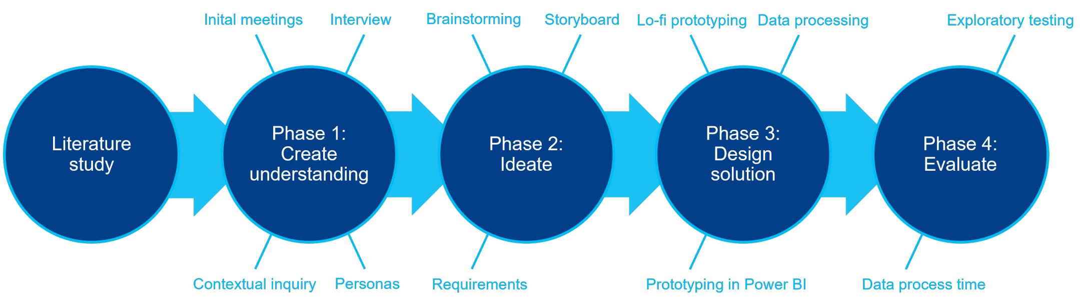


Figure 4.1: Overview of the design process.

4.2 Literature study

The first few weeks of the project were spent conducing a literature study. The goal of the study was to gain a better understanding of the various methods and concepts of interaction design as basis for the design process. The findings are presented in chapter 2. The literature study also covered several technical subjects related to the project, as presented in chapter 3. Research into both suitable software tools and the process of flexographic printing was conducted.

4.3 Phase 1: Create understanding

The objective of the first design phase was to institute a solid understanding of the users and the context in which R2-DiToo will solve problems currently faced. this was achieved through discussions with the product owner, and methods of observational research such as interviews and contextual inquiry (see section 2.5).

4.3.1 Initial meetings with product owner

The first step in the first phase was to establish a general understanding of R2-DiToo (see section 3.4). Initial meetings were held with the product owner for the introduction of the R2-DiToo project. The product owner is a development engineer and one of the users of the application. During the initial meetings It was established that the system will be used by operations engineers and development engineers. R2-DiToo will be used globally across Tetra Pak's converting factories and the international applicability of the diagnostic tool requires that it can be easily understood and managed despite language barriers. Since the system will be mobile it will feature a dedicated laptop to collect and store sensor data in text based format. The sensor data should be processed and accessible in a comprehensible format for further analysis. Dedicated data storing is necessary to support analysis given that the control and data acquisition system (CDAS), storing all the various sensor data from the flexographic presses, only collects data once every 10 seconds or once every minute. At full production speed 10 seconds equals 100 meters which is far too infrequent to support analysis of color-to-color register data.

In the R2-DiToo project a test workflow for sensor data processing had previously been created using the Sympathy for Data framework (see section 3.5.2). The test workflow was based on mock data representing color-to-color register coordinates. In the workflow the lateral and longitudinal distance between the control mark of the first print unit and the color mark for each subsequent print unit was calculated. Based on the calculated distances, the color-to-color register marks of each package repeat were labeled as either normal, error, or according to the print issue which they indicated. For example, if the color mark on the outer webs were too far away in lateral direction from the color mark on the middle web then the register marks were labeled as a board shrinkage issue. The issue categorization was based on data from two print units and included two print issues: board shrinkage and mounting error (see Figure 4.2 and 4.3). Tetra Pak typically uses up to seven print units in the flexographic presses. Four print units to print CMYK and up to three additional print units for spot colors. The data processing therefore needed to be further developed to support five additional print units. The issue categorization could also be improved by including additional print issues.

During the meetings, delimitation of the master thesis project were discussed and agreed upon. The delimitation are presented in section 1.7.

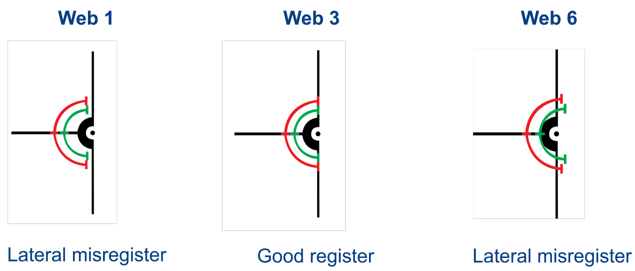


Figure 4.2: Lateral misregister in left and right web indicating board shrinkage.

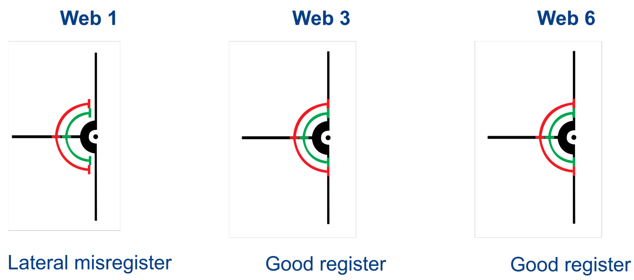


Figure 4.3: Later misregister only in left web indicating a mounting error.

4.3.2 Interview with process manager of Vietnam factory

An interview was conducted with a previous prepress and printing process manager of Tetra Pak's factory in Vietnam. The interviewee worked as a project leader of a five man team during the construction of the factory. He was responsible for the machinery regarding prepress and printing. After the construction was completed he continued working as a prepress and printing manager at the factory. The objective of the interview was to gain insight about potential differences in how work is conducted in factories across different nations. The objective was also to establish further understanding of how operations engineers manage register control during production. The interview was semi-structured and organised as described in section 2.5.1. The interviewee was introduced to the subject and purpose of the interview, followed by a set of questions as basis for the conversation. The introduction script and interview questions are presented in appendix A.

The interview resulted in the following knowledge:

- Inline quality inspection: Continues quality checks are conducted using strobe light special equipment and the current control system can detect small defects. However, both inline and offline inspection are necessary. Offline inspection is primarily conducted after test runs, for example due to improvement changes of the plate manufacturing process or when conducting multicolor printing with speciality inks. Certain print issues, for example dirty print of the Scandinavian letter *Å*, will not be visible during inline inspection because of the limited image definition of the stroboscope (see section 3.3.2).

- Offline quality inspection: Offline inspection is conducted using a manual graduated lens to detect and measure small scale defects. Operators are trained to identify print issues and take countermeasures based on a decision making matrix. The challenge of quality inspection is the deviation in individual perception between operators, as well as the tolerances of the print and design specification. Together these factors can add up to a large scale deviation in the print quality.

- Difference between factories: The factories operate very similar in regard to the processes of prepress and printing. There are no considerable differences between factories.
- Process and quality improvements: Customer complains caused by misaligned colors have been reduced greatly in the last few years. Efficiency and quality are improved by gradually removing the subjectivity of the inspection process. The process should be less dependent on the decision making matrix through increased automation and improved register control. Generational shifting of the work force is creating new challenges. People are more frequently switching jobs causing the operator force to generally be less experienced and more prone to making errors. The transition into industry 4.0 is therefore of great importance to be a future competitor in the production industry.
- Substrate waste during ramp up: Potential future integration of the R2-DiToo system into the production presses could potentially reduce waste of substrate during ramp up. At the beginning of production the speed of printing is gradually increased until reaching full production speed. The temperature threshold limit for which misalignment occurs due to overheating is relative to the print speed. Lower print speed results in overheating at lower temperature. During ramp up several hundred meters of substrate is wasted. If the R2-DiToo system could be integrated and used as basis for the temperature control during ramp up then production quality could be obtained at lower speed with less waste of material.

4.3.3 Contextual inquiry at the Tetra Pak test facility

In order to better understand the context in which development engineers will use R2-DiToo, a contextual inquiry was conducted. The inquiry took place in the testing facility for flexographic printing at the Tetra Pak Lund site. The testing was conducted by a group of development engineers to evaluate the print capability of a new type of anilox (see section 3.2.4). The testing did not concern color-to-color register alignment since only one color was printed. Therefore R2-DiToo would not have been applicable for this type of print evaluation. However, the contextual inquiry provided a general insight as to how development engineers conduct analysis during capability testing, for example the terminology used and how the work is divided. When conducting evaluation of a new press component, for example a new anilox, the goal is to verify that the capability of the press has been improved. A benchmark of the current capability therefore needs to be established at the beginning of the test session, before replacing the current component with the new one. During the testing of the anilox the color density of the prints was measured using a densitometer to calculate the dot gain. Between test runs calibrations were made to the set up in order to make the conditions as similar as possible to actual factory production. The calibration took substantially more time than the manual print quality measuring and inspection. This indicated that quality inspection during testing is not limited by the available time in between test runs. Since R2-DiToo will automatically collect data development engineers working with the diagnostic tool will have even more time to analyse the print quality in regard to color-to-color register.

4.3.4 Personas

The first phase of the design process was concluded by defining the users of R2-DiToo based on the established knowledge from the various methods that had been conducted throughout the phase. The users were defined using personas, a method of visual sense-making (see section 2.6). Personas were created to illustrate goals of typical users and the struggles currently faced. Two separate personas were defined. One persona, Alice, representing development engineers and one persona, Bob, representing process engineers. The personas are presented in Figure 4.4 and Figure 4.5.

Figure 4.4: The development engineer persona.

Figure 4.5: The process engineer persona.

4.4 Phase 2: Ideate

In the ideation phase a brainstorming session, as described in section 2.8, was conducted as well as the creation of a storyboard, as described in section 2.6.2. The ideation phase resulted in a list of high level requirements as basis for prototyping.

