Bachelor assignment: Dashboard on lead times

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Preface

Dear reader,

First, thank you for reading my thesis. It is my honor. I have been working on it for a few months, starting in February 2023, to graduate from the bachelor Industrial Engineering and Management. It has been quite a challenge to do such a project on my own for the first time, but it is fulfilling now it is finished. It was a valuable experience to bring some knowledge and skills into practice. Additionally, I have gained some more skills through this project in programming, working with a large dataset, and conducting research. This experience will be of great value in the future.

Second, I would like to thank the people from Company X for giving me this opportunity and supporting me through the process. It has been a great experience to work with a real, large dataset and to work in a professional environment like this. A special thanks to Supervisor X, the external supervisor of this research, for thinking along with me when I was stuck and for all the other support. Furthermore, I would like to thank the two other managers I got to interview and demonstrate the dashboard to. Lastly, I would like to thank an employee that explained me a lot about the process and the track-and-trace system.

Third, I would like to thank the first and second supervisor. There have been two people that have been the first supervisor as I switched halfway. Gayane Sedrakyan, thank you for your all ideas and feedback through the first part of the research. Daniel Braun, thank you for the new energy and essential support right after the switch from supervisor, and for making it possible to still complete this research in time. Sebastian Rachuba, thank you for being enthusiastic about my research since the poster market and the feedback.

Finally, I would like to thank my family and friends for being there for me, and for the distraction when I needed it. A special thanks to Camiel, Yur, and Josefien, who were my buddies through the entire process, and to Jip, who all made the whole period easier and a lot more fun.

Due to confidentiality issues, some pictures are blurred, some parts are censored, the lead times are multiplied with a random factor, and the company name, employees' names, and process names are anonymized.

Enjoy reading!

Kindest regards,

Iris te Koppele

July 2023

Management summary

Introduction

This part is removed due to confidentiality issues, but it is important to know that Company X is a laboratory.*

Every day, it receives a high number of samples that need to go through several steps to get results. It takes a certain lead time for the samples to move through the process to get the results and decision support to the farmers.

Company X struggles with the problem that they often find samples waiting in the process. As a result, the lead time is higher than they target. However, they do not know specifically what the causes are for the samples waiting in between the steps, thus what the bottlenecks are. Therefore, the following main research question is set up: *"How can a performance measurement system assist Company X in gaining insight to trace bottlenecks?"*

KPI selection

A systematic literature review is conducted to identify KPIs that describe the production process. From these KPIs, the ones that were most suitable for this research and the company were selected. To determine the most relevant KPIs to the future users, interviews are conducted with three managers. Based on these interviews, four KPIs are finally selected to be implemented: lead time, value-added ratio, on-time-in-full, and average time per step.

Performance measurement system development

Based on theory, it is determined to create a dashboard and to visualize the lead time in a column chart, the on-time-in-full in a doughnut chart, the value-added ratio in a card, and the average time per step in a column chart. Additionally, brushing and filtering are used as visualization techniques. Finally, the raw data file is loaded into Excel, where several steps are performed to ensure the data is clean and ready as input for Power BI. This research focuses on the processes of three analysis methods: Process A, Process B, and Process C, as they are requested most often by customers. In Figure 1, an overview of the created dashboard is provided.

This figure is removed due to confidentiality issues.*

Figure 1: Overview dashboard

Evaluation

First, the dashboard's capability to detect bottlenecks is evaluated. Therefore, the utility of the four charts is analyzed. The lead time chart provides an overview of the total lead time for each analysis method. The value of the on-time-in-full chart is limited, as it consistently resulted in 0%. The value-added ratio chart indicates current performance and room for improvement. It can be derived from the average time per step chart in what phase of the process the bottlenecks are, by comparing the actual lead time with the benchmarks.

Second, the perceived usefulness and ease of use for future users are evaluated by demonstrating the dashboard to the future users and asking them to fill in an evaluation form. Overall, the perceived usefulness is rated highly, which is justified by the remarks resulting from the form. The respondents state that they expect to use the dashboard daily and that they believe the dashboard provides quick insights to identify bottlenecks and will ultimately increase customer satisfaction. However, they acknowledge the need for further improvement, particularly in using real-time data.

The perceived ease of use is rated averagely, based on the System Usability Scale. The respondents find the dashboard easily understandable with some explanation and they found the dashboard user-friendly, as the user is one click away from finding the answer. On the other hand, they believe further development is needed for the dashboard to be ready for use on the production floor.

Recommendations

To improve the process, the specific bottleneck should be traced by diving into the concerned departments and addressing them. It could be derived from the average time per step chart that there is a bottleneck in Process A for both DA and MS between the pipetting and the beginning of the verification. For DA and MS, the bottleneck in Process B occurs between the weigh-in and the pipetting, and for MS, another one occurs between the pipetting and the verification. Between the weigh-in and the pipetting, as well as between the analysis and the verification, is where the bottlenecks in Process C lie.

Additionally, several recommendations are provided to improve the dashboard:

- Display real-time data instead of historical data on the dashboard, to enable Company X to trace and address bottlenecks before it is too late, maintaining customer satisfaction.
- Include additional track-and-trace points at the beginning and end of the process, as well as within the existing timestamps that cover significant portions. Particularly, focus on adding timestamps within the steps currently identified as bottlenecks to pinpoint the exact points in the process where samples are delayed.
- It might be interesting to additionally examine the individual performance of employees. However, Company X should address confidentiality issues, seek informed consent from employees, and consider the potential resistance of employees.
- Use a histogram of the lead time outside of the timestamps instead of an average to estimate a more representative on-time-in-full percentage, as it is currently reported as 0% for each analysis method.
- The dashboard should be accessible in a user mode rather than an editor mode, allowing functions such as viewing history and extracting relevant information.

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Table 1 and 2 are removed due to confidentiality issues.

1. Introduction

This chapter introduces the company for which this research is conducted. Additionally, the problem statement and research aims are given, and the validity of this research is examined.

1.1. Company context analysis

To introduce the company and to analyze the environment in which Company X operates, a company context analysis is provided to give some insights into the market, financials, technologies, culture/society, and environment that affect Company X. Additionally, a SWOT analysis is performed.

This part is removed due to confidentiality issues.

1.2. Problem identification

1.2.1. Action problem

Company X struggles with the problem that they often find samples waiting in the production process of the analysis methods. As a result, the lead time is higher than they target. This is not the desired situation, as they want to deliver the results at the earliest possibility the system can process the data once it is made available. Otherwise, customers switch to competitors in this field with a faster process. This concludes in the action problem that Company X suffers from lead times that are not optimal.

1.2.2. Norm and reality

The action problem is translated into a measurable norm and reality, to concretize the research aims. In Table 3, the lead times are displayed from three processes that are investigated in this research. There has been decided on those specific processes as they are some of the most frequently demanded. The numbers in the table are given by the external supervisor in an informal context. They describe the total lead time of the entire process from receiving the sample to giving the customer their results. The abbreviations and how the processes of these analysis methods are conducted are elaborated on in section 2.4. The lead times that are targeted can be found in the second column, which correspond to the lead times in which the customers are promised to get their results. These targets are also considered as the norm of this research. Within this target, it *should* be easily feasible to complete the process, based on the durations of the actual proceedings. However, the average lead time over the last year in reality is given in the last column, which is higher for all processes.

Analysis method	**Norm in days**	**Reality in days**
Process 1 (Process A)	13	20.07
Process 2 (Process B)	1.1	4.44
Process 3 (Process C)	12.75	16.49

Table 1: Norm and reality lead times

1.2.3. Problem cluster

To define the core problem this thesis tackles, we trace back the causes of the action problem of experiencing high lead times by talking with a company representative. In Figure 2, the problem cluster is displayed, which is used to find the causal relationship between all the problems that relate to high lead times, especially the relation between the core problems and the action problems is of interest. The arrows go from cause to effect.

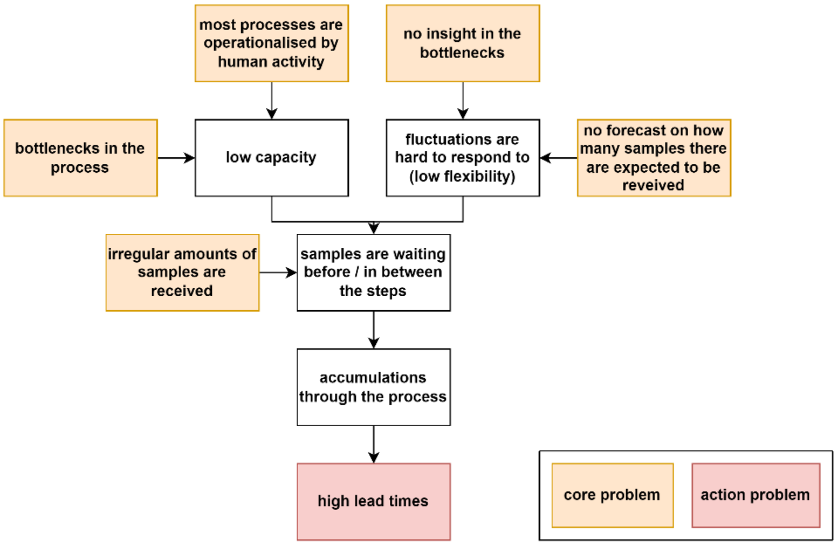


Figure 2: Problem cluster

As can be seen in the problem cluster, five core problems could be addressed to eventually tackle the action problem:

1. **Most processes are operationalized by human activity:** At this moment, a big part of the work is done manually. However, most manual tasks could be (partly) replaced by machines.
2. **Bottlenecks in the process:** Certain steps of the process take longer than other steps. The former are bottlenecks.
3. **No insight into the bottlenecks:** Company X does not know specifically what the causes are for the samples waiting in between the steps, thus what the bottlenecks are. As they do not know the bottlenecks they must consider, they do not know how to respond to fluctuations in demand. In other words, they have low flexibility, as they do not know how they should 'scale up' when the demand is suddenly high.
4. **Irregular amounts of samples are received:** Company X is already aware of the fact that there are fluctuations in demand. It looks like factors like the weather play a role, so the demand varies over the year.
5. **No forecast on how many samples are expected to be received:** There are some presumptions in factors that play a role in these fluctuations, but there is no actual forecast of how many samples are expected to be received. As a result, they cannot respond to the fluctuations in time.

1.2.4. Core problem

Company X is already working towards the solution for core problem 1 (most processes are operationalized by human activity), by automating some of their processes. Core problem 2 (bottlenecks in the process) can only be addressed after the specific bottlenecks are traced. Core problem 4 (irregular amounts of samples are received) is an external factor, as the demand cannot be controlled by Company X. Furthermore, the company is already working on creating a forecast to solve core problem 5 (no forecast on how many samples are expected to be received). This leaves us with one core problems that we can address:

"No insight into the bottlenecks."

This core problems can be influenced, is relevant, and contributes to the action problem.

1.3. Research aims

In this subsection, the research aims are determined, which will ultimately help to solve the core problem.

1.3.1. Main research question

To reduce the lead time at Company X, we aim to get insight into the bottlenecks in the process. To reach this goal, a performance measurement system is designed, including Key Performance Indicators (KPIs) that describe the production process of the analysis methods regarding the lead time to trace bottlenecks. Thus, the formulated research question that describes the aims of the research is:

"How can a performance measurement system assist Company X in gaining insight to trace bottlenecks?"

1.3.2. Theoretical perspective

The research aims to gain insight to trace bottlenecks at Company X. The theoretical perspective that fits best with these aims is the Theory of Constraints, which is a management philosophy that views improvement as a continuous process of improvement. The most important assumption of this philosophy is that the output of a process is determined by its constraints. (Sivasubramanian et al., 2003) The Theory of Constraints uses methodologies to identify and eliminate the constraints that withhold a system to improve (Stratton, 2000).

This theory fits with this research because in this research a methodology is used to identify the constraints. The methodology that is used is creating a performance measurement system out of historical data. The constraints refer to the bottlenecks. The elimination of the bottlenecks is out of the scope of this research. The system we are trying to improve consists out of the different analysis methods that Company X operationalizes.