4.4.1 Brainstorming

During one of the product owner meetings a brainstorming session was conducted. The objective of the session was to generate ideas of how an efficient and user friendly process could be designed for the transferal of raw sensor data into processed data, and finally visualization of the processed data. The brainstorming session resulted in a decision to develop the application using the Power BI platform (see section 3.5.1). Power BI was chosen to support scalability and to enable various features for extensive data visualization. A decision was also made to base the prototype on the simplification that raw sensor data could be saved from the sensors directly to a text based file on the dedicated laptop of the diagnostic tool. In reality the sensor data needs to be parsed before it can be saved as a text file. This parsing software will not be part of the prototype. In order to enable an efficient and user friendly process flow, the data will be saved in a specific folder on the laptop where the data can be retrieved and processed by the workflow in Sympathy for Data. The processed data will then be saved and automatically exported to the Power BI platform and visualized in a user interface (see section 2.4).

The brainstorming session concluded the preliminary work to define the structure for the prototype. A presentation of the project plan and structure of the prototype was held with the project supervisors, of which one is also the product owner as well as a user of R2-DiToo. The presentation resulted in a common understanding and formalization of the prototype structure.

4.4.2 Storyboard

A storyboard was created to illustrated a typical user scenario where a development engineer is analysing register data with the support of R2-DiToo. The storyboard is presented in figure 4.6.

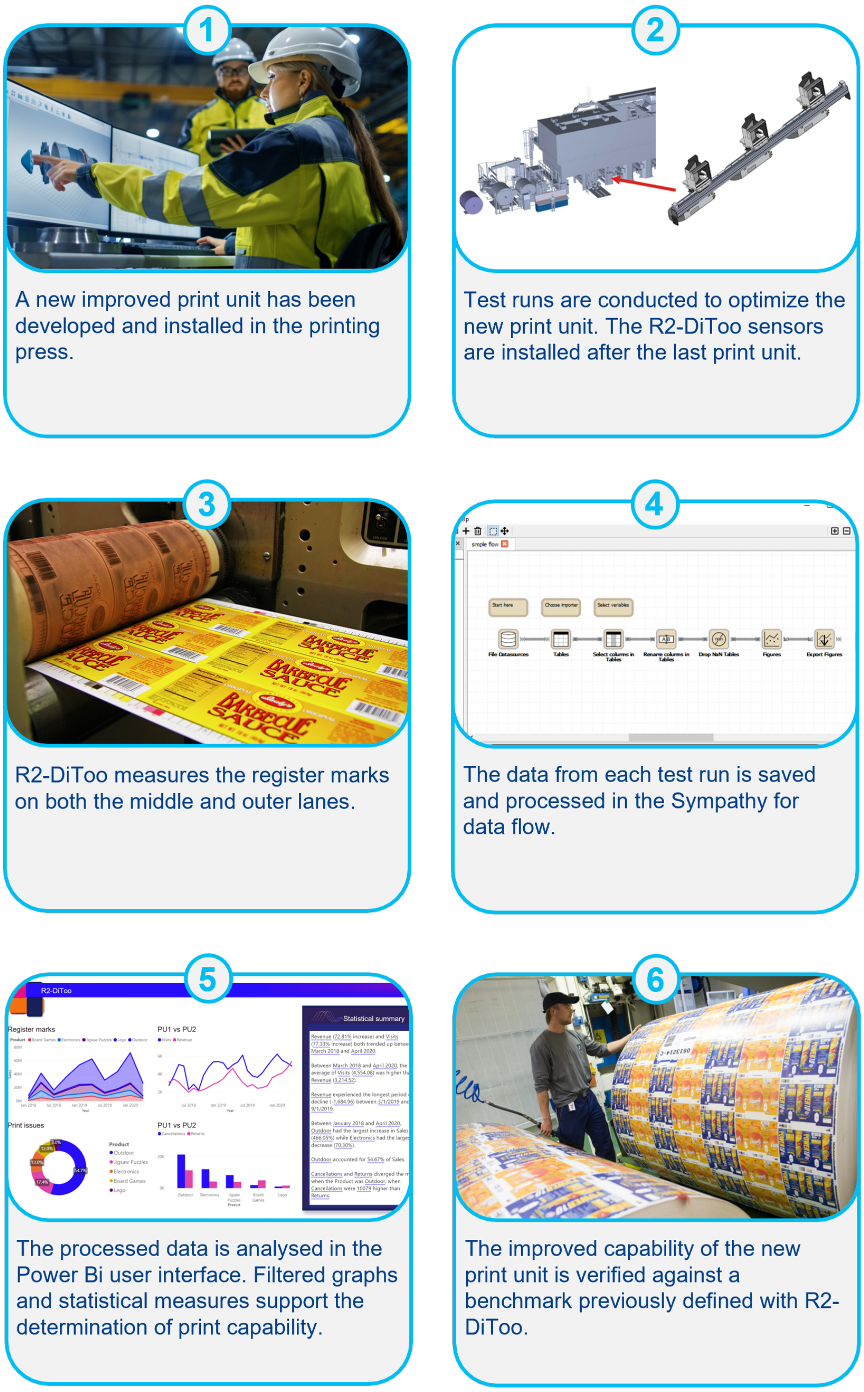


Figure 4.6: Storyboard of a development engineer working with R2-DiToo [38, 39, 40, 41, 42].

4.4.3 Requirements

Based on the contextual research and ideation process, the following high level requirements were defined for the development of the R2-DiToo prototype:

1. The system shall include two separate parts: (a) data processing and (b) data visualization.
2. Data processing and data visualization shall be deployed on a dedicated laptop for R2-DiToo.
3. The system shall process raw sensor data (coordinates of color-to-color register) from three inline cameras and calculate distance between each color mark.
4. The data processing shall be developed using the Sympathy for Data framework.
5. The system shall identify and categorize print issues based on data trends.
6. The system shall feature the following two print categories: (a) board shrinkage and (b) faulty mounting.
7. The user interface for data visualization shall feature graph filters and statistical measures to support the analytical work of print issue detection and capability determination.
8. The user interface shall present simplified capability metrics, for example the percentage of data within the specification.
9. The user interface for data visualization shall be developed in Power BI.

4.5 Phase 3: Design solution

The goal of the third design phase, *Design solutions*, was to materialize a prototype of R2-DiToo based on the defined requirements of the previous phase. This phase was initialized through the creation of a low-fidelity prototype, followed by the implementation of a new workflow in Sympathy for Data to support the implementation of the R2-DiToo data visualization. The phase was finalized through the creation of a fully working prototype of R2-DiToo to be evaluated in the following phase. The design decisions were based on the design guidelines and principles presented in section 2.10. The designing of prototypes was an iterative process and several meetings were held with the product owner throughout the process to ensure the solution evolved in the right direction. The major design iterations are presented in this section.

4.5.1 Low-fidelity prototyping

A conceptual design was presented to the product owner using the prototyping method known as low-fidelity prototyping (see section 2.7.1). A low-fidelity prototype consisting of two separate pages of the interface was created using paper and pen (see Figures 4.7 and 4.8). The first page was an overview of the color-to-color register data featuring three separate modules: (a) filter menu, to select which data to include in the statistical analysis; (b) *% within tolerance*, showing the percentage of package repeats with acceptable color-to-color register according to the specification; and (c) *issues*, showing a pie chart of the issue categorization, as well as a graph of the labeled register marks. The second page of the low-fidelity prototype featured a more detailed view of the sensor data. This view also contained a filter module where the user would be able to select which print units and sensor cameras to visualize in the data analysis. For example, by selecting the operator side camera (OS), the driver side camera (DS), and the fourth print unit (PU4), the user would be able to compare the fourth print unit register of the middle web and the web on the drive side. Based on the filter selection the graphs and statistical measurements of the detailed view would be updated accordingly.

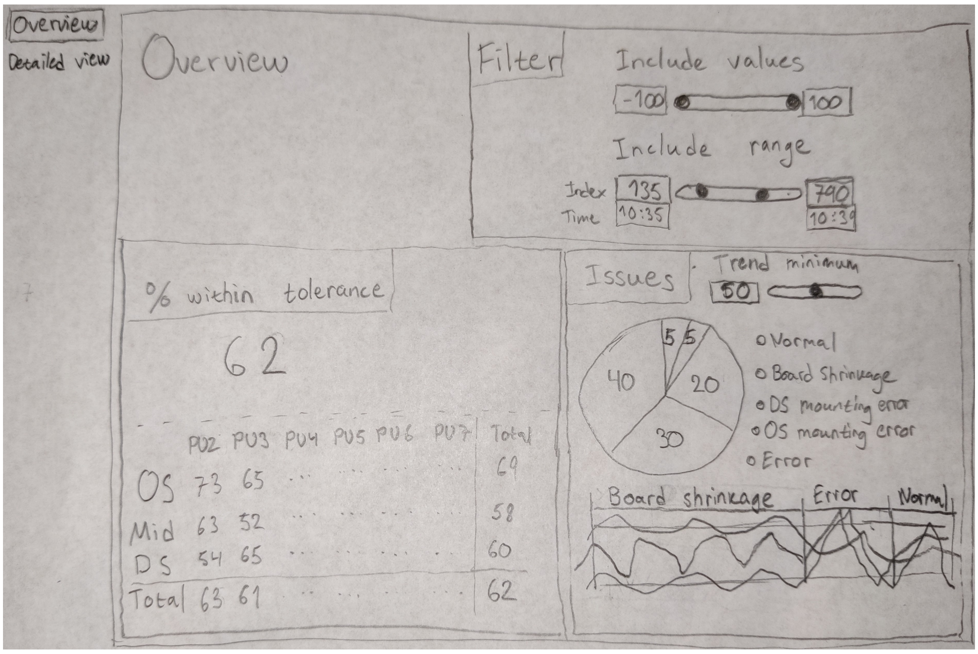


Figure 4.7: The *Overview* page of the Low-fidelity prototype.

The low-fidelity prototype was discussed with the product owner and a decision was made to extend the *% within tolerance* module of the *Overview* page with separate measures of tolerance based on x-coordinate, y-coordinate, and max distance for each print unit. The filter function in the *issues* module was decided to be removed and replaced with a fixed value of 100 to calculate an average register deviation directly in the Sympathy for Data workflow.

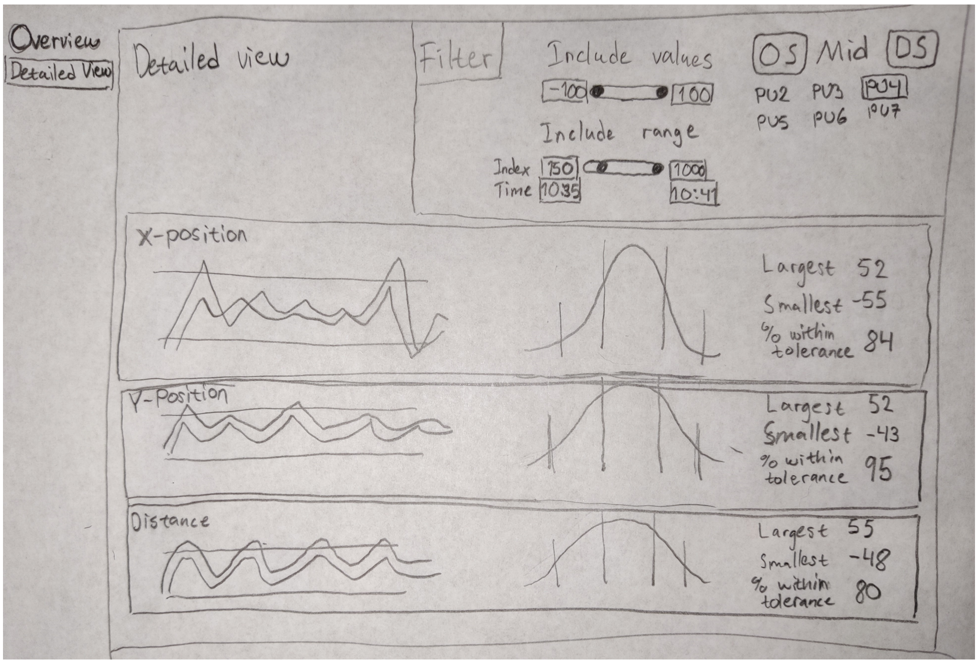


Figure 4.8: The *Detailed View* page of the low-fidelity prototype.

4.5.2 Workflow in Sympathy for data

The first step in the implementation of the R2-DiToo data visualization was to create a new workflow in Sympathy for Data to process the raw sensor data from the inline cameras (see Figure 4.9). The workflow calculated the distance between each print unit as well as the average of the x-coordinate, y-coordinate, and max distance to the remaining print units. The average was based on each 100 data rows where each row represents one print repeat. One print repeat is one rotation of the print plate, as described in section 3.2.5. Each print plate typically contains the design imprint of several packages, as the length of the plate is a few times larger than the length of a typical package design.

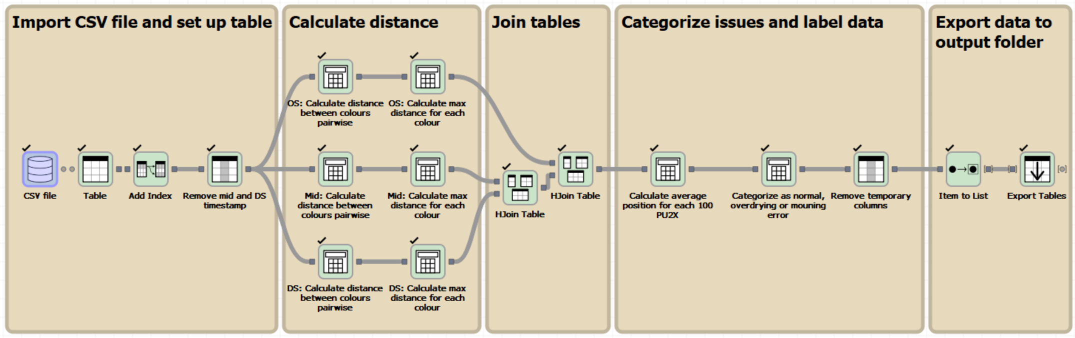


Figure 4.9: The workflow in Sympathy for Data.

4.5.3 Partly implemented prototype

The initial idea for the *Design solution* phase was to create a high-fidelity prototype based on the feedback and discussion with the product owner regarding the low-fidelity prototype. However, when further exploring the capability of Power BI a lot of previously unknown functionalities and visualization tools were discovered that could potentially improve the user experience. A decision was made to not create a high-fidelity prototype and instead directly create a partly implemented prototype in Power BI and to further explore the feasibility of the various visualization tools in Power BI. The decision was based on the perception that a high-fidelity prototype might be limiting to the exploration of new ideas within Power BI. Extensive work would already have been conducted towards a certain design direction without properly assessing the possibilities of the platform, ultimately resulting in a limited user experience.

The partly implemented prototype consisted of a pie chart showing the distribution of print issues and an associated scatter plot showing the underlying data (see Figure 4.10).

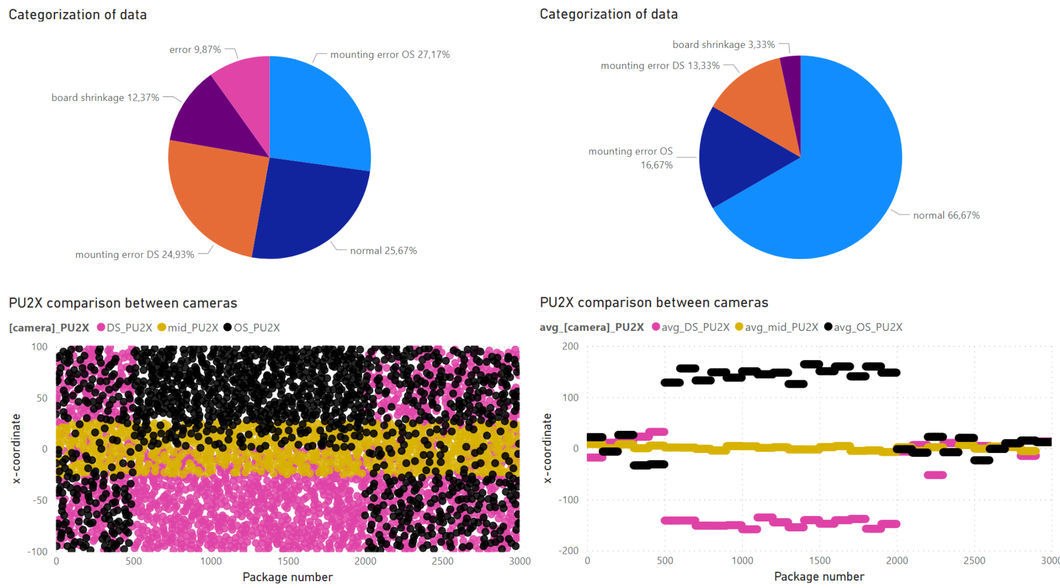


Figure 4.10: The data categorization of the partly implemented prototype. Visualizations of single sensor values are presented on the left side and the average of each 100 rows of data are presented on the right side.

The design featured two separate pie charts and scatter plots. The one on the left is based on single sensor values and the one on the right is based on the average of each 100 rows of data. The pie chart and scatter plot was largely based on the low-fidelity prototype. However, the party implemented prototype also featured the capability to focus on data for a specific print issue. By pressing on one of the slices in the pie chart the scatter plot was updated accordingly to only show the data belonging to that category. In Figure 4.11 the issue category *mounting error OS* has been selected, representing a mounting error on the operator side of the printing press.