1.3.3. Problem solving approach and sub questions

To guide the research, the Design Science Research Model (DSRM) is used, which is displayed in Figure 3. This model is chosen, because design science is about creating and evaluating IT artifacts intended to solve identified organizational problems, which is exactly what is done in this research with a performance measurement system. The DSRM Process Model provides a mental model for the characteristics of research outputs and illustrates the structure of the process. This process is structured in a nominally sequential order, which means that there is no expectation that researchers would always proceed in sequential order from phase 1 through phase 6 but may start at almost any step and move outward. In the lower box, several possible research entry points are provided. This illustrates that for a problem-centred approach, like this research, it is usual to start with the first phase. (Peffers, 2007)

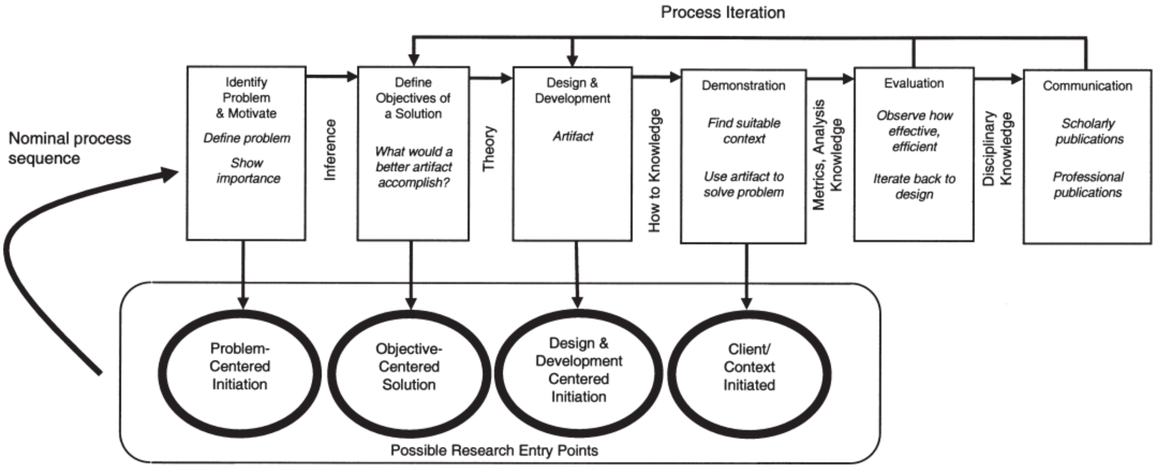


Figure 3: DSRM Process Model (Peffers, 2007)

As there is a limited timeframe, only the first iteration loop is executed in this research. All phases of the first loop of the DSRM, and the activities for each phase, are described below:

Phase 1: Identify the problem & motivate

The problem has already been identified and motivated before. The sections 1.2.1, 1.2.3, and 1.2.4 describe the definition and motivation of the problem.

Besides the identification and motivation of the problem, one research question is part of this phase:

1. *"How is the lead time defined and measured?"*

To answer this research question, we define where the different steps in the process begin and end, using a Business Process Model and Notation (BPMN). Besides, we explain how the lead time is measured, which is through track-and-trace. This means that there are timesteps created in a database when the samples are at certain points in the process.

Phase 2: Define the objectives of a solution

The objective of the solution is already defined, which is to give Company X insight to trace the bottlenecks. This eventually aims to reduce the lead time from the reality to the norm, which is described in section 1.2.2.

Phase 3: Design & development

This phase is the largest part of the research. Here, KPIs are defined, the benchmarks are defined, and the performance measurement system is designed and developed.

2. *"What KPIs describe the production process of the analysis methods?"*

Before the performance measurement system can be created, we need to know what KPIs would be appropriate to display on it. Therefore, a Systematic Literature Review (SLR) is used to get an overview of what KPIs are established in the literature that describe the production process, regarding lead time. After that, interviews with the managers, the future users of the performance measurement system, are conducted to find out what KPIs they think are relevant. In these interviews, relevant KPIs that are found in the literature are discussed, and there is room for them to add some of their ideas for KPIs. To ensure that the reporting of this qualitative interview is done explicitly and comprehensively, a checklist from Tong et al. (2007) is used. This article is studied during the interview preparation, and all relevant points of the check list are considered. Finally, the sub question is answered by merging the KPIs found in the literature and the KPIs the managers find relevant into one unique set of KPIs to be displayed in the performance measurement system.

3. *"What is an effective way to visualize the KPIs in the performance measurement system to give more insight to the users?"*

To answer this question, we need to find out how the KPIs could be displayed visually in an effective way. Relevant chart types are listed in a theoretical framework, based on which it is possible to choose which ones are most suitable for the selected KPIs. The choice of a chart type is based on the objective of the visualization. Besides, we dive into techniques that make visualizations more effective and easier to read for the intended users. To answer this question, a literature review is conducted. Furthermore, some benchmarks are defined that correspond to the theoretical minimum lead times and the maximum acceptable lead time, which are implemented into the performance measurement system.

After answering all these sub questions, we have the compound knowledge to design and develop the actual performance measurement system.

Phase 4: Demonstration
Once the performance measurement system is designed, it is demonstrated to the future users. All visuals and functionalities are explained and there is a possibility for the future users to reflect and bring up questions.

Phase 5: Evaluation
This phase consists of two parts. The performance measurement system is evaluated regarding the capability of tracing bottlenecks. Besides, it is evaluated by the future users by asking them to fill in a questionnaire.

For the evaluation phase, the final sub question is formulated:

4. *"Can the developed performance measurement system help to detect bottlenecks?"*

The performance measurement system is analyzed to see if bottlenecks can be identified. As explained earlier, the actual lead times and the benchmarks are the starting point to find the bottlenecks of the process. The delays of all the steps are compared and based on that, the steps with the most delay are found. The answer to this sub question could also be that we are not able to find the bottlenecks, thus that the performance measurement system does not help to detect bottlenecks.

For the part in which the future users evaluate the performance measurement system, future users are asked to fill in an evaluation form about the perceived usefulness and perceived ease of use to measure user acceptance (User Sense, 2021b). Elaboration on this evaluation can be found in section 1.4.1.

Phase 6: Communication
Finally, the performance measurement system and the recommendations are communicated to Company X. The recommendations include improvements for the production process and improvements for the performance measurement system, based on the findings of the first iteration loop of the DSRM.

1.3.4. Research design
Table 4 elaborates on the research design. The research is approached per sub question in the sense of the type of research, research strategy, data gathering method, and activity plan.

'How can a performance measurement system assist Company X in gaining insight to trace bottlenecks?'				
	Type of research	**Research strategy**	**Data gathering method**	**Activity plan**
How is the lead time defined and measured?	Descriptive	Qualitative	-Informal interview with company representative	-Interview company representative about current process -Explaining track-and-trace -Creating BPMN -Creating overview of timestamps
Which KPIs describe the production process of the analysis methods?	Descriptive	Qualitative	-Systematic Literature Research -Semi-structured interviews with intended users	-Literature study -Interviews with intended users -Overview of unique set of KPIs
What is an effective way to visualize the KPIs in the performance measurement system to give more insight to the users?	Descriptive	Qualitative	-Literature review -Data set	-Literature review -Overview of selected charts -Define benchmarks -Data cleaning -Create performance measurement system
Can the developed performance measurement system help to detect bottlenecks?	Exploratory	Qualitative	-Evaluation form	-Performance measurement system evaluation regarding the capability of tracing bottlenecks -Overview of any traced bottlenecks -Evaluation form for intended users -Evaluation of results obtained from the form

Table 2: Research design

1.3.5. Deliverables

After all the steps of the DSRM cycle have been carried out, several deliverables are created. They are listed below:

- Business process model
- Set of relevant KPIs
- Prototype performance measurement system
- Recommendations including improvements for the production process and improvements for the performance measurement system
- Written research report detailing the development and evaluation

1.4. Validity

1.4.1. Internal validity

Internal validity examines whether the research design answers the research question without bias (Andrade, 2018). Therefore, we should check whether our research question, ''How can a performance measurement system assist Company X in gaining insight to trace bottlenecks?", is answered without bias. This is assessed by evaluating the design in sub question 4, where the performance measurement system is evaluated against its capability to trace the bottlenecks. Additionally, the developed performance measurement system is evaluated by the managers, who are the future users of the artefact. The Technology Acceptance Model (TAM) is used to evaluate the performance measurement system to ensure user acceptance and continuous use. This model claims that the adoption rate does not depend on the features of a technology, but especially on the user experience. The TAM states that perceived usefulness and perceived ease of use, influenced by external variables are the most important influences on the attitude towards using and the behavioural intention to use, ultimately influencing the adoption rate. (User Sense, 2021b) The full picture of the TAM is schematically displayed in Figure 4.

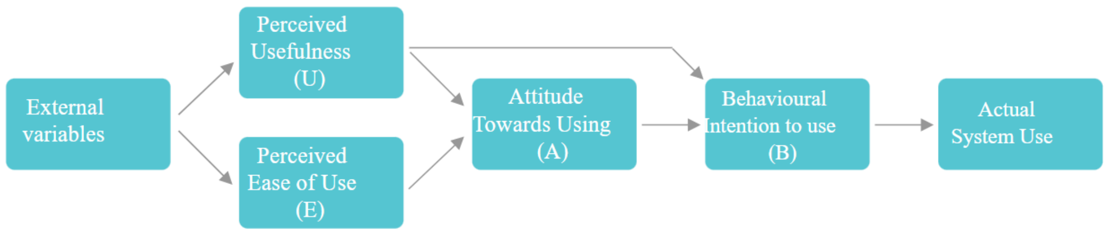


Figure 4: TAM model (User Sense, 2021b)

To determine the adoption rate (actual system use), the perceived usefulness and perceived ease of use are determined.

The perceived ease of use is determined by using the System Usability Scale (SUS). This is a pre-set-up questionnaire of ten questions that are asked to be answered on the Likert Scale. The advantage of this scale is that the SUS score can be computed and evaluated systematically, as both a roadmap to compute the score and limits to evaluate the perceived ease of use have been pre-set-up as well. Those limits determine whether the product is excellent, good, OK, below average, or poor in perceived ease of use compared to other products. (User Sense, 2021a)

The perceived usefulness is determined by asking the respondents to fill in a questionnaire with six questions that are proposed by the TAM model. This way, we can determine whether the respondents strongly disagree, disagree, are neutral, agree, or strongly agree with the statements about usefulness. The Likert scale itself evaluates the perceived usefulness, but the comparison with other products is not considered in this score like in the SUS score. (User Sense, 2021b)

After those two evaluations are completed, the internal validity of the design can be assessed. If the internal validity is low, recommendations are given to increase it.

1.4.2. External validity

External validity examines whether the study findings can be generalized to other contexts (Andrade, 2018). Although the performance measurement system design and the selected set of KPIs might particularly be useful for production companies, this report can act as a guideline for developing a performance measurement system for a company in any sector.

Ecological validity is a subtype of external validity, and it examines whether the findings of the study can be generalized to real-life settings. In other words, it examines whether the study findings are practical in everyday situations, which is based on judgement. (Andrade, 2018) While the general external validity has been judged as arguable, the ecological validity of this specific research is judged to be higher, as the research context is representative of the context in reality. The data that is used, is representative of the lead time in reality. That is why there can be concluded that the study findings are generalizable to daily practice. When looking from the ecological validity perspective, the study findings could also be of value for companies with similar interest in tracing bottlenecks.

2. Definition and measurement of lead time

This chapter gives an overview of the process flows at the company, which is important in order to understand the overall research. Furthermore, it is explained how the data, that will be used as input for the performance measurement system, is created, and what information it contains. Altogether, this chapter answers the first sub question: “How is the lead time defined and measured?”

2.1. Definition of lead time

First, it is important to know how the general definition of lead time is described, as this is one of the most important concepts throughout this research. Therefore, a few definitions that are established in the literature are listed below:

- Lead time is defined as an interval calculated between the time point when the order has been finished at the previous workplace and the time when the order at the treated workplace has been finished (Starbek & Grum, 2000).
- Lead time is defined as the time between placing an order and receiving it (Kim et al.,2003).
- Lead time is defined as the number of time units needed to complete the order from opening to closing (Alqahtani, 2020).

The definition that suits this research the best is the first one: “an interval calculated between the time point when the order has been finished on the previous workplace and the time when the order on the treated workplace has been finished”. In this research, the lead times of different analysis steps, which are the workplaces in this case, are assessed and investigated. Thus, to compute the lead time of one step, the difference between the time point when the sample is finished in the previous step and the time point when the sample is finished in the treated step is computed.

2.2. Explanation of timestamps

At Company X, timestamps are created through a track-and-trace system. This means that the samples are tracked following their path throughout the process. This leaves a ‘trace’ of timestamps. For this research, raw data resulting from the track-and-trace is requested. Consequently, a CSV file containing 1048576 rows, each row representing a timestamp of December 2022, is provided by the ICT department of the company. The file contains raw data and still needs to be cleaned.

Timestamps can be created on two different scales: per sample or per tray. In some cases, the timestamps are created per sample. This means that the barcode on one sample pot is scanned and information about the current state of the sample is sent to the system. In other cases, the timestamps are created per tray. The maximum number of samples that fits in a tray is 10, 60, and 45 for Process A, Process B, and Process C respectively, and information about the current state of all the samples in one tray is sent to the system in one go. The link with the concerning samples is again made by scanning a barcode. The timestamp that is created in both cases contains a lot of information. Only information relevant to this research is used, the other characteristics of the timestamp are removed from the received data. The following information of the timestamps is relevant and utilized in this research:

- Sample number: A string that exists out of letters and digits that is unique for the concerning sample.
- Method: The analysis method in which this timestamp is made. This could be Process A, Process B, or Process C.
- Instrument: The step of the analysis method in which this timestamp is made. This could be weigh-in, the actual analysis method, or a lablink for example. These steps are elaborated on in section 2.3.

- Date of inflow: The date on which the sample entered this instrument. The data is displayed as YYYYMMDD.
- Time of inflow: The time at which the sample entered this instrument. The time is displayed as (H)HMMSS.
- Workplace: A code that refers to the workplace where this instrument was used.

2.3. Current general process flow

To understand at what points time stamps are made, we first need to understand the process flow. A Business Process Model and Notation (BPMN) is created to visualize and to give a quick overview of the process.

There are several symbols in a BPMN, all serving another function. An overview of the symbols is given in Table 5.

Symbol	Function	Explanation
	Activity	A single sub process or task of the overall process.
	Start event	The process trigger that starts the process.
	End event	The result of the process that ends the process.
	Flow	The sequence in which the activities are performed.
	Gateway	A choice, that is given inside the gateway symbol, determines the next activity.