The scatter plots showed that the high density of the data makes it difficult to observe data trends. Even with high contrast colors the data is hard to visually separate as the values stack on top of each other. The average data was easier to observe, however by averaging groups of data it matters to some extend at what position along the x-axis each grouping begins. For example, grouping each 100 starting from index 0 or index 10 might change how the data is categorized as well as how the graph appears. However, at full print speed of 600 meter per second 100 rows of data is just a few seconds of printing. Therefore this simplification will not have a major impact on the result of the data analysis. Nevertheless, to further improve the statistical reliability of the data simplification, a second measurement was featured in the partly implemented prototype. In Figure 4.12 three different line charts are featured showing the x-coordinate, y-coordinate, and max distance as a simple moving average of 100 rows of data. The simple moving average calculates the average of each index based on the following 100 rows of data. This levels out the data and makes it easier for the user to visually distinguish the different data sets from each other. On the left side of the line charts the specification compliance is presented for the x-coordinate, y-coordinate, and max distance for each of the three

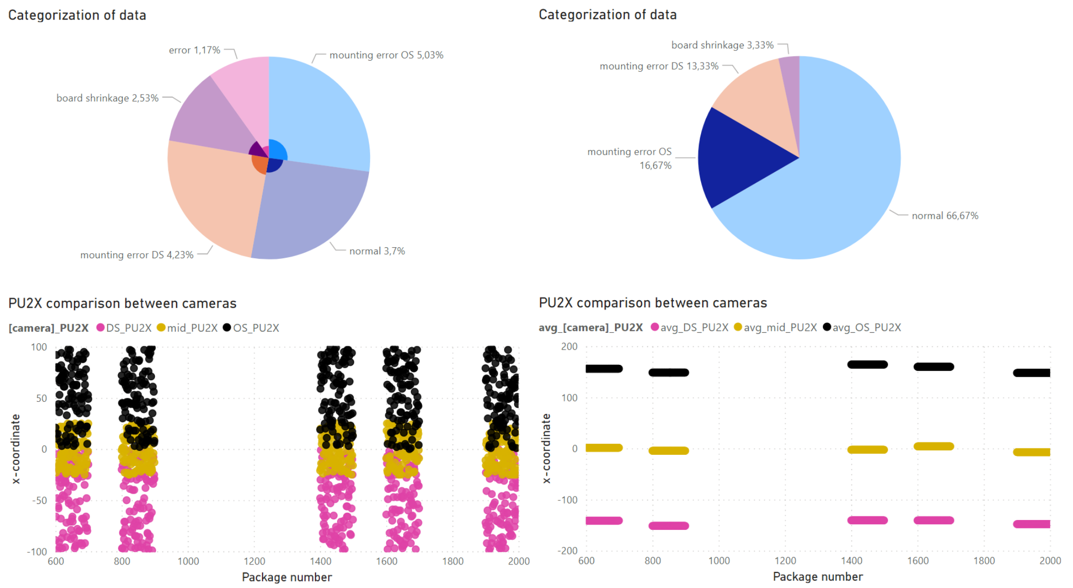
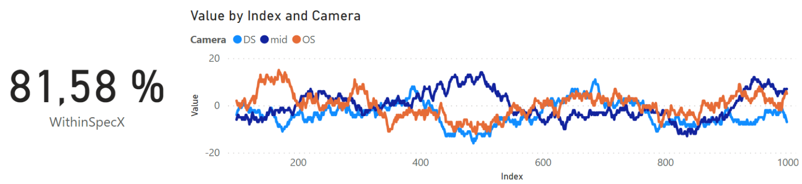


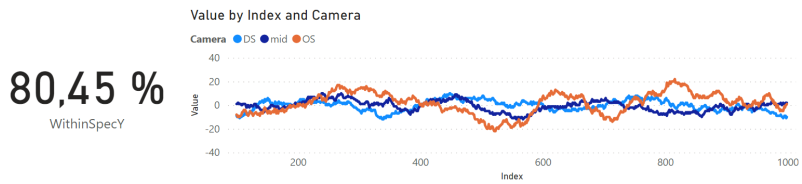
Figure 4.11: The data categorization of the partly implemented prototype with *mounting error OS* selected. Visualizations of single sensor values are presented on the left side and the average of each 100 rows of data are presented on the right side.

cameras, DS, mid, OS, as well as for each print unit. The specification compliance is based on the unofficial print quality specification of Tetra Pak.

Print Unit	DS	mid	OS	Total
PU2	81,60 %	81,70 %	82,30 %	**81,87 %**
PU3	81,90 %	80,90 %	82,00 %	**81,60 %**
PU4	82,90 %	78,80 %	81,70 %	**81,13 %**
PU5	81,70 %	81,90 %	80,50 %	**81,37 %**
PU6	81,90 %	80,70 %	82,70 %	**81,77 %**
PU7	81,60 %	80,90 %	82,70 %	**81,73 %**
Total	**81,93 %**	**80,82 %**	**81,98 %**	**81,58 %**



Print Unit	DS	mid	OS	Total
PU2	81,00 %	81,90 %	81,10 %	**81,33 %**
PU3	78,60 %	80,90 %	80,70 %	**80,07 %**
PU4	79,70 %	79,20 %	81,10 %	**80,00 %**
PU5	78,50 %	79,50 %	82,20 %	**80,07 %**
PU6	80,70 %	80,40 %	78,90 %	**80,00 %**
PU7	81,00 %	80,70 %	82,00 %	**81,23 %**
Total	**79,92 %**	**80,43 %**	**81,00 %**	**80,45 %**



Print Unit	DS	mid	OS	Total
PU2	75,20 %	74,70 %	77,40 %	**75,77 %**
PU3	75,20 %	74,40 %	76,00 %	**75,20 %**
PU4	77,50 %	74,00 %	75,80 %	**75,77 %**
PU5	76,10 %	73,20 %	77,80 %	**75,70 %**
PU6	76,40 %	74,60 %	74,90 %	**75,30 %**
PU7	76,60 %	74,60 %	74,90 %	**75,37 %**
Total	**76,17 %**	**74,25 %**	**76,13 %**	**75,52 %**

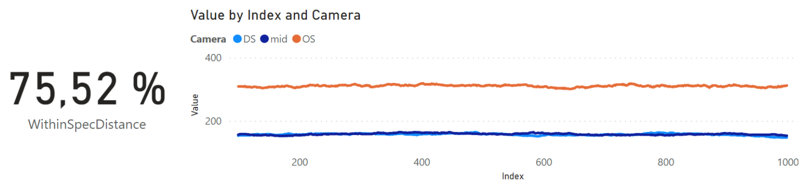


Figure 4.12: The specification compliance and line chart with simple moving average of the partly implemented prototype.

4.5.4 Fully functional prototype

Based on discussions regarding the partially implemented prototype, the prototype was further implemented to support filtering of data and additional visualizations to aid the user in understanding the connections between different data sets and trends in the underlying data. In order to support the visualizations and data filtering the processed data needed to be extensively restructured in Power BI. A decision was made to replicate the workflow from Sympathy for Data directly in Power BI to improve data management, since the data would need to be restructured in Power BI either way to be compatible with the data filtering and visualizations. Power BI is mainly focuses on business intelligence and the relationship between different data sets such as sales data across different stores, product categories, regions and so on. The sensor data for R2-DiToo is essentially an index list of one object type, the printed package repeat, containing a list of sensor variables. The natural structure of the sensor data therefore lacks compatibility with the built in functionality of Power BI. Compatibility was created by restructuring the data in a hierarchical order based on index and timestamp, camera position, and print unit.

By transferring the data processing to Power BI the user would not need to open the Sympathy for Data application and execute the workflow. Instead the user would be able to directly process and load new data in the Power BI UI by refreshing the data. This simplification improved the user experience and reduced the risk of human error that could previously occur. For example, the user forgetting to execute the workflow or misnaming the input file in the workflow. However, when the required process steps had been added, supporting the full functionality of the UI, the data processing in Power BI was substantially slower than the previous implementation in Sympathy for Data. Therefore the querying of data needed to be optimized for speed. This was done by testing different configurations of data buffering and reducing the number of operations in the data processing. The optimized data processing was still significantly slower than the Sympathy for Data workflow. The difference was especially noticeable for large data sets. For example, when conducting testing of an entire roll of substrate which is approximately 7000 meter long. However, for smaller sets of data the Power BI process could potentially be faster since the time it took to load the Sympathy for Data application had a relatively large impact on the total process time.

The *Overview* page of the fully functional prototype is presented in Figure 4.13 and Figure 4.14. The overview featured two alternative visualizations of specification compliance. The user could toggle between a matrix grid and a radar chart by pressing the buttons in the lower left corner.

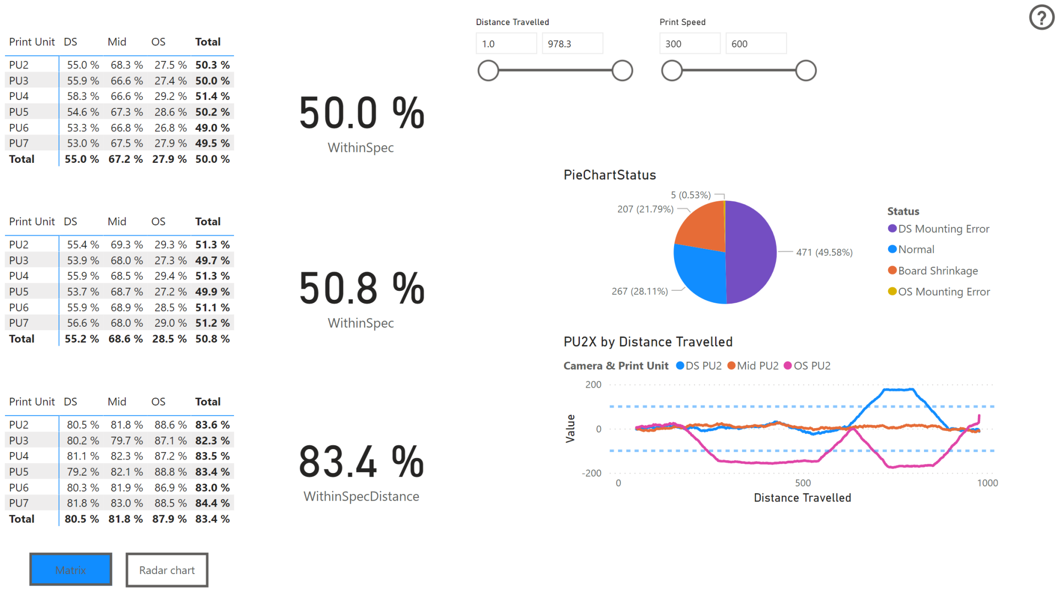


Figure 4.13: The *Overview* page of the fully functional prototype with *Matrix* selected.

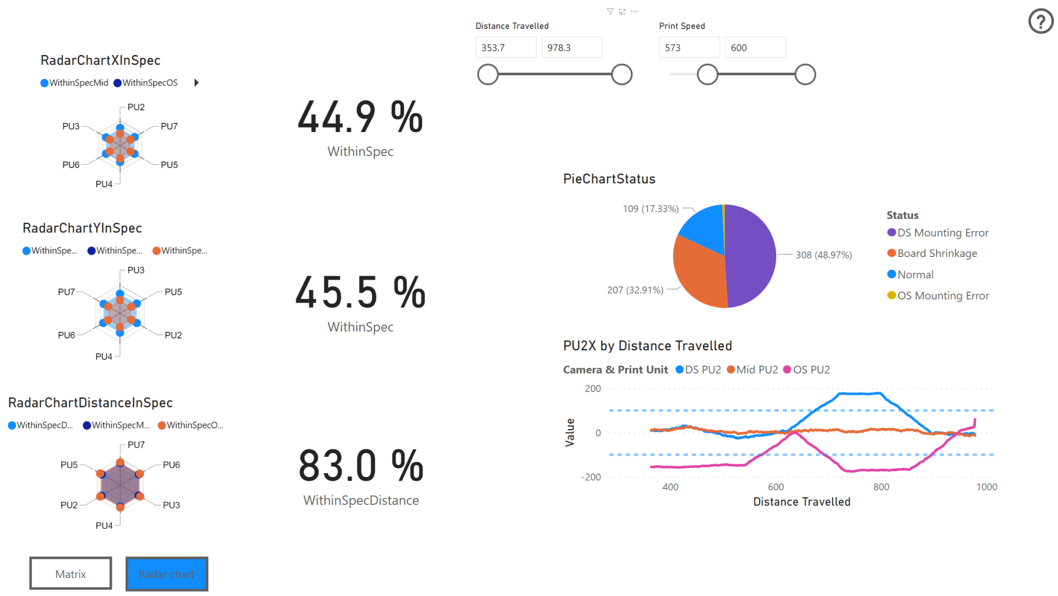


Figure 4.14: The *Overview* page of the fully functional prototype with *Radar* selected.

The *Detailed View* page of the fully functional prototype is presented in Figure 4.15. This page also featured buttons to toggle between two views. By selecting one of the two buttons on the bottom of the page the user could toggle between displaying the data in the line chart as either single value or based on a central moving average of the previous 50 values and following 50 values for each row.

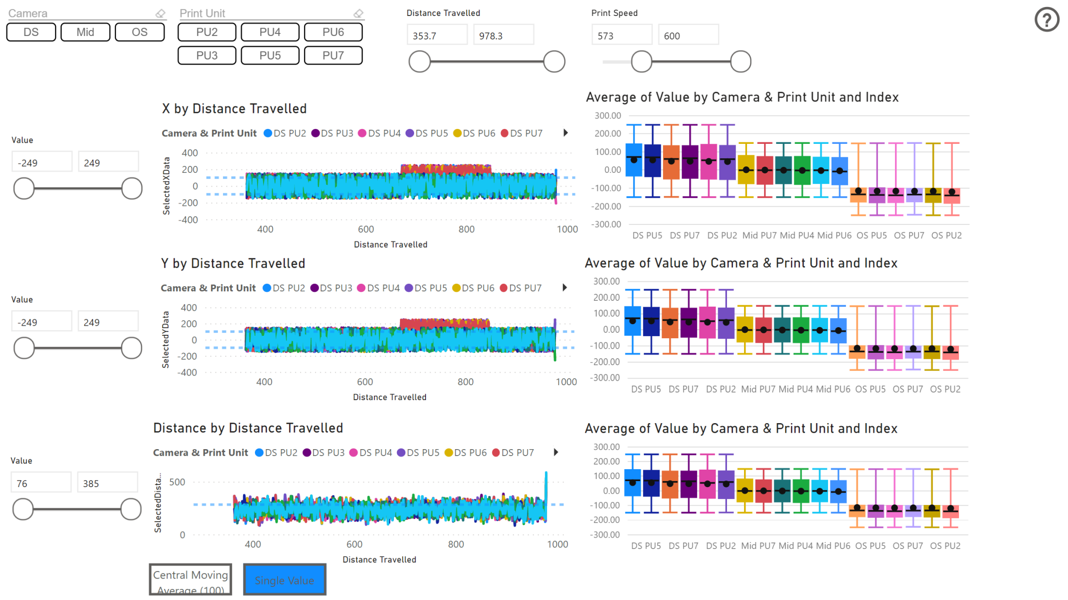


Figure 4.15: The *Detailed View* page of the fully functional prototype.

The prototype also featured a global filter menu that filtered data on both pages of the UI (see Figure 4.16). By dragging the slicers or entering new values in the input boxes, the user would be able to filter the sensor data to show a specific interval of the measured distance as well as sensor data at a certain print speed. On the *Detailed View* page the global filter menu also contained a filter to select which of the three camera and which of the six print units, PU2 to PU7, to include in the visualizations.

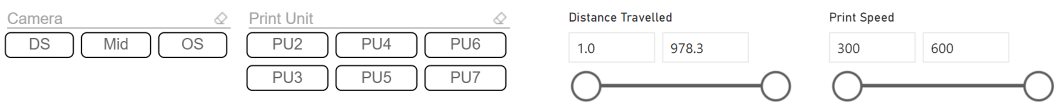


Figure 4.16: The global filtering menu of the fully functional prototype.

4.5.5 Completing the prototype

The fully functional prototype featured all the essential visual elements of the final prototype. However, the placement, coloring, and sizing needed to be improved in order for the prototype to be completed and ready for final user evaluation. In Figure 4.17 and Figure 4.18 the *Overview* page and *Detailed View* page of the complete prototype is presented.

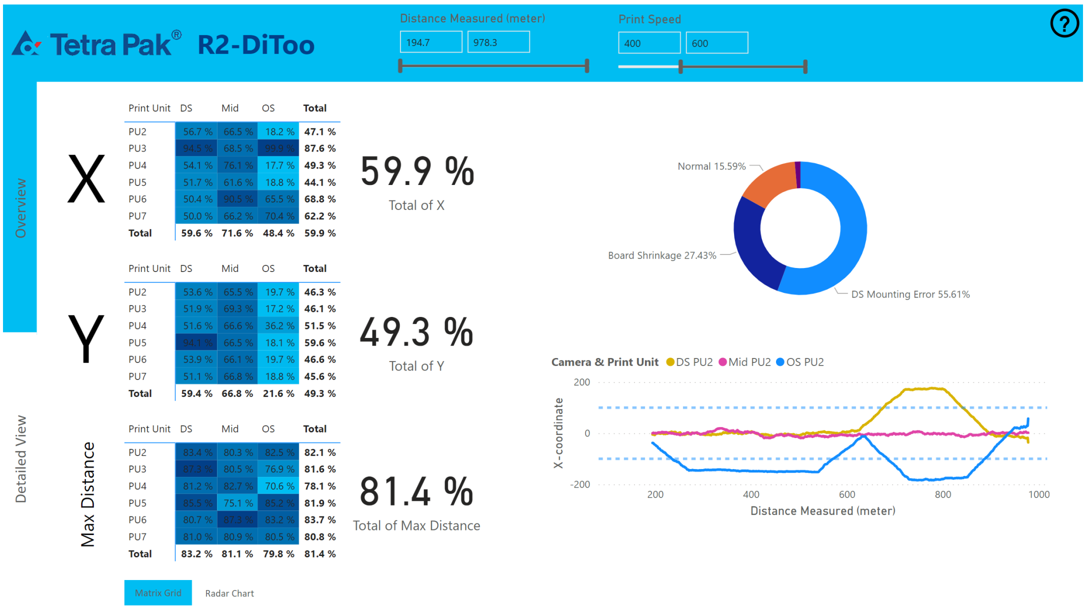


Figure 4.17: The *Overview* page of the complete prototype.