Table 3: BPMN language (Del Marmol, 2017)

Using a BPMN, a process flow is created in Figure 5, to give a simplified overview of the general process at Company X. Throughout the whole process, links are made between the production and information system. Those links are called 'lablinks'. Such a link is created when data is sent to the information system for example. All lablinks are registered by the track-and-trace system as a timestamp. It is important to note that customers sometimes want a duplicate of their material to go through the process. In this case, the sample goes through the process twice, resulting in double timestamps. Below, all steps are explained.

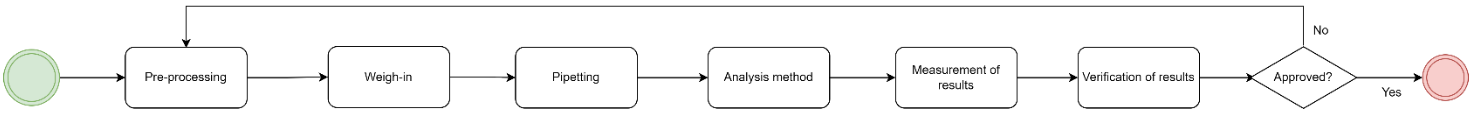


Figure 5: General process flow

Pre-processing

This part prepares the samples to be analyzed. First, a bit of the material is crumbled and dried. After drying for hours, the material is put into a pot with a unique barcode on it. Finally, the barcode is scanned and put in a tray.

Weigh-in

Now the sample is pre-processed, some general measurements are done with the sample, creating a lablink. For example, the weight is determined. After that, some liquid is added, as a sample is more suitable for analysis in a liquid state.

Pipetting

Here, some of the liquid is pipetted into another pot that is suitable for the analysis method that follows. When customers want the sample to be analyzed by more than one analysis method, the liquid is divided over more than one pot. In this case, each pot goes separately and in parallel through the process from now on.

Analysis method

The actual analysis method is carried out, which can vary from a lot of different options. The analysis methods this research focuses on are Process A, Process B, and Process C.

Measurement of results

The results from the analysis method are measured.

Verification of results

The results are verified, creating a lablink. This means that the results of the measurement are checked by someone else to make sure they are valid. If the verificatory does not approve the results, then the process starts again from pre-processing.

2.4. Explanation of analysis methods

In this research, the focus lies on the processes of three analysis methods: Process A, Process B, and Process C. Those are the most relevant ones, as they are requested most often by customers. Thus, reducing the lead times of these methods has the largest impact. For this research, there is no need to understand exactly what is happening in the concerning methods. However, a brief description is provided to give an idea of the analysis methods:

This part is removed due to confidentiality issues.

2.5. Control groups

Besides samples with material received from customers, there are also some 'fake' samples going through the process, which are also displayed in the data resulting from the track and trace. There are two kinds of 'fake' samples:

- Blanco samples: This is a control group, which means that there is no material in these samples, except for the liquid. Consequently, all measured concentrations should be equal to zero. By using a control group, the company makes sure that there is no cross-contamination or other contamination in the process.
- Z/G/K numbers: This is another control group, from which the barcode starts with the letter Z, G, or K. These samples consist out of material that Company X already knows the results of, or at least the range that the results should be in. By checking whether the results of these samples fall into this range, the company makes sure that the results of the analysis are valid.

The timestamps resulting from those two kinds of samples are removed from the data, as they are not representative of the lead time that customers experience.

2.6. Types of timestamps

Not all timestamps that are created are of proper use for this research. Therefore, it is decided that some timestamps are removed from the data. Some of them are not created consistently, as they are only created for some of the samples. Other removed timestamps concern those that are created at the exact same time as another one, so the information of those does not add any value.

The points in the process where the timestamps are created are deduced from the data resulting from the track-and-trace. To calculate the duration of one step, the difference between the concerning and the next timestamp is calculated, based on the date and time of inflow of those timestamps. Note that the next step is not always the next bullet point in the list, as the process is sometimes split up into DA (Discrete Analyzer) and MS (Mass Spectrometry). The used timestamps, including the next timestamps to calculate the duration, are listed in Table 6, 7, and 8.

Timestamp of Process A	**Next timestamp (to calculate the duration)**
Weigh-in + extraction (Process A)	Pipetting until start verification (Process A DA)
Pipetting until start verification (Process A DA)	Verification (Process A DA)
Pipetting until start verification (Process A MS)	Verification (Process A MS)
Verification (Process A DA)	Final lablink
Verification (Process A MS)	Final lablink
Final lablink	-

Table 4: Process A timestamps

Timestamp of Process B	**Next timestamp (to calculate the duration)**
Weigh-in + pipetting (Process B DA)	End pipetting until start verification (Process B DA)
Weigh-in + pipetting (Process B MS)	End pipetting until start verification (Process B MS)
End pipetting until start verification (Process B DA)	Lablink for DA
End pipetting until start verification (Process B MS)	Lablink for MS
Lablink for DA	-
Lablink for MS	-

Table 5: Process B timestamps

Timestamp of Process C	**Next timestamp (to calculate the duration)**
Weigh-in + pipetting (Process C)	End pipetting until end analysis (Process C)
End pipetting until end analysis (Process C)	End analysis until start verification (Process C)
End analysis until start verification (Process C)	Lablink
Lablink	-

Table 6: Process C timestamps

To indicate where in the process the timestamps take place, an individual process flow is created for each analysis method in Figure 6,7 and 8.

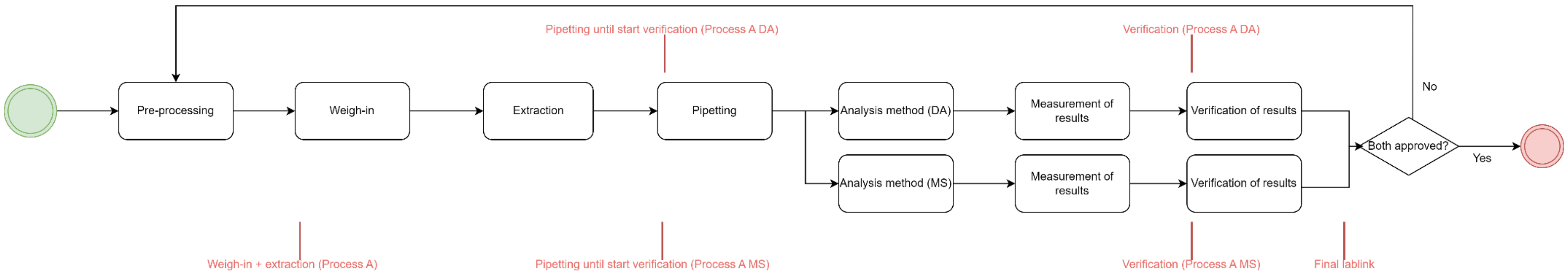


Figure 6: Process flow Process A

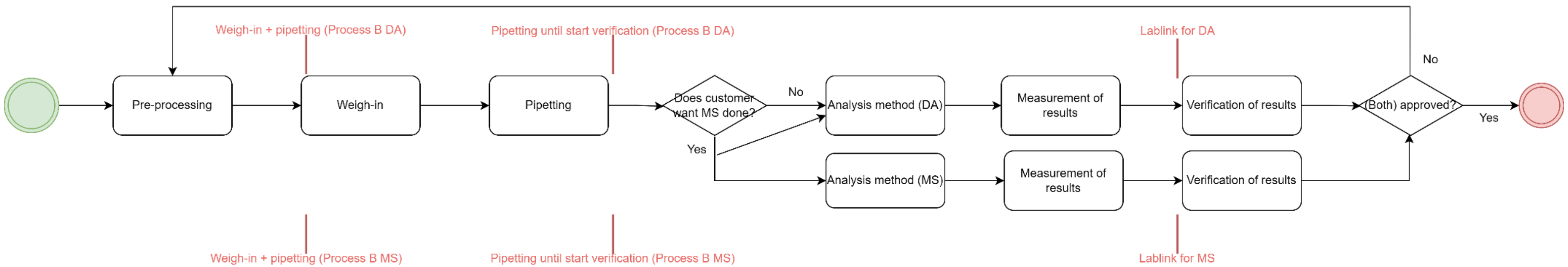


Figure 7: Process flow Process B

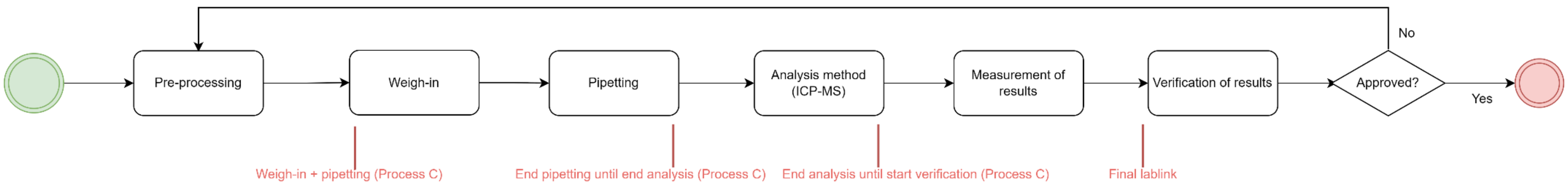


Figure 8: Process flow Process C

3. Selection of KPIs

This chapter serves to select the KPIs that will ultimately be implemented into the performance measurement system. Therefore, a systematic literature review is conducted to examine KPIs established in literature that describe the production process, regarding lead time. After that, the final selection of KPIs is determined with the support of interviews. Ultimately, this chapter answers the second sub question: “What KPIs describe the production process of the analysis methods?”

3.1. KPIs in the literature

With the support of a systematic literature review, which can be found in Appendix A, the following KPIs are found that are established in the literature that describe the production process, regarding lead time:

- Lead/throughput/process time
- Utilized equipment effectiveness
- Units produced per labor hour
- Total production
- Rejections/scrap rate/number of items getting reprocessed
- Good parts produced per day / OK rate
- Overall equipment efficiency (%)
- Number of operators
- Customer returns
- Rejection costs
- Value-added ratio
- Customer tact
- On-time-in-full
- Inventory turns
- Average time per step
- Reliability
- Human resource costs
- Operating expenses
- Inventory

However, not all KPIs are suitable for the company's context and this research's aims. That is why some of these KPIs are eliminated from this list. In Table 9, the KPIs that are eliminated are listed with the reason for eliminating these KPIs.

Eliminated KPI	**Reason**
Number of operators	This research aims not directly to reduce costs, so KPIs describing costs or labor expenses are irrelevant.
Rejection costs	
Human resource costs	
Operating expenses	
Inventory turns	Company X is a laboratory, and KPIs related to inventory are not as relevant as they would be for a regular production company. Most of the articles in which the KPIs were established were focused on production companies.
Inventory	
Customer returns	Returning is not relevant, because returning a service is not possible.
Reliability	Reliability is the percentage of sets that are

	delivered, according to the demands. This is not relevant, as the sample is analyzed repeatedly if the results are not approved. Resultantly, 100% of all delivered results should fulfil the demand.

Table 7: Eliminated KPIs

Consequently, we are left with nine KPIs that are suitable for the performance measurement system. In Table 10, those KPIs are listed, and the definition is given. In the case of more than one KPI expressing the same thing, the most clear or relevant expression is chosen.

KPI	Definition
Lead time	The period from order intake to product delivery to the end customer (Oberhausen & Plapper, 2017).
Utilized equipment effectiveness	The achieved quantity divided by the standard quantity in the total scheduled run time (%) (Habib et al., 2023).
Units produced per labor hour	The total dispatched quantity in a day divided by the total amount of labor hours that day (Habib et al., 2023).
Total production	The total number of finished items ready to be sent to the customer. This is composed of the reworked items plus the first-time good items. It is measured in parts per day (Tébar-Rubio et al., 2022).
Scrap rate	The number of incorrect items divided by the total amount (%). (Oberhausen & Plapper, 2017).
Overall equipment efficiency	OEE = Availability x Performance x Quality (%) Availability = Run Time / Planned Production Time (tracks down time) Performance = (Ideal Cycle Time x Total Count) / Run Time (takes into account anything that causes the process to run less than the maximum speed) Quality = Good Count / Total Count (takes into account samples that need to be repeatedly analyzed) (OEE, n.d.)
Value-added ratio	Share of value adding time of total lead time (%) (Oberhausen & Plapper, 2017).
On-time-in-full	Percentage of complete and in-time deliveries (Oberhausen & Plapper, 2017).
Average time per step	The lead times of the individual activities related to the fulfillment cycle time (Moatari-Kazerouni & Bendavid, 2017).

Table 8: Relevant KPIs and definitions

3.2. Interviews

Now the KPIs established in the literature that describe lead time are found and we have a list with suitable KPIs and their definitions. Subsequently, interviews with the managers, the future users of the performance measurement system, are conducted to find out what KPIs they think are relevant.

Throughout the interviews, a grounded research approach is employed, which means that a theory is systematically obtained through research and is grounded in data (Goulding, 1998). This approach consists of systematic techniques of collecting and analyzing data, and exploring ideas and concepts that emerge through analytical writing (Charmaz, 2006). The grounded theory applies to the selection of the KPIs, as the interviews to determine the relative relevance of the KPIs are done according to a fixed plan, thus in a systematic way. Furthermore, the final selection of KPIs is based on reasoning, thus through analytical writing. To understand the subjective reality of the managers, the participants are asked why they rate the KPIs as they do. This fits with the philosophy of phenomenology, as it plays a key role in understanding the point of view of the participants. (Qutoshi, 2018)

To explore the relevance of the defined KPIs, the following managers are interviewed, as they are the most important future users:

- Manager A
- Manager B
- Manager C

In these interviews, relevant KPIs that are found in the literature are discussed, and there is room for them to add some of their ideas for KPIs. The interviews are semi-structured so that there is possibility for follow-up questions as well. Furthermore, the whole interview is recorded, to make sure nothing is forgotten. As required, the participants are asked for approval, see the introduction to the interview below. The participants are already aware of the goal and deliverables of the research. However, a brief introduction to the interview is given, with the following content (Van Ravenstein, 2020):

- The participant is thanked for participating in the interview.
- The interviewer introduces herself briefly; the name, study, and bachelor assignment's content are briefly explained.
- The goal of the interview is described; to explore what KPIs the managers think are relevant to implement in the performance measurement system.
- The expected duration of the interview; 15 to 30 minutes.
- It is explained that the results are managed confidentially; the results are only used for the sake of this research.
- The participant is asked for approval to record the audio of the interview.

The interviews consisted of two parts:

Rating the KPIs that are found in the literature:

The participants are asked to use the Likert scale to rate the nine KPIs that are found in the literature. It is most common to use 5, 7, or 9 rating bars (Cai et al., 2016). An experiment was done by Cai et al. (2016) to find out that the optimal number of rating bars for the Likert scale is 7, in terms of reliability, validity, and accuracy. That is why 7 rating bars are used for each question in this part of the interview. As the KPIs are rated on relevance, this results in the following 7-point scale (Bhandari, 2023):

- Very irrelevant
- Irrelevant
- Slightly irrelevant
- Neutral
- Slightly relevant
- Relevant
- Very relevant

To make sure that the participants have an overview of the rating bars, they are printed out on a piece of paper, which lays on the table in front of them. Besides, the participants are asked to explain why they rate the KPIs as they do. To conclude, for each KPI the following question is asked: "How would you rate the relevance of this KPI, choosing from these rating bars, and why?".

Opportunity for the participants to explain their ideas regarding KPIs:

The managers probably have some idea in mind of what they would find interesting to see on the performance measurement system. Therefore, they are given some space here to explain what more KPIs they would like to see implemented. This part of the interview is unstructured, as the respondents explain their view, and the interviewer comes up with follow-up questions to make sure their view is understood. To conclude, the question that is asked to initiate this part is: "What more KPIs do you think would be relevant to implement in the performance measurement system, and why?".

To ensure that the reporting of this qualitative interview is done explicitly and comprehensively, a checklist from Tong et al. (2007) is used. This checklist is called COREQ (COnsolidated criteria for REporting Qualitative research) and contains 32 criteria of what should be reported when doing a qualitative interview. It supports researchers to ensure reporting all important aspects of the research team, study methods, context of the study, findings, analysis, and interpretations. A question is defined for each item that covers an aspect of the interview. (Tong et al., 2007) In preparation for the interview, an attempt is done to answer the questions. This way, awareness for the aspects is raised, so that there can be anticipated on those. There may be some information that is known only after the interview is conducted, so those answers are complemented or adjusted after the interview. The COREQ checklist including answers can be found in Appendix B.

3.3. Data coding

After conducting the interviews, transcripts are written and subsequently edited. This means that the written transcriptions are cleaned up and edited to increase readability and clarity. For example, grammar is corrected, and some parts may be summarized for the sake of clarity for the reader of this research. (Delve, n.d.) The transcript and field notes of all three interviews can be found in Appendix C. After that, the transcripts are validated by sending them to the participants for review. Some minor comments are made, and the transcripts are adjusted accordingly.

Now, the data is coded to structure the interviews into themes or patterns for analysis. Furthermore, data coding increases the transparency, validity, and systematicity of the data interpretation. (Delve, n.d.)

The answers in the first part of the interview are given on a 7-point scale and can be systematically coded as displayed in Table 11.

Very irrelevant	1
Irrelevant	2
Slightly irrelevant	3
Neutral	4
Slightly relevant	5
Relevant	6
Very relevant	7

Table 9: Data coding

Using this coding scheme, the total score is calculated for each KPI in Table 12. The opinion of the Manager A is more important, so his rating weighs twice as much as the other two ratings.

	Manager A	**Manager B**	**Manager C**	**Total score**
Lead time	Very relevant	Very relevant	Very relevant	7+7+2x7=28
Utilized equipment effectiveness	Neutral	Neutral	Relevant	4+6+2x4=18

Units produced per labor hour	Relevant	Relevant	Relevant	6+6+2x6=24
Total production	Slightly relevant	Slightly relevant	Relevant	5+6+2x5=21
Scrap rate	Very relevant	Relevant / very relevant	Neutral	6.5+4+2x7=24.5
Overall equip-ment efficiency	Neutral	Relevant	Slightly relevant	6+5+2x4=19
Value-added ratio	Relevant	Very relevant	Very relevant	7+7+2x6=26
On-time-in-full	Relevant	Very relevant	Very relevant	7+7+2x6=26
Average time per step	Very relevant	Slightly relevant	Very relevant	5+7+2x7=26

Table 10: Total score for the KPIs

This results in the following list of KPIs are listed in ascending order of rated relevance. Three KPIs have the same total score, so they are placed on the same line.

1. Lead time
2. Value-added ratio / On-time-in-full / Average time per step
3. Scrap rate
4. Units produced per labor hour
5. Total production
6. Overall equipment efficiency
7. Utilized equipment efficiency

In the second part of the interview, the KPIs in Table 13 are suggested for implementation in the performance measurement system. There are no overlapping KPIs mentioned in the second part of the interview.

KPI	**Definition (stated by participant)**
Work-in-progress	The number of samples in each department at that moment.
Safety	The number of incidents per day.
On-time-in-full gap between calendar and work-ing days	The difference in the on-time-in-full between using a standard lead time in calendar days and using a standard lead time in working days.
Trend in repetition	The historical, present, and expected percentage of repeatedly analyzed samples.
Mean Time Between Failure	Average time or number of samples in between repairs.

Table 11: Suggested KPIs by managers

3.4. Final selection of KPIs

Considering the limited timeline of this research and the need to avoid overcrowding on the performance measurement system, the number of implemented KPIs should be limited. Furthermore, it is foreseen that not all KPIs can be computed with the available data. The following KPIs are foreseen to not be computable for the following reasons in Table 14.

KPI that is not computable	**Reason**
Scrap rate	The number of repetitions can be counted, but a repetition can be the result either of an error or a customer request for a repetition.

Units produced per labor hour	There is no available data on labor hours.
Overall equipment efficiency	There is no available data on performance, availability, and quantity.
Utilized equipment efficiency	There is no available data on the standard quantity and run times.

Table 12: KPIs that are not computable

The KPIs suggested in the second part of the interview are very specific. The performance measurement system is aimed to give a general overview, not specifically with KPIs that are only of interest to one of the managers. That leaves us with five KPIs: lead time, value-added ratio, on-time-in-full, average time per step, and total production. As the total production is rated low compared to the other four KPIs, the total production is excluded from the final set of KPIs. This results in the conclusion that the KPIs listed in Table 15 are selected to aim to implement. It is also defined how each KPI is aimed to be computed with the data.

KPI	**Computation**
Lead time	Average of samples in December 2022: [Last timestamp] – [First timestamp]
Value-added ratio	Average of samples in December 2022: [Lowest lead time possible] / [Lead time]
On-time-in-full	Percentage of samples in December 2022: [Number of samples with a lead time lower than the target] / [Total number of samples]
Average time per step	Average of samples in December 2022: [Timestamp of next step] – [Timestamp of concerning step]

Table 13: Final selected KPIs

4. Visualization and performance measurement system development

When developing a performance measurement system, decisions about the design must be made. Therefore, theory about performance measurement systems is provided to base the choice of performance measurement system on. Additionally, a theoretical framework considering chart types is set up, to support the selection of chart types. Another theoretical framework concerning layout is developed, as a foundation for the layout choices. Finally, now the content of the system is determined, the development of the chosen performance measurement system is described in the last section. Altogether, this chapter answers the third sub question: "What is an effective way to visualize the KPIs in the performance measurement system to give more insight to the users?"

4.1. Performance measurement systems

Although the company specifically requests a dashboard to gain insights into lead times and bottlenecks, it is also necessary to explore other performance measurement systems. Therefore, some literature research is conducted on both the regular dashboard and other performance measurement systems. Only then it can be determined whether a regular dashboard is indeed the most suitable performance measurement system.

Tableau de Bord (regular dashboard)

The Tableau de Bord, introduced in France, is the same concept as a regular dashboard (Bessire & Baker, 2005). It consists of a set of KPIs which are developed to track the organization's performance (Epstein & Manzoni, 1998). These KPIs are presented as ratios or graphs to inform decision makers and guide their organization (Bessire & Baker, 2005). Although a Tableau de Bord originally includes both financial and nonfinancial measures, there is often more emphasis on the financial measures than the nonfinancial ones (Epstein & Manzoni, 1998).

Financial and non-financial measures

Organizations are struggling with the use of solely financial measures, as there are several shortcomings that arise when solely using financial measures (Ittner & Larcker, 1998):

- They focus too much on historical data.
- They lack predictive ability.
- They reward especially short-term or incorrect behaviour.
- They are not actionable.
- They do not capture key business changes in time.
- They are too summarized to guide decision makers effectively.
- They are departmentalized instead of cross-functional.
- They do not effectively consider intangibles.

Due to these limitations, organizations are adopting new financial measures that focus more on cash flow and value creation, such as Economic Value Added and Cash Flow Return on Investment. Additionally, more forward-looking non-financial measures are used, including customer and employee satisfaction, product and process innovation, community involvement, and defect rates. (DeBusk et al., 2003)

Balanced Scorecard

The Balanced Scorecard is a one-page document including 18 to 25 key measures comparing organizational performance to planned targets. These measures are divided into four perspectives, forming a framework for categorizing strategic objectives (Kaplan & Norton, 2001):

- Financial: Shareholder-oriented, focussing on growth, profitability, and risk.
- Customer: Customer-oriented, focussing on value creation and differentiation.
- Internal Business Processes: Focussing on business processes that enhance customer and shareholder satisfaction.
- Learning and Growth: Focussing on creating a climate that supports organizational change, innovation, and growth.

By utilizing these four perspectives, cause-and-effect relationships can be defined between them. Understanding these relationships allows for the formulation and implementation of strategies throughout all levels of the organization. The idea is that a strategy is initially developed at the top levels and cascades downward to impact the lower levels. (Porth et al., 1998)

Choice of performance measurement system

A set of financial and non-financial measures is the most limited performance measurement system, as these are some individual measures without insight into their relationships. The financial measures are not relevant for this research, as financials are not the focus. Although non-financial measures are of interest, it would be more valuable to explore their relationships and visualize them using one of the other performance measurement systems. This approach would provide decision makers with a better overview.

The regular dashboard, which is also referred to as the Tableau de Bord, and the Balanced Scorecard would be more interesting for the decision makers. Although they share similarities, Smith (2003) identified several significant differences:

- The Balanced Scorecard supports managing the performance, measuring progress, and assessing whether the planned targets have been achieved. A dashboard, on the other hand, supports monitoring the performance and measuring the performance.
- A dashboard is intended for individual use by specific managers, while the Balanced Scorecard is designed for the entire company.
- A dashboard shows current performance and is ideally updated continuously, while the Balances Scorecard is updated periodically.

Considering these differences, a dashboard is the most suitable choice for gaining insight into lead times and bottlenecks for the following reasons:

- The performance measurement system should support Company X in monitoring and measuring the performance of different departments, enabling an exploration of their performance and identification of departments causing bottlenecks.
- The performance measurement system should serve specific managers rather than the entire company. For this individual managers, only specific KPIs are of interest, and not all perspectives of the Balanced Scorecard.
- Ideally, the performance measurement system should be continuously updated to provide real-time information.

To conclude, a regular dashboard is the most suitable performance measurement system to design and implement. The development of the dashboard is done in Power BI, as this software has a great advantage over other tools with its high number of design related options (Shivakumar, 2019).

4.2. Theoretical framework chart types

During the designing phase of the dashboard, it is essential to have theory to guide the selection of appropriate chart types. For that reason, a theoretical framework is developed in which is discussed what kinds of visual analytics are relevant and when to use each one of these.

It is advised by Stoltzman (2018) to only use a chart to visualize the data if it meets the following criteria within one single chart type:

- The chart clearly illustrates a specific point.
- The chart is tailored to the intended audience, considering the level of detail that is preferred by the audience.
- The chart is tailored to the presentation medium, considering the extensiveness with which the audience analyzes the chart.
- The chart is memorable to those who are interested and make a significant impact on increasing the understanding of the subject.

If these criteria cannot be fulfilled with one chart type, it is recommended to explore alternative chart types or to consider not using a chart at all.

Stoltzman (2018) classifies visualization objectives into five categories: trend over time, comparison, relationship, distribution, and composition. Focussing on these desired outcomes helps to determine the most suitable chart types for the data. However, the choice of the most suitable chart remains subjective. (Sedrakyan et al., 2019)

In Table 16 to 21, all chart types available in Power BI are categorized in one of these five visualization objectives, with the support of an article by Mihart (2023). Note that some chart types are categorized in more than one visualization objective. Additionally, an extra category, 'single value', is added to categorize two chart types that do not fit within Stoltzman's categories, as they display one single value. Below each chart type, an example of the chart is displayed, made by Mihart (2023).