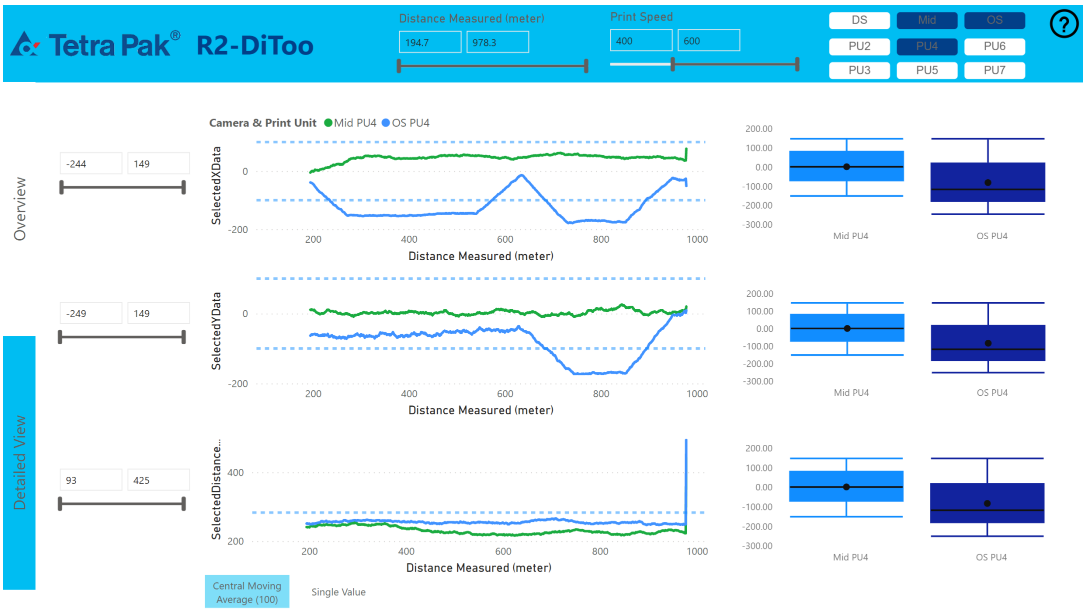


Figure 4.18: The *Detailed View* page of the complete prototype.

4.6 Phase 4: Evaluate

The forth and final phase of the design process was focused on the evaluation of the complete prototype. The evaluation consisted of exploratory user testing as well as measurement of the data process time to assess the usability and capability of the R2-DiToo prototype. Based on the results of the evaluation final changes to the UI and data processing were implemented. The final prototype of the thesis project is presented in chapter 5.

4.6.1 Exploratory testing

Structure

The exploratory user testing was conducted together with a development engineer and the product owner. The development engineer had not previously been introduced to the development of the prototype and could therefore provide a new perspective on the design. The testing was divided into two sessions, the first one completed by the development engineer as the test subject, followed by the second session completed by the product owner a few days later. The product owner was part of the first session as an observer and took part in the discussions with the test subject regarding the usability of the prototype. Since the product owner was the second test subject, a decision was made to implement improvements to the prototype based on the first session in order to not rediscover the same problems during the second session.

User scenario and tasks

The usability testing was based on the following user scenario:

> "*A new print unit has been developed and installed as print unit four (PU4) in the printing press. A test run was conducted and the data from the R2-DiToo system was analysed in the Power BI UI. There were some issues with the print quality at full production speed and improvements where therefore made to the configuration of the print unit based on the result of the analysis. A second test run has just been conducted and the data from the test run has been processed and is currently loaded in the Power BI UI. Your objective is too analyse data from PU4 based on a given set of tasks to determine the current print capability.*"

The test subject was given the following set of tasks to complete using the R2-DiToo prototype:

1. Filter the visualizations to only display data at full production speed of 600 meter per minute.

2. Examine the specification compliance for the x-coordinate of PU4. Determine the highest and lowest specification compliance between the three webs.

3. You want to examine the underlying data in more detail. Navigate to the *Detailed View* page.

4. Filter the visualizations to only display PU4 for the three different cameras: DS, Mid, and OS.

5. Examine the correlation between the selected graphs.

6. Determine the average, minimum, and maximum value of the x-coordinate for PU4.

Before introducing the user scenario the test subject was given some time to explore the UI of the prototype. In a real life situation an engineer new to R2-DiToo would be provided with sufficient training before using the diagnostic tool. The idea was therefore to establish a certain level of experience with the UI before moving on to the user scenario. Potential questions regarding the various visuals and interactive elements of UI were addressed. During the completion of the user scenario tasks the test subject was encouraged to express thoughts and ideas aloud in accordance with the think aloud method, as described in section 2.9.1.

Post test interview

After the final test session with the product owner, an interview was conducted with open ended questions based on the SUS questionnaire (see section 2.9.2):

1. Did you find the UI to be unnecessarily complex?

2. Did you find the UI to be easy to use?

3. Did you find the various functions of the UI to be well integrated?

4. Did you think that there was too much inconsistency in the UI?

5. Would you imagine that most users would learn to use the UI very quickly?

6. Did you find the UI to be very cumbersome to use?

7. Did you feel confident using the UI?

8. Did you need to learn a lot of things before you could get going with the UI?

SUS is a relative measurement of usability and since R2-DiToo is a completely new system there is no previous system or solution to compare with, which is why the assessment tool could not be directly applied to measure the usability in a meaningful way.

Findings

The main usability issues discovered during the user testing was the lack of information describing the different visualizations. Even though the user will be provided sufficient training before using the diagnostic tool, there should be more information to help remind the user of the less apparent aspects of the visualisation if needed. The test subjects stated that it is better to explain excessively rather than risking the user misunderstanding or not being able to use the full capability of the tool, resulting in poor analysis.

The radar chart proved difficult to understand for both test subjects and did not provide much additional value compared to the matrix grid. Potential replacement visualizations, proving a more meaningful addition to the matrix grid, were discussed. For example, a histogram showing the distribution of the sensor data. Additional future features for the UI were also discussed. For example, the ability to test different specification tolerances in order to assess the extend to which a customer can be guaranteed a certain print quality. A button to export specific processed data to excel was also discussed as a potential improvement.

The flow and positioning of the various visualizations was considered highly intuitive and made it easy for the test subjects to understand how to interact with the UI in order to complete the different tasks of the user scenario. However, contrasts between colors could be further improved and the sizing of certain text elements could be increased for improved readability. During the usability testing it was also discovered that the coloring of data sets did not match between the line chart and box plot in the *Detailed View* page when filtering to display certain cameras and print units.

4.6.2 Data process time

As part of the prototype evaluation the process time for a small data sample, approximately 1000 meters, and a large data sample, approximately 7000 meters, were measured. The process time had previously been measured during the speed optimization of the workflow. The process time for a small sample was previously measured at approximately 1 minute 30 seconds and for the large sample approximately 15 minutes. However, during the final evaluation the process time, with similar number of calculations and visual elements, the small sample required almost 4 minutes to finish loading and the large sample had yet to finish loading after more than 1 hour. This meant that the data processing in Power BI was very unreliable in terms of execution time and unreasonably slow for large data samples. In order to maintain the workflow when implementing additional calculations and visualisations one would need to know not only how to optimize for speed, but also how to detect and manage issues and bugs in the Power BI platform causing sudden increases in processing time and complexity.

Chapter 5

Final prototype

This chapter presents the final prototype of R2-DiToo with the final improvements implemented based on the result of the prototype evaluation.

5.1 Data processing

Based on the evaluation of the data process time, a decision was made to further develop the workflow in Sympathy for Data in order to replace the data processing in Power BI. The process time was measured from execution of the new workflow in Sympathy for Data until the processed data had been loaded in Power BI and the visualizations of the UI updated. The total time for the large sample was approximately five and a half minutes. The new workflow is presented in Figure 5.1.

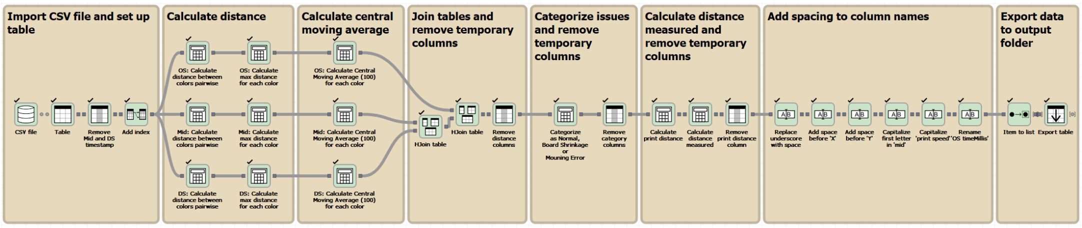


Figure 5.1: The final workflow in Sympathy for Data.

5.2 User interface

The main changes implemented in the final version of the UI are the improved contrast between colors and the implementation of instructions that can be toggled on and off to minimize clutter in the limited space of the screen, while still providing the user with further instructions when needed (see Figure 5.2 and Figure 5.3). However, the instructions have not been fully implemented for all pages.
Furthermore, The radar chart has been replaced with a histogram showing the distribution of sensor values (see Figure 5.4).