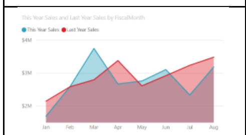
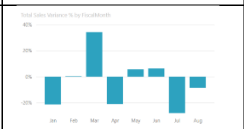
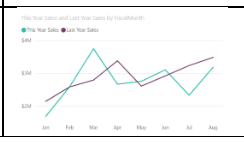
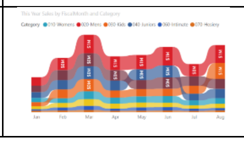
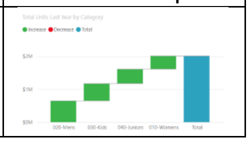
Trend over time				
Area chart	Column chart	Line chart	Ribbon chart	Waterfall map
				

Table 14: Charts for trend over time

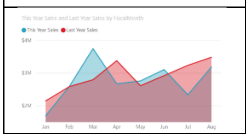
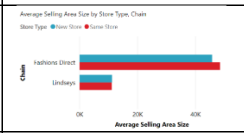
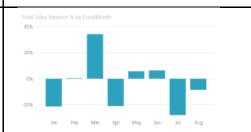
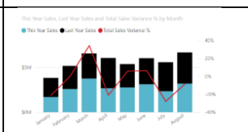
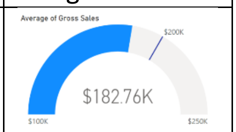
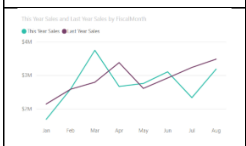
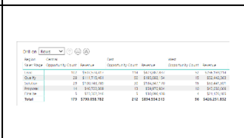
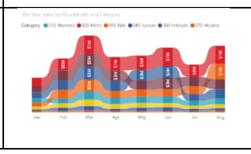
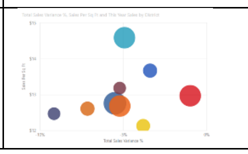
Comparison				
Area chart	Bar chart	Column chart	Combo chart	Gauge chart
				
Line chart	Matrix	Ribbon chart	Scatter chart	Table
				

Table 15: Charts for comparison

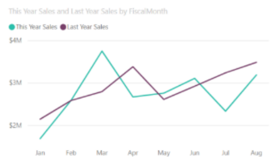
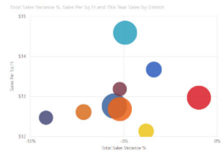
Relationship	
Line chart	Scatter chart
	

Table 16: Charts for relationship

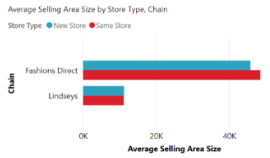
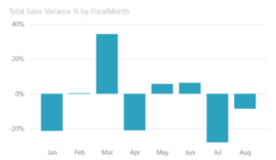
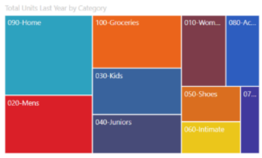
Distribution			
Bar chart	Column chart	Map	Treemap
			

Table 17: Charts for distribution

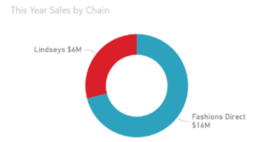
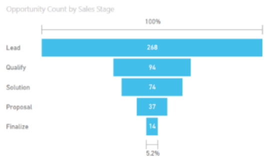
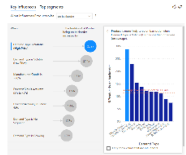
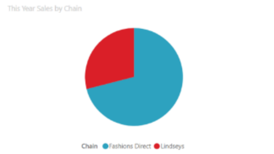
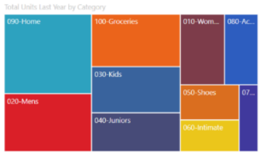
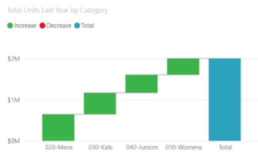
Composition			
Decomposition tree	Doughnut chart	Funnel chart	Key influencers chart
			
Pie chart	Treemap	Waterfall map	
			

Table 18: Charts for composition

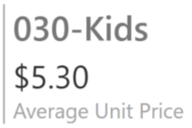
Single value	
Card	KPI
	

Table 19: Charts for a single value

After determining the visualization objective, we are left with a set of options for chart types. Now, it is important to take dimensionality into account (Sedrakyan et al., 2019), which can vary from one-dimensional, to two-dimensional, three-dimensional, and multi-dimensional (Schneiderman, 2003). Finally, we can choose what chart type suits the KPI the best.

4.3. Theoretical framework dashboard layout

An ideal dashboard should incorporate the concept of interactive visualization (Schneiderman, 2003), enabling a graphical presentation of information and allowing users to begin with an overview of the dashboard. They can then zoom in and apply filters to focus on information they are interested in, and they can finally obtain details-on-demand. The following key aspects outline this approach (Schneiderman, 2003):

- Overview: the user gains an overview of the entire collection.

- Zoom: the user can zoom in on specific KPIs that interest them.
- Filter: the user can apply filters so that the charts only display the data they are interested in.
- Details-on-demand: the user can select a group and gets the details of this group in a pop-up or similar feature.
- Relate: the user can explore relationships between charts by clicking on an item, causing a corresponding item in another chart to light up.
- History: the user can view their previous searches and has the option to undo any refinements.
- Extract: the user can extract charts, for printing or sharing purposes.

Furthermore, Lawrence et al. (2017) used design mining to establish design rules, by building a dataset comprising hundreds of dashboards and using a design mining tool to identify these rules. Subsequently, an expert study is conducted to validate the extracted design rules, demonstrating their reasonableness, usefulness, and adherence to expert design practices. Apart from the fact that this tool is a promising starting point for design mining visualizations to build recommenders, the most appropriate design rules were extracted from this research:

- Adjust the size of the charts based on their importance.

Chart size should correspond to their importance. This ensures that attention is drawn to the most important charts and uses the limited space available in the dashboard as useful as possible. For instance, text on the dashboard should have small dimensions, as it usually serves to support or describe the data, rather than having a significant meaning itself. (Lawrence et al., 2017)

- Present two charts intended for comparison similarly and close to each other.

When two charts both have the same chart type and Y-axis, they should be easy to compare. To enhance comparability, they should be arranged horizontally next to each other. Additionally, these charts should follow the same information hierarchy (Lawrence et al., 2017), meaning that they should have the same arrangement according to their importance (Bridgewater Learning, 2022). Similar formatting in terms of width, height, and scale is also recommended to enable effective comparison by dashboard users. While vertical arrangement is a possibility, but horizontal arrangement facilitates comparison to a greater extent. (Lawrence et al., 2017)

- Incorporate coordination to facilitate data exploration.

This concept, known as brushing, linked selection, or cross-filtering aligns with the 'relate' suggestion of Schneiderman (2003). It involves encoding two charts with corresponding categories in the same colors to facilitate exploration of relationships. Such coordination is necessary to support users in identifying related points, to improve the efficiency of data exploration. Brushing becomes particularly useful when dealing with a high number of colors or objects within one single chart. (Lawrence et al., 2017)

- Adjust the relative position of charts based on their level of detail.

Text providing statistical values serves as an overview and should be positioned above more detailed charts on the dashboard to initially attract the user's attention. The overview chart should be simple and contain minimal details. Consequently, charts with higher levels of detail are positioned toward the bottom of the dashboard. (Lawrence et al., 2017)

4.4. Selection of chart types

Now that the KPIs are selected and a theoretical framework concerning chart types is made, a chart type can be selected for each selected KPI, based on section 4.2. Before selecting the chart type, the visualization objective, dimensions, and benchmarks are defined in Table 22. Based on those, the chart types are selected. Note that all four KPIs are computed three times, as they are computed for all three analysis methods.

KPI	Objective	Dimensions	Benchmarks	Chart type
Lead time	Comparison	1 – Lead times 2 – Analysis methods	-	Column chart
Value-added ratio	Single value	1 – Percentages	-	Card
On-time-in-full	Composition	1 – Percentages	-	Doughnut chart
Average time per step	Comparison	1 – Durations 2 – Steps	1 – Lower limit 2 – Upper limit	Combo chart

Table 20: Objective, dimensions, benchmarks, and chart type of each KPI

To increase the clarity of charts that are more detailed and include benchmarks, one chart is made for each analysis method for the 'average time per step', 'value-added ratio' and 'on-time-in-full' chart. For the 'lead time' chart, the three analysis methods are combined in one chart. First, several chart types are tried out to select the ultimate chart type.

The **lead time chart** compares the lead times of the three analysis methods, with the lead time on the y-axis and the analysis method on the x-axis. The most suitable chart type, choosing out of the chart types for comparison, is a column chart, because it visualizes the three analysis methods independently. For instance, a line chart is not suitable, since it gives the impression to show any kind of progress.

The **value-added ratio chart** provides a single value, presenting a percentage. The most suitable chart type, choosing out of the chart types for a single value, is a card. The KPI chart is not suitable, as the progress is not aimed to be presented.

The **on-time-in-full chart** provides a composition of two percentages: samples that are on-time-in-full and samples that are not. The most suitable chart type, choosing out of the chart types for a composition, is a doughnut chart, because they show the relationship of parts to a whole.

The **average time per step chart** provides a comparison of the average time per step with the corresponding benchmarks, with the process steps on the x-axis and the duration on the y-axis. The benchmarks conclude a lower limit (the lowest lead time possible) and an upper limit (maximum time a step should take). The most suitable chart type, choosing out of the chart types for a comparison, is a combo chart, because the benchmarks can be easily included.

4.5. Determination of layout

Based on section 4.3, the layout of the dashboard can be determined:

Position of charts

- Lead time: Since this research is focussed on lead time, it is obvious that the lead time should be prioritized and presented at the top of the dashboard, to attract the user's attention first. To emphasize its importance, the chart that displays the lead time should be the largest.

- Average time per step: Among the three remaining KPIs, average time per step provides the highest level of detail. Therefore, it should be presented at the bottom of the dashboard.
- Value-added ratio and on-time-in-full: The two remaining KPIs, value-added ratio and on-time-in-full, contain a low level of detail. Therefore, they should take up less space compared to the other two KPIs. To conclude the positions of the charts, the value-added ratio and on-time-in-full should be positioned close to each other, as they have about the same level of importance and the same level of detail.

Brushing

To enhance the efficiency of data exploration, charts with corresponding categories should be encoded using the same colors. This enables the user to easily explore relationships between the charts. Applying brushing in this specific dashboard means that corresponding analysis methods should be encoded in the same colors throughout the dashboard.

Filters

Due to significant differences in the processes of the three analysis methods, they should be visually separated. An option that should be considered is to filter on analysis method. Since the timestamps do not have other interesting characteristics that are not displayed in the dashboard already, filters are not needful for other characteristics.

Zoom

To facilitate exploration of details that are presented in the charts, a zoom function should be incorporated to allow the user to zoom in on specific charts. For instance, the 'average time per step' chart contains a relatively high level of detail, due to the composition of numerous steps in the process, and corresponding benchmarks. This can be easily incorporated into Power BI, as the software has the function to show the exact data points when moving the mouse over them.

Other layout aspects

As there is no available data about additional details of interest, it is not needful to include a details-on-demand function that presents further information that is not presented initially in the dashboard.
The 'history'- and 'extract' functions do not need to be anticipated on, as their availability depends on the Power BI software. There should be investigated whether these options can be made accessible to the user. Furthermore, the availability of these options does not impact the dashboard layout.

4.6. Dashboard development

Before loading the data into Power BI, it is necessary to clean the data. This data cleaning is conducted in Excel, as it has been experienced that the cleaning of data is more efficient in Excel than in Power BI. The raw data file is loaded into Excel, where several steps are performed to ensure the data is clean and ready for input Power BI. These steps are detailed in Appendix D.

Once the Excel file is cleaned, it can be loaded into Power BI. The specific steps taken in Power BI to prepare the data for chart input are listed in Appendix E.

Subsequently, the dashboard is designed, incorporating the following elements:

- Lead time chart
- Average time per step chart
- On-time-in-full chart

- Value-added ratio chart
- Slicer with analysis methods
- Company X logo
- Title: Dashboard on lead time

The specific steps taken to create these elements are listed in Appendix F.

Ultimately, all concepts from sections 4.3 and 4.4 are implemented, except for the history and extract functions.

5. Evaluation of the dashboard

Now, the dashboard is developed, it must be evaluated. First, the dashboard is evaluated regarding the capability of tracing bottlenecks. Second, the dashboard is evaluated by the future users by asking them to fill in a questionnaire. Altogether, this chapter answers the last sub question: "Can the developed performance measurement system help to detect bottlenecks?"

5.1. Evaluation of capability to trace bottlenecks

In this section, the dashboard is analyzed to identify any potential bottlenecks. All charts are examined to extract meaningful insights from the data, with a particular focus on comparing the average time per step with the benchmarks as a starting point for identifying bottlenecks.

Appendix G presents an overview of the dashboard, including four charts: 'Lead time within timestamps', 'Assumed on-time-in-full', 'Value-added ratio within timestamps', and 'Average time per step'. Additionally, the dashboard features a Company X logo, title, and slicer for selection purposes.

5.1.1. Lead time within timestamps

This figure is removed due to confidentiality issues.

Figure 9: Lead time within timestamps chart

Among these charts, the 'Lead times within timestamps' bar graph (Figure 9) should immediately catch the user's attention. It presents the lead time for each analysis method by calculating the average duration between the first and last timestamp. The lead times within the timestamps of Process A, Process B, and Process C are 3.51, 0.33, and 3.06 days respectively. It is essential to note that this chart only represents a portion of the total lead time, as the total lead time that the customer experiences is the duration between the application of the sample and the delivery of the results. Additionally, the track-and-trace only starts after the 'pre-processing', so this step is not factored into these calculations. In other words, a significant part of the process, both before the first timestamp and after the last timestamp, remains unaccounted for in these numbers. In fact, this chart presents only 7-19% of the total lead time, based on the lead time in reality in section 1.2.2. While this chart gives an overview of the lead times of alle three analysis methods, it alone cannot effectively trace bottlenecks.

When utilizing the slicer on the dashboard, that applies on the three lower visuals, users can select the analysis method of their interest. This selection reveals the charts in Figure 10, 11 and 12, providing further data related to the chosen method.

5.1.2. Process A results

The charts in Figure 10 present information regarding the Process A process, representing the data from approximately five thousand Process A samples.

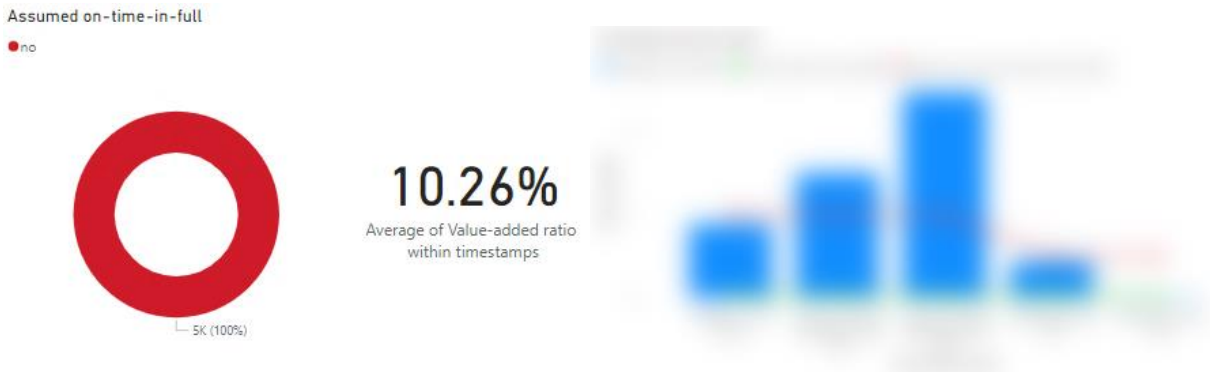


Figure 10: Process A charts

The left chart indicates that none of the Process A samples were delivered on time, as per the specified target. The timestamps only cover a part of the process, thus the assumed lead time outside the timestamps (see Appendix E for the computation) has been added to each sample's lead time within the timestamps. As the assumed lead time outside the timestamps (15.99 days) already surpasses the target for Process A (13 days), it is obvious that the on-time-in-full results in 0%. As the assumed total lead time outside the timestamps is an average, it is likely that there exist samples that are significantly processed faster than the average, thus are on time. A histogram of the lead time outside of the timestamps could be used instead for a more developed version to estimate a more representative on-time-in-full percentage.

In the middle chart, it is revealed that the value-added ratio within the timestamps for the Process A process is 10.26%. This signifies that roughly one tenth of the lead time within this part of the process is utilized effectively, adding value. The remaining nine tenth of the time, the samples are waiting to be processed. This indicates plenty room for improvement in reducing the lead time.

The right chart shows the average time per step within the Process A process. In Table 23 the lead times of the steps and the corresponding benchmarks of the steps in the Process A process are provided.

Steps of Process A	**Lowest lead time possible in hours**	**Actual lead time in hours**	**Maximum lead time the step should take in hours**
Weigh-in + extraction	1.3	27.77	31.2
Pipetting until start verification (DA)	0.65	46.80	31.2
Pipetting until start verification (MS)	0.65	76.75	31.2
Verification (DA)	1.3	13.73	15.6
Verification (MS)	0.65	0.62	15.6

Table 21: Average time per step of the Process A process

It can be observed that the average time for the steps 'Weigh-in + extraction', 'Verification (DA)', and 'Verification (MS)' are lower than the provided maxima, implying that these steps have a reasonable lead time. Conversely, the pipetting until start verification for both DA and MS takes more time than the maximum allows. As the actual lead times surpass the lowest possible lead times by far, it means that the samples are waiting between the pipetting and the verification. In general, the analysis method of DA takes less time than MS. As a consequence, the ‘Verification (DA)’ timestamp has a longer duration, as the end time of both the ‘Verification (DA)’ and ‘Verification (MS)’ timestamps is equal to the point in time at which the final lablink happens (see section 2.6). In other words, the duration of ‘Pipetting until start verification (DA)’ + ‘Verification (DA)’ is equal to the duration of ‘Pipetting until start verification (MS)’ + ‘Verification (MS)’. This does not necessarily mean that the verification of DA takes longer than the verification of MS, as the results of the verification of DA probably need to ‘’wait’’ for the results of MS, to be entered with all results at once in the system in the final lablink. This also explains the low lead time of ‘Verification (MS)’, because there is likely no ‘’waiting time’’ included in this step, as the timestamp only starts when the verification starts and when it is completed the final lablink is made immediately.

5.1.3. Process B results

The charts in Figure 11 present information regarding the Process B process, representing the data from almost eight hundred Process B samples.

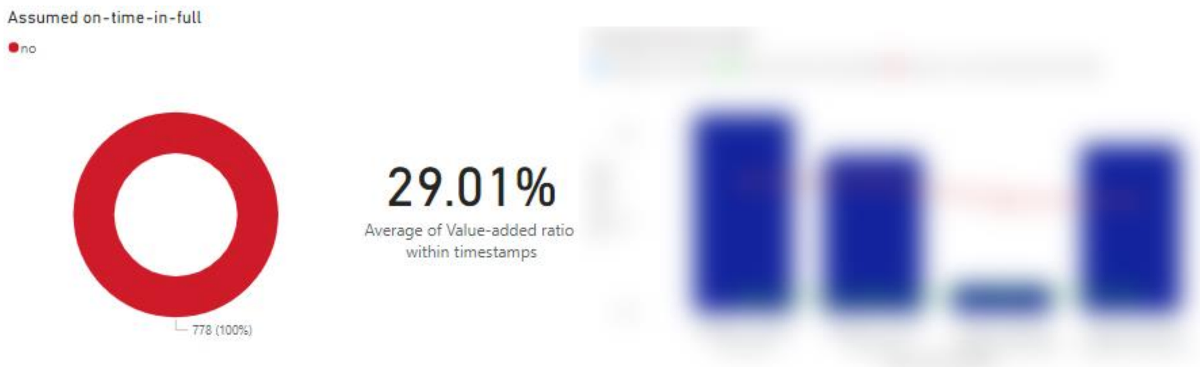


Figure 11: Process B charts

The left chart indicates that none of the Process B samples were delivered on time, as per the specified target. This can be explained similarly to the explanations for the Process A process. As the assumed lead time outside the timestamps (4.13 days) already surpasses the target for Process B (1.1 day), it is obvious that the on-time-in-full results in 0%.

In the middle chart, it is revealed that the value-added ratio within the timestamps for the Process B process is 29.01%. This signifies that roughly three tenth of the lead time within this part of the process is utilized effectively, adding value. The remaining seven tenth of the time, the samples are waiting to be processed. This indicates plenty room for improvement in reducing the lead time.

The right chart shows the average time per step within the Process B process. In Table 24 the lead times of the steps and the corresponding benchmarks of the steps in the Process B process are provided.

Steps of Process B	**Lowest lead time possible in hours**	**Actual lead time in hours**	**Maximum lead time the step should take in hours**
Weigh-in + pipetting (DA)	0.44	5.81	3.85
Weigh-in + pipetting (MS)	0.44	4.75	3.85
End pipetting until start verification (DA)	0.55	0.79	3.3

End pipetting until start verification (MS)	0.55	5.02	3.3

Table 22: Average time per step of the Process B process

It can be observed that the average time for the step ‘End pipetting until start verification (DA)’ is lower than the provided maximum, implying that only this step has a reasonable lead time. Conversely, the other three steps take more time than the maxima allow. As the actual lead times surpass the lowest possible lead times by far, it means that the samples (DA and MS) are waiting between the weigh-in and the pipetting and the MS samples also somewhere between the pipetting and the verification. Instead of or in addition to the suggestion that samples are waiting, it could also be that the steps (weigh-in, pipetting, analysis, and measurement of results) take longer than they should, as the differences between the actual lead time and the given maxima are just one or two hours.

5.1.4. Process C results

The charts in Figure 12 present information regarding the Process C process, representing the data from approximately 16 thousand Process C samples.

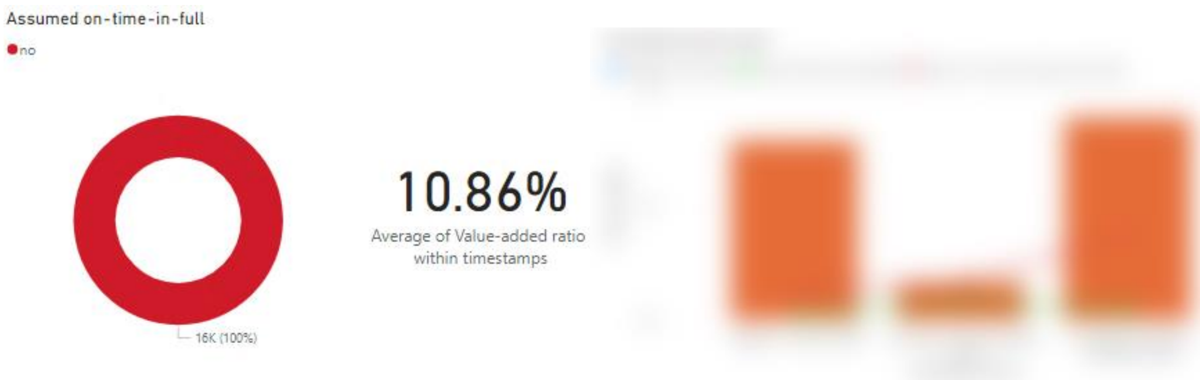


Figure 12: Process C charts

The left chart indicates that none of the Process C samples were delivered on time, as per the specified target. This can be explained similarly to the explanations for the Process A and Process B processes. As the assumed lead time outside the timestamps (13.38 days) already surpasses the target for Process C (12.75 days), it is obvious that the on-time-in-full results in 0%.

In the middle chart, it is revealed that the value-added ratio within the timestamps for the Process C process is 10.86%. This signifies that roughly one tenth of the lead time within this part of the process is utilized effectively, adding value. The remaining nine tenth of the time, the samples are waiting to be processed. This indicates plenty room for improvement in reducing the lead time.

The right chart shows the average time per step within the Process C process. In Table 25 the lead times of the steps and the corresponding benchmarks of the steps in the Process C process are provided.

Steps of Process C	**Lowest lead time possible in hours**	**Actual lead time in hours**	**Maximum lead time the step should take in hours**
Weigh-in + pipetting	0.68	31.82	5.1
End pipetting until end analysis	3.4	6.53	6.8
End analysis until start	1.7	36.31	15.3

verification			

Table 23: Average time per step of the Process C process

It can be observed that the average time for the step ‘End pipetting until end analysis’ is lower than the provided maximum, implying that only this step has a reasonable lead time. Conversely, the other two steps take more time than the maxima allow. As the actual lead times surpass the lowest possible lead times by far, it means that the samples are waiting between the weigh-in and the pipetting and somewhere between the analysis and the verification.

5.2. Evaluation by future users

For this section, future users are asked to fill in an evaluation form about the perceived usefulness and perceived ease of use to measure user acceptance (User Sense, 2021b). Therefore, a meeting is set up to demonstrate the dashboard to the future users, which are the same three mangers that have been interviewed before to determine the KPIs. After the demonstration and explanation of the dashboard, there is room for questions. After the meeting, the managers are asked to fill in the evaluation form, to rate several aspects of the perceived usefulness and ease of use of the dashboard. In Appendix H, more details on how the evaluation form looks can be found. Below, the results of the evaluation form are evaluated.

5.2.1. Perceived usefulness

The first six questions address the perceived usefulness of the dashboard.