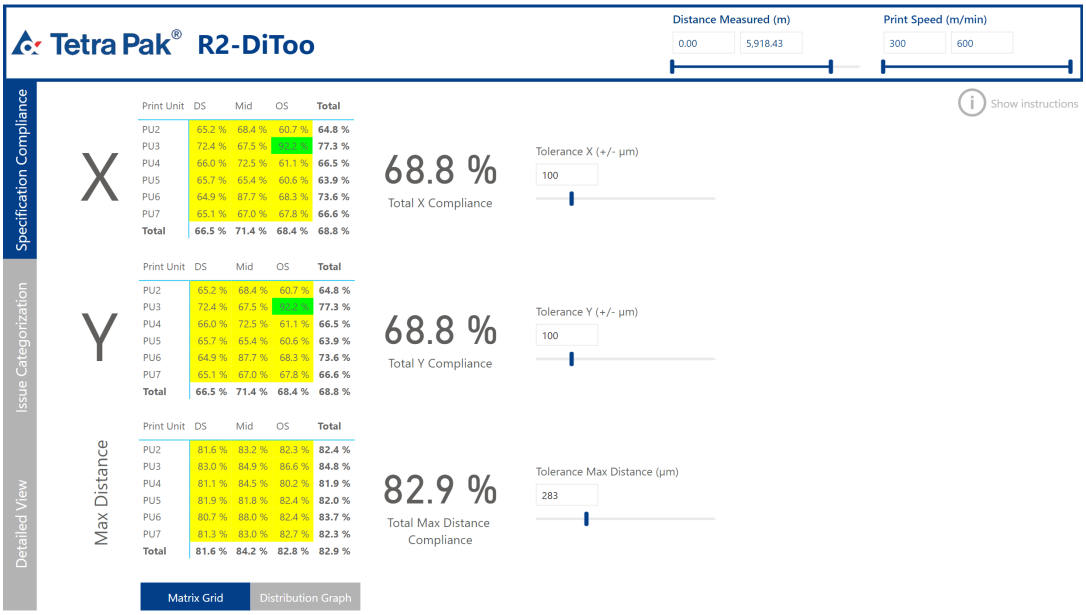


Figure 5.2: The *Specification Compliance* page of the final prototype with *Matrix Grid* selected.

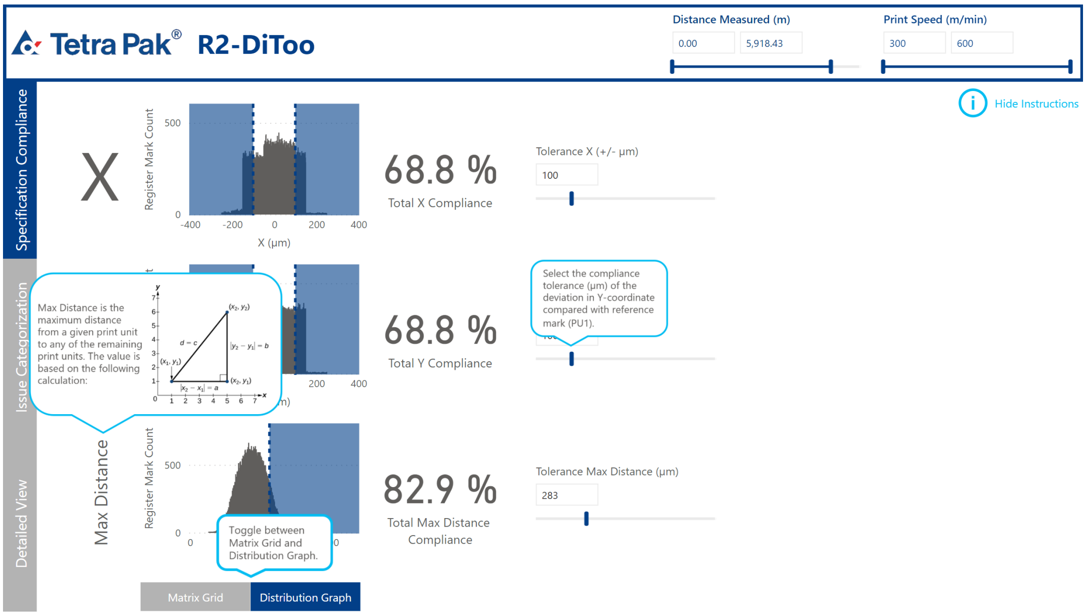


Figure 5.3: The *Overview* page of the final prototype with instructions enabled.

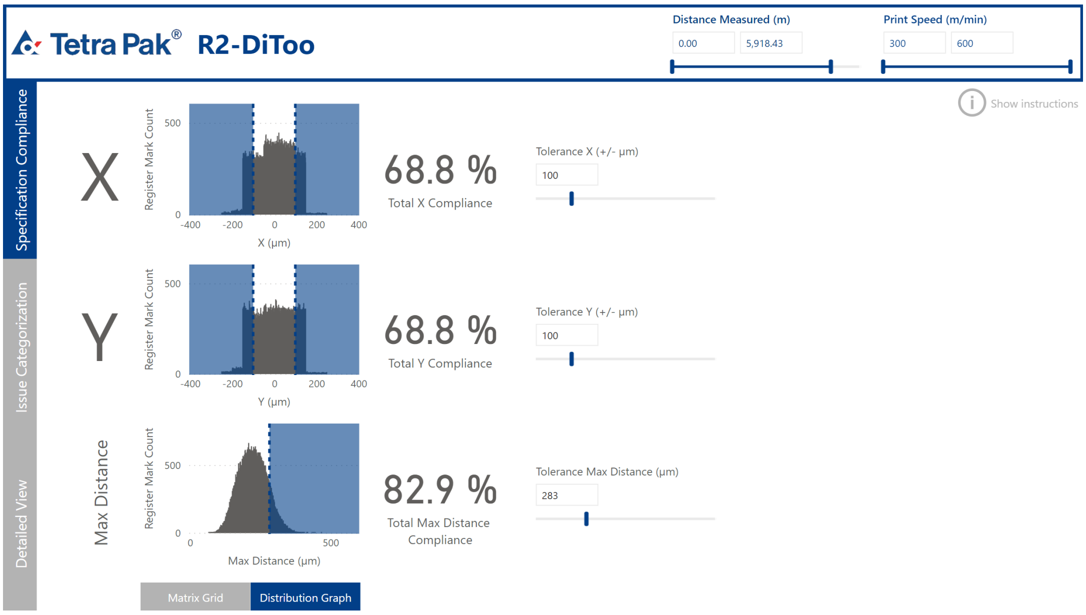


Figure 5.4: The *Specification Compliance* page of the final prototype with *Distribution Graph* selected.

The last major change in the UI is the separation of the *Overview* page into two separate pages: *Specification Compliance* and *Issue Categorization* (see Figure 5.5). These two unrelated parts of the UI caused some initial confusion for the test subjects during the usability testing because of their positioning, side by side, in the previous prototype.

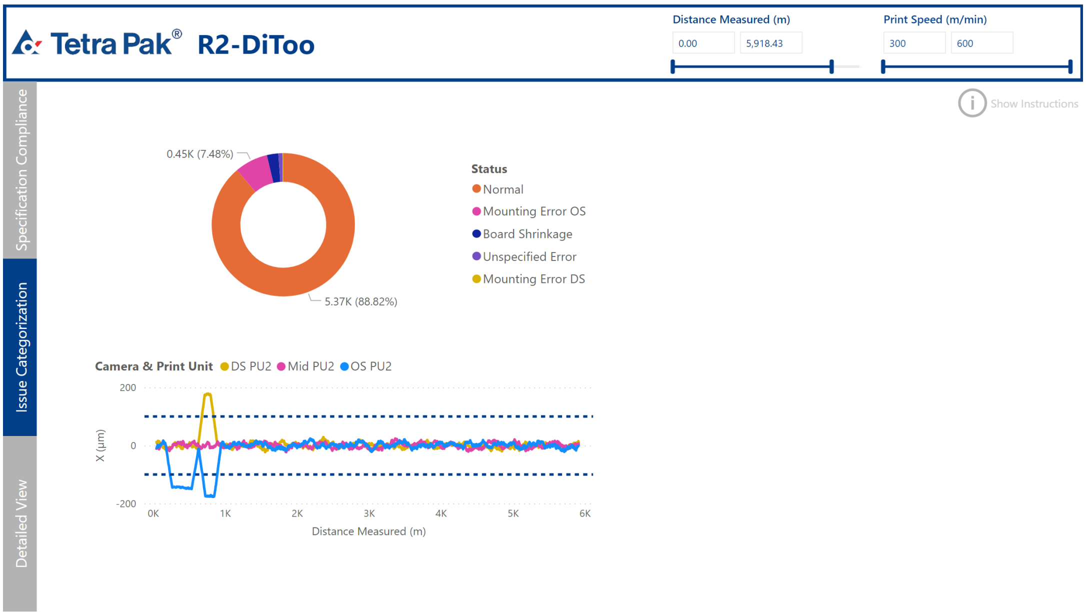


Figure 5.5: The *Issue Categorization* page of the final prototype.

The *Detailed View* page also contains minor visual design updates, such as increased text size for the tool tip. The tool tip appears when the user hover the mouse cursor over a specific data point in a visualization, showing additional information about the selected data point. The color coding for the box plot was also removed to avoid potential confusion caused by the asynchronous coloring of data sets between the line chart and box plot (see Figure 5.6 and 5.7). Furthermore, two built in options of the Power BI platform was added. When the user hover the mouse cursor over a visualization a menu is displayed in the top right corner. In the menu the user can select to export the filtered data to excel, as well as expanding the selected visual to cover the entire view of the UI to have a closer view.