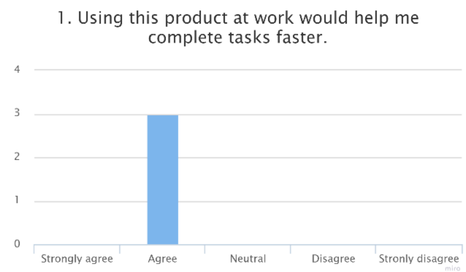


Figure 13: Results question 1

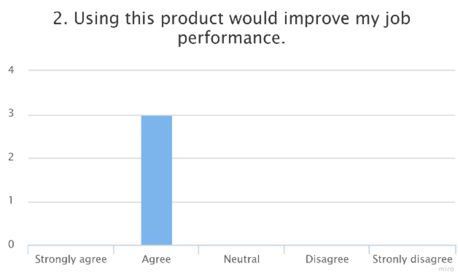


Figure 13: Results question 2

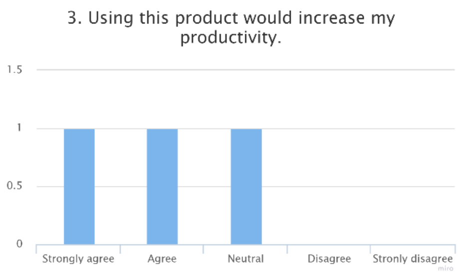


Figure 15: Results question 3

Based on Figure 13, it can be concluded that all managers agreed that the use of the dashboard would help them to complete tasks faster. One respondent commented that the user can see in one glance where the bottleneck is. Another respondent noted that he is already looking forward to a good, real-time dashboard to use in the morning call to act swiftly and decisively on issues/problems at that moment. Unfortunately, this dashboard relies on historical data rather than real-time.

The managers again unanimously agreed on the second question (Figure 14), as they all thought that using the dashboard would improve their job performance. One respondent remarked that the faster he can react on the production problems, the higher the customer satisfaction will be.

In Figure 15, the answers on the third question are presented. One respondent strongly agreed, one agreed, and one remained neutral regarding the dashboard’s impact on productivity. One respondent commented that a better and faster reaction time will focus activities, as action is rather late or sometimes too late now, which is not effective and not good for the productivity.

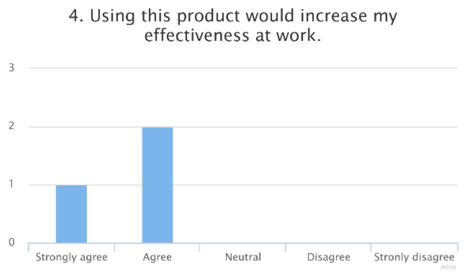


Figure 16: Results question 4

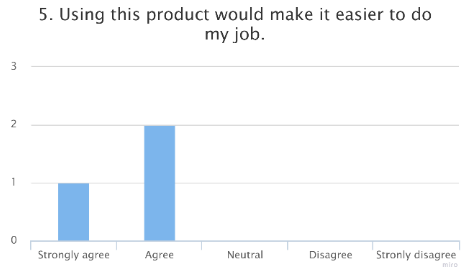


Figure 17: Results question 5

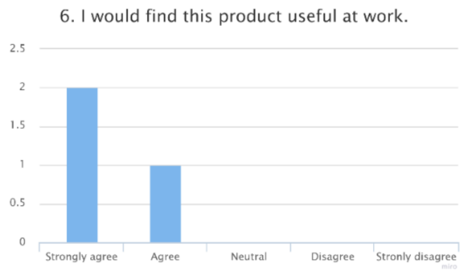


Figure 18: Results question 6

Two respondents agreed and one strongly agreed with the dashboard ability to increase their effectiveness at work, see Figure 16. While they did not provide specific comments, it can be inferred that the product would improve their ability to bring about intended results by identifying the departments with issues that require support or action.

The same distribution of answers resulted from the question after, see Figure 17. All respondents thought that the dashboard would make it easier to do their job. Again, there were not any comments provided, but it is obvious that the dashboard would facilitate the identification of bottlenecks.

Furthermore, Figure 18 indicates that one respondent agreed, and two respondents strongly agreed on the product being useful at work. One respondent pointed out that it is a big compliment that they want to implement it in the daily start, which is a meeting that takes place each morning. Another respondent emphasized the need for real-time, good data and dashboards indicating current problems.

Overall, the perceived usefulness of the dashboard is rated highly. Especially the effectiveness at work, ease of doing their job, and overall usefulness of the product received high ratings. The speed of task completion, improved job performance, and increased productivity were rated slightly lower, but still more than sufficiently. The comments suggest that the managers believed the dashboard provides quick insights to identify bottlenecks and to ultimately increase customer satisfaction. Additionally, the comments point out the expectation of daily use, but they acknowledged the need for further improvement, particularly in using real-time data.

5.2.2. Perceived ease of use

The final ten questions address the ease of use of the dashboard.

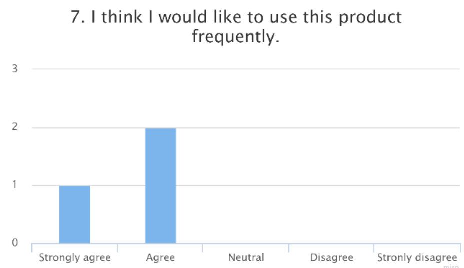


Figure 14: Results question 7

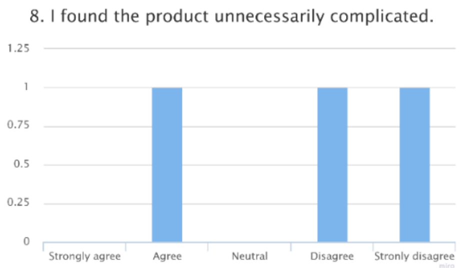


Figure 20: Results question 8

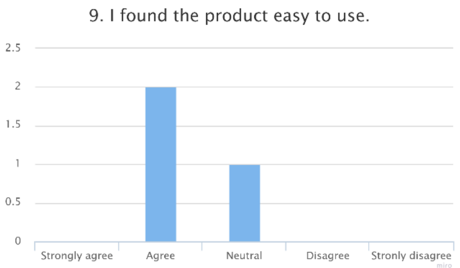


Figure 21: Results question 9

Figure 19 illustrates that two respondents agreed, and one respondent strongly agreed on thinking to frequently use the product. One respondent mentioned that he would use the dashboard on a daily basis, and another respondent commented that he thought dashboards would be an important feature of his working life.

In Figure 20, the answers regarding the complexity of the dashboard are presented. Although the answers are not unanimous, it is possible that the respondent who agreed on the product being unnecessarily complicated misunderstood the question, as no comment explains this opinion. The only comment provided states that the respondent found the dashboard not complicated as it was easily understandable with some explanation. Overall, it seems like the dashboard is not perceived as overly unnecessarily complicated.

Furthermore, two respondents agreed, and one respondent remained neutral regarding the overall ease of use of the product (Figure 21). One respondent remarked that with the dashboard, the user is just one click away from finding the answer.

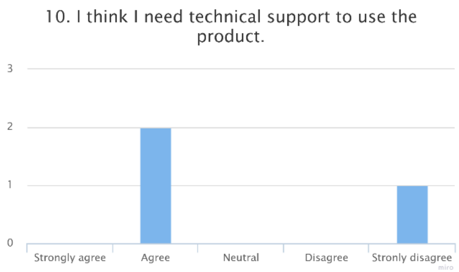


Figure 15: Results question 10

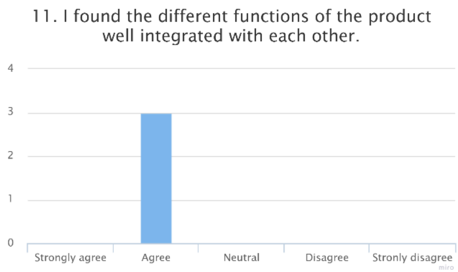


Figure 16: Results question 11

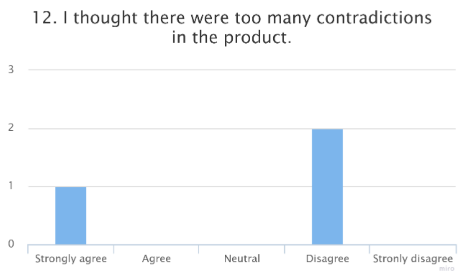


Figure 17: Results question 12

The subsequent question focuses on the need for technical support while using the product. The responses in Figure 22 indicate that most respondents believed that they need technical support to use the product. One respondent commented that this is just the beginning, and that further development is needed for a dashboard ready to be used at the production floor. This suggests that he believed that a more developed version of the dashboard should be usable without the need for technical support.

Moving on to Figure 23, it is evident from the responses regarding the integration of different functions of the product that all respondents agreed on the integration of these functions being well done. One respondent commented that he could enable a different analysis with one click, referring to the slicer that provides specific information about one of the analysis methods.

The question thereafter is about possible contradictions in the product (Figure 24). There is one outlier as one respondent strongly agreed that there were too many contradictions. However, this could be a misunderstanding, as there is again no comment explaining this answer. The other two respondents disagreed that there would be too many contradictions in the product. One respondent stated that he could not find any contradictions.

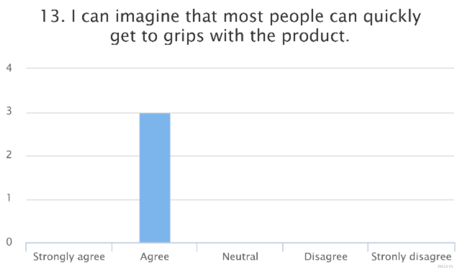


Figure 25: Results question 13

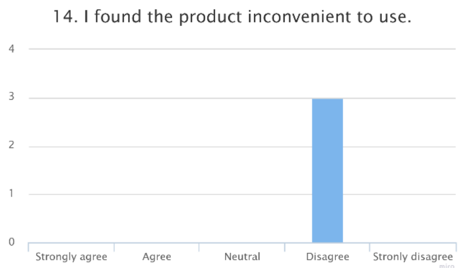


Figure 26: Results question 14

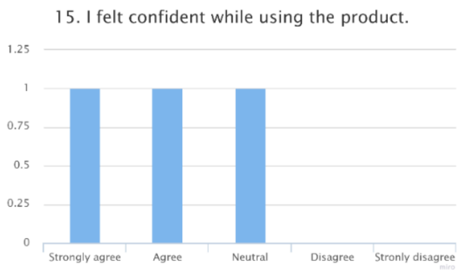


Figure 18: Results question 15

In Figure 25, it is presented that all respondents agreed that they could imagine that most people can quickly get the grips with the product. One respondent elaborated on this by commenting that he found the product user-friendly.

The subsequent question asked the respondents whether they found the product inconvenient to use, on which they all disagreed (Figure 26). One respondent made a remark that a dashboard is needed and that there was nothing inconvenient about it.

Figure 27 indicates that the confidence felt by the respondents while using the product varied, as one respondent strongly agreed, one agreed, and one remained neutral regarding the confidence they felt. There were no specific remarks provided about this question.

The responses on the last question are presented in Figure 28, which addresses how much they had to learn about the product before they could use it properly. Two respondents disagreed on having to learn a lot about the product before they could use it properly, and one respondent remained neutral. One of the respondents emphasized finding the product ease to use.

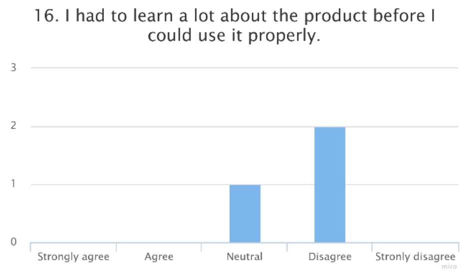


Figure 19: Results question 16

Now that all responses regarding the ease of use are evaluated, the System Usability Scale (SUS) can be used to compare the ratings of the ease of use, following the steps indicated by User Sense (2021a). For this method, Table 26 is used to code the results.

Strongly agree	5 points
Agree	4 points
Neutral	3 points
Disagree	2 points
Strongly disagree	1 point

Table 24: Data coding for evaluation form

Step 1: Calculate score of odd numbers

The score of the odd numbers is calculated by subtracting 1 from the score for each question. The computation of the score of the odd numbers is provided in Table 27, resulting in a total score of 14.67.

Question	Average number of points	Score (= average number of points – 1)
Question 7	(5+4+4)/3=4.33	3.33
Question 9	(4+3+3)/3=3.33	2.33
Question 11	(4+4+4)/3=4	3
Question 13	(4+4+4)/3=4	3
Question 15	(5+4+3)/3=4	3
Total score	-	**14.67**

Table 25: Computation score of odd numbers

Step 2: Calculate score of even numbers

The score of the even numbers is calculated by subtracting the number of points from 5. The computation of the score of the even numbers is provided in Table 28, resulting in a total score of 12.33.

Question	Average number of points	Score (= 5 – average number of points)
Question 8	(4+2+1)/3=2.33	2.67
Question 10	(4+4+1)/3=3	2
Question 12	(5+2+2)/3=3	2
Question 14	(2+2+2)/3=2	3

Question 16	(3+2+2)/3=2.33	2.67
Total score	-	**12.33**

Table 26: Computation score of even numbers

Step 3: Calculate SUS score

The total SUS score is calculated by adding the total number of points from step 1 to the total number of points from step 2. The result is multiplied by 2.5 to calculate the final SUS score, resulting in the following computation:

(14.67 + 12.33) x 2.5 = 67.5

Step 4: Interpreting the result

This method results in a score between 1 and 100. A score of 68 points is the average. With a score of 67.5, this product can be considered as average in terms of ease of use.

At the end of the evaluation form, respondent have the opportunity to fill in any remaining comments. The remaining comments are the following:

- Good job.
- Dashboard looks nice and is useful.
- This is a good dashboard and fulfils a need for this company. However, this is a first step, and we need to develop this further.

The comments indicate an overall satisfaction.

6. Conclusion, limitations, and recommendations

This chapter discusses the conclusion, limitations, and recommendations of this research.

6.1. Conclusion

To address the main research question, four sub questions were formulated. Below, each sub question is answered separately, leading to the overall answer on the main research question.