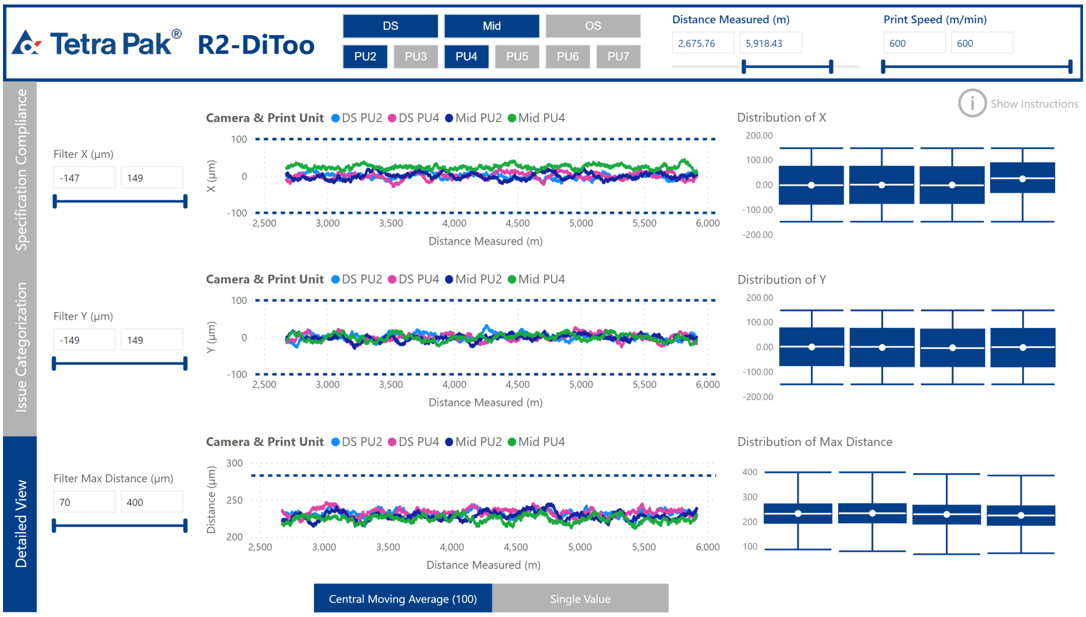


Figure 5.6: The *Detailed View* page of the final prototype.

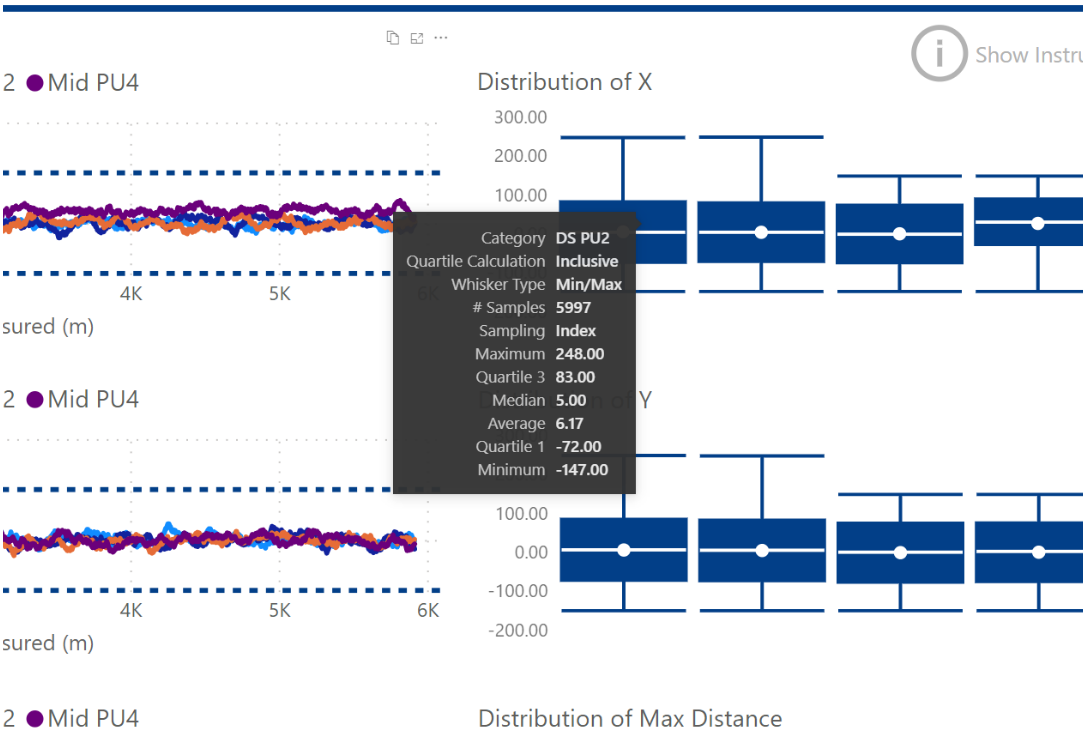


Figure 5.7: The *Detailed View* page with tooltip showing for the distribution of X.

Chapter 6

Discussion

This chapter presents reflection of the project work process and future work related to the development of R2-DiToo.

6.1 Reflection of the work process

The greatest challenges of the project was to find a good balance between the design focus and establishing a sufficient understanding of the technical background. The literature study, covering design theory and the principles of print technology, required a substantial part of the total project time. This effort could potentially have been reduced in favor of the design process, allowing for more iterations and further usability testing, given the limited time frame. However, the technical nature of the project required a certain level of knowledge within the field of printing in order to properly understand the problem to be solved and how to solve it. Balancing the time and resources between the various parts of the project would have been easier if the project was conducted by a team of two engineering students, as recommended by the faculty. This would have allowed for continuous discussion to better optimize the prioritization of tasks and interim targets of the design process. Without continuous team discussion it is difficult to distinguish requirements between must-haves and nice-to-haves.

6.2 Future work

The R2-DiToo prototype serves as a proof of concept for the capability and usability of the system. It is fully working and ready to be tested during a real test run. However, the physical camera equipment have not yet been installed in a printing press. Once the equipment has been installed the R2-DiToo prototype will need to be properly tested with actual data from the cameras to verify the capability of the diagnostic tool. With more testing of the tool and further development the features could be extended to improve the usability. So far usability testing has only been conducted with development engineers. It is therefore important to conduct future testing with process engineers as well since they represent one of the two main user groups of R2-DiToo. Furthermore, the issue categorization should be further developed. In the current prototype the issue categorization is only based on one print unit, PU2, and only based on the x-coordinate. By extending the algorithm with all print units and the y-coordinate more types of print issues could be categorized and the categorization would be more reliable. Additional variables related to print quality, such as substrate and drying temperature, could also be featured in future implementations for improved analysis.

Chapter 7

Conclusion

This chapter presents answers to the research questions in section 1.4 based on the work conducted during the course of the project and the result of the design process.

7.1 Besides color-to-color register data, what other sensor data can be useful for the purposes of R2-DiToo?

There are many print variables that affect color-to-color alignment. For example, substrate material, temperature of the dryers, web tension, and vibration in the system. These variables could be useful to integrate together with the color-to-color register data for improved issue categorization and capability determination.

7.2 On what software platforms and tools should R2-DiToo be developed?

Power BI proved to be a useful platform for the visualization of data and raw sensor data can be directly processed within the platform. However, Sympathy for Data is far superior in terms of processing speed and is therefore the preferable choice for the R2-DiToo data processing.

7.3 How should data be added and managed in the system?

Loading of data into the Power BI UI can be executed efficiently by reading the output file from the Sympathy for Data workflow and configuring it within Power BI to suit the visualizations of the UI. A new test file is executed in Sympathy for data, followed by the user refreshing the visualizations in Power BI by pressing the refresh button found in the header menu to load the latest processed data.

7.4 How and to what extent should R2-DiToo be integrated with existing systems?

Since the diagnostic tool will feature a dedicated laptop, all data management can be conducted offline and files can be stored on the computer's hard drive. The system will not need to be integrated with any existing systems related to the printing press. The system will simply receive a text file containing raw sensor that the user saves to a specific input folder, ready to be processed in Sympathy for Data. The input data could however be extended in the future with data from various sensors on the printing press. This data would be fetched from CDAS and added to the input file together with the data from the sensor cameras.

7.5 What features are most important for the usability of R2-DiToo?

The purpose of the diagnostic tool is to categorize issues and enable capability determination of the printing press. The most important features are therefore the issue categorization, which will need to be further extended to better fulfill the purpose, as well as the visual representation of data from the different print units, together with measurements of the specification compliance.

7.6 How good is the usability of the final prototype?

Based on the exploratory testing conducted in the evaluation phase, the final prototype has a high level of usability. The UI is easy to navigate and the user interaction has an intuitive flow. The processing time was improved substantially for the final prototype and is now fast enough to process the largest plausible input data in a few minutes. This is faster than necessary and leaves room for further implementation with limited risk of slow process time impacting the usability. The issue categorization is currently highly simplified and needs to be further developed in order to properly support the analytical work conducted by the user.

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Appendix A

Interview with process manager of Vietnam factory

A.1 Introduction script

"*R2-DiToo is a mobile diagnostic tool for investigating register behavior. The diagnostic tool uses 3 separate inline sensors enabling the measuring of distance between all register marks on three different webs simultaneously. The purpose of this interview is to gain further understanding as to how print issues are investigated and detected today to better understand what features are important for the diagnostic tool.*"

A.2 Questions

1. What was your role at the Vietnam factory?
2. How often is there a need to further investigate the print quality?
3. Are there any differences in the way operators and engineers conduct quality assurance, specifically regarding register control, in Vietnam compared to other factories? Does it differ in any way between different factories?
4. How do you conduct further investigation of print issues today?
5. What are the greatest pain points with the current way of conducting print issue investigation?
6. How could the work process be improved?
7. Are there any additional related aspects which you think might be of value to the design of the diagnostic tool?