1. *"How is the lead time defined and measured?"*

Lead time is defined as "an interval calculated between the time point when the order has been finished on the previous workplace and the time when the order on the treated workplace has been finished". However, only the inflow times from the data resulting from the track-and-trace are representative. Because of that, the lead time of each step is determined by the difference between the date and time of inflow of the concerning and the next timestamp.

2. *"Which KPIs describe the production process of the analysis methods?"*

A systematic literature review is conducted to identify KPIs that describe the production process, from which the ones that are most suitable for this research and the company are selected. Based on the interviews with the future users, the most relevant KPIs are finally selected: lead time, value-added ratio, on-time-in-full, and average time per step.

3. *"What is an effective way to visualize the KPIs in the performance measurement system to give more insight to the users?"*

Several performance measurement systems are investigated, on which the choice for the dashboard is based. Furthermore, dashboard visualization techniques are examined and applied to this specific case. Based on the theory, it is determined to visualize the lead time in a column chart, the on-time-in-full in a doughnut chart, the value-added ratio in a card, and the average time per step in a column chart. Additionally, brushing and a filter were used as visualization techniques.

4. *"Can the developed performance measurement system help to detect bottlenecks?"*

First, the dashboard's capability to detect bottlenecks is evaluated. The lead time chart provides an initial overview of the total lead time for each analysis method. The value of the on-time-in-full chart is limited, as it consistently resulted in 0%. The value-added ratio chart turns out to be an excellent measure for indicating current performance and room for improvement. The average time per step chart is very helpful to detect in what phase of the process the bottlenecks were, by comparing the actual lead time with the benchmarks.

It is derived from the average time per step chart that there is a Process A bottleneck for both DA and MS between the pipetting and the beginning of the verification. For DA and MS, the bottleneck in Process B occurs between the weigh-in and the pipetting, and for MS, another one occurs between the pipetting and the verification. Between the weigh-in and the pipetting, as well as between the analysis and the verification, is where the Process C's bottlenecks lie.

Second, the perceived usefulness and ease of use for the future users are evaluated. Overall, the perceived usefulness is rated highly. The respondents remarked that they believed the dashboard provides quick insights to identify bottlenecks and to ultimately increase customer satisfaction. Additionally, they expected to use the dashboard daily, but acknowledged the need for further improvement, particularly in using real-time data. The perceived ease of use is rated averagely, which results from calculating the SUS score. The respondents found the dashboard easily understandable with some explanation. Additionally, they found the dashboard user-friendly, as the user is just one click away from finding the answer. Furthermore, one respondent pointed out that further development was needed for the dashboard to be ready to be used at the production floor.

Now the main research question can be answered, which was stated as follows:

"How can a performance measurement system assist Company X in gaining insight to trace bottle-necks?"

To assist Company X in gaining insight to trace bottlenecks, a performance measurement system in the form of a dashboard is developed.

Specific KPIs are incorporated to enable the users to effectively trace the bottlenecks. First, the lead time chart provides a general overview of the total duration for each analysis method. By examining this chart, users can quickly identify which methods require more time compared to others. Second, the on-time-in-full chart provides insight into the current performance, by measuring the percentage of results delivered within the target lead time. This KPI helps users to determine the efficiency and timeliness of the analysis methods. Third, the value-added ratio chart is an indicator of the room for improvement, as it shows what percentage of the lead time is effectively used and what part of the lead time does not add value, caused by bottlenecks. Finally, the average time per step chart is instrumental in detecting bottlenecks. By comparing the durations of each step with the corresponding benchmarks, users can pinpoint the specific steps where bottlenecks occur.

To facilitate exploration of relationship, the implementation of brushing is recommended. This involves encoding each analysis method with a specific color. Furthermore, a filtering functionality should be implemented to enable the user to focus on specific analysis method of interest.

By integrating all these function into one dashboard, Company X is assisted by an effective performance measurement system to gain insight to trace bottlenecks.

6.2. Limitations

Below, the limitations of this research are described:

- Restricted time: Due to limited time, only the first iteration loop of the DSRM Process Model (section 1.3.3) could be executed. Consequently, the dashboard could not be refined, as it was only designed, demonstrated, evaluated, and communicated once. Thereby, there was no opportunity to implement improvements that were examined by the evaluation.
- Limited respondents: There were only three respondents for both the interviews (section 3.2) and the evaluation form (section 5.2), which may affect the reliability of the results.
- Historical data: The dashboard is based on historical data, although a real-time dashboard would be preferable to enable the users to act upon bottlenecks in time. Developing a real-time dashboard poses challenges due to the extensive data cleaning required. The data cleaning process involved both Excel and Power BI, adding complexity to real-time data cleaning.
- Limited number of timestamps within the process: The limited number of timestamps within the process made it difficult to trace specific bottlenecks. There were no timestamps at the start and end of the process, and some timestamps covered a big part of the process. This made it challenging to pinpoint the exact points in the process where samples are delayed.
- On-time-in-full is 0%: The dashboard consistently showed an on-time-in-full percentage of 0% for each analysis method. This was because the average time outside the timestamps is already higher than the target lead time. However, it is likely that some samples finished on

time, as some samples may have a shorter time outside the timestamps than the average, resulting in a shorter total lead time.

By acknowledging these limitations, further improvements can be made to the dashboard.

6.3. Recommendations

In this section, the recommendations following from this research for Company X are described.

The first recommendation is to trace the specific bottlenecks, by diving into the concerning departments and addressing them. The bottlenecks are in the following phases:

- Process A: There is a bottleneck for both DA and MS between the pipetting and the beginning of the verification.
- Process B: There is a bottleneck for both DA and MS between the weigh-in and the Pipetting, and for MS between the pipetting and the beginning of the verification.
- Process C: There is a bottleneck between the weigh-in and the pipetting, as well as between the analysis and the beginning of the verification.

Further recommendations are provided to improve the dashboard:

- Display real-time data instead of historical data on the dashboard. This could be executed in either Power BI or another suitable software. This will enable Company X to trace and address bottlenecks before it is too late, maintaining customer satisfaction.
- Include more track-and-trace points within the process. Increasing the number of timestamps throughout the process will facilitate the identification of bottlenecks. Implement track-and-trace points at the beginning and end of the process, as well as within the existing timestamps that cover significant portions. Particularly, focus on adding timestamps within the steps currently identified as bottlenecks to pinpoint the exact points in the process where samples are delayed.
- It might be interesting to examine the individual performance of employees in addition to the overall performance of departments. This is possible, since a code representing the employee that performs the step is included in each timestamp. However, Company X should address confidentiality issues and seek informed consent from employees. It is important to be aware that some employees may resist this type of individual monitoring, as they may feel they are controlled too much.
- Use a histogram of the lead time outside of the timestamps instead of an average to estimate a more representative on-time-in-full percentage. Currently, the on-time-in-full is reported as 0% for each analysis method, which does not accurately reflect performance.
- Incorporate a history and extract function into the dashboard. The dashboard should be accessible in a user mode rather than an editor mode, allowing functions such as viewing history and extracting relevant information.

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Some references are removed due to confidentiality issues.

8. Appendices

8.1. Appendix A: Systematic Literature Review

In this systematic literature research, the following knowledge question is answered:

'What KPIs are established in literature that describe lead time?'

The answer on this question is useful for sub question 2, in which we come up with a set of KPIs that describe the lead time at Company X.

First, the inclusion and exclusion criteria are defined in Table 29, to ensure we only use relevant literature.

Inclusion criteria	**Reason**
Published after 1990	The concept of KPIs was first used as a port of a holistic management framework (*KPI (Key Performance Indicator) History | Infographics | Corporater*, 2022).
Search terms are in title, abstract, or keywords	Otherwise, the article is not relevant enough.
Exclusion criteria	**Reason**
Not peer-reviewed	Peer review encourages authors to strive to produce high quality research (Kelly, 2014).
Full text cannot be accessed	If the full text is not accessible, the findings are not supported. This makes the findings less credible (University of Maryland, 2023).
Articles in another language than English and Dutch	They cannot be understood.
Subjects: computer science, energy, medicine, mathematics, social science, earth and planetary sciences, physics and astronomy, economics econometrics and finance, nursing, psychology, neuroscience, arts and humanities	These subjects differ too much from the laboratory (and agriculture) sector.

Table 27: Inclusion and exclusion criteria

Second, a search matrix is set up in Table 30 to define what search terms are used.

Key concept	**Related terms**
KPI	Key Performance Indicator
Lead time	Throughput time

Table 28: Search terms

This resulted in the following search string that is put into Scopus:

'KPI' OR 'Key Performance Indicator' AND 'Lead time' OR 'Throughput time'

Using this search string, 829 results are found. This number of articles is too high to read all of them. That is why the following steps are taken to select the most relevant articles:

1. Apply search terms.
2. Apply inclusion and exclusion criteria.
3. Exclude articles based on the titles.
4. Exclude articles based on the abstract.

Following these steps, we find the number of results that is displayed in Table 32.

Total in Scopus with search terms	**829**
Excluded based on inclusion and exclusion criteria	-716
New total	**113**
Excluded based on the titles	-83
New total	**30**
Excluded based on the abstract	-25
Final total	**5**

Table 29: Number of results

Finally, an overview of the articles that are used is given in Table 32.

Title	**Author and year**	**Number of citations**
1 - Implementing lean manufacturing for improvement of operational performance in a labeling and packaging plant: A case study in Bangladesh	Habib, M.A., Rizvan, R., Ahmed, S. (2023)	2
2 - Conducting Action Research to Improve Operational Efficiency in Manufacturing: The Case of a First-Tier Automotive Supplier	Tébar-Rubio, J.V., Ramírez, F.J., Ruiz-Ortega, M.J. (2022)	0
3 - Cross-enterprise value stream assessment	Oberhausen, C., Plapper, P. (2017)	5
4 - Improving logistics processes of surgical instruments: case of RFID technology	Moatari-Kazerouni, A., Bendavid, Y. (2017)	14
5 - The application of the theory of constraints and activity-based costing to business excellence: The case of automotive electronics manufacture firms	Huang, S.-Y., Chen, H.-J., Chiu, A.-A., Chen, C.-P. (2014)	10

Table 30: Selected articles for SLR

After reading the articles, an overview is created in Table 33 of the KPIs describing lead time that are established in those five articles.

	Article 1	**Article 2**	**Article 3**	**Article 4**	**Article 5**
Lead / throughput / process time	X	X		X	X
Utilized equipment effectiveness	X				
Units produced per labour hour	X				
Total production		X			
Rejections / scrap rate / number of items getting reprocessed		X	X	X	
Good parts produced per day / OK rate		X	X		
Overall equipment efficiency (%)		X			
Number of operators		X			
Customer returns		X			
Rejection costs		X			
Value added ratio			X		
Customer tact			X		

On-time-in-full			X		
Inventory turns			X		
Average time per step				X	
Reliability				X	
Human resource costs				X	
Operating expenses					X
Inventory					X

Table 31: Overview of KPIs in literature

8.2. Appendix B: COREQ checklist

Item	Guide question	Answer
Domain 1: Research team and reflexivity		
Personal Characteristics		
1. Interview/facilitator	Which author conducted the interview or focus group?	Iris te Koppele
2. Credentials	What were the researcher's credentials?	None
3. Occupation	What was their occupation at the time of the study?	Graduating for Bachelor of Industrial Engineering and Management
4. Gender	Was the researcher male or female?	Female
5. Experience and training	What experience or training did the researcher have?	No experience or specific training, but awareness for important aspects of an interview was raised by answering the questions of the COREQ.
Relationship with participants		
6. Relationship established	Was a relationship established prior to study commencement?	One of the participants is the supervisor of the interviewer. There was not any relationship prior to the study with the other two participants.
7. Participant knowledge of the interviewer	What did the participants know about the researcher?	All participants knew that the reason for doing the research for the interviewer is to fulfill a bachelor assignment. The supervisor was more familiar with the assignment than the other two participants. Besides, they are all aware of the lack of insight into lead times the company has, which the research aims to resolve.
8. Interviewer characteristics	What characteristics were reported about the interviewer/facilitator?	As relevant content for the dashboard has already been discussed a bit before, the interviewer is already thinking in a certain direction for the KPIs. From this point of view, the interviewer is biased in a certain way. However, the KPIs that are rated by the participants are systematically derived from the literature. This way, the influence of the bias is minimized.
Domain 2: study design		
Theoretical framework		
9. Methodological orientation and Theory	What methodological orientation was stated to underpin the study?	Grounded theory and phenomenology.
Participant selection		
10. Sampling	How were participants selected?	The participants were selected on purpose, as they are the intended users of the dashboard.
11. Method of approach	How were participants approached?	The participants were approached via email or text.
12. Sample size	How many participants were in	There were three participants.

	the study?	
13. Non-participation	How many people refused to participate or dropped out? Reasons?	Fortunately, no one refused to participate or dropped out.
Setting		
14. Setting of data collection	Where was the data collected?	The interviews are conducted at the workplace.
15. Presence of non-participants	Was anyone else present besides the participants and researchers?	No, all interviews are conducted with only the interviewer and the participant in the room.
16. Description of sample	What are the important characteristics of the sample?	All interviews are conducted on the 15th of May. Apart from their function, there was no demographic data reported.
Data collection		
17. Interview guide	Were questions, prompts, guides provided by the authors? Was it pilot tested?	The questions were set up prior to the interview, except for the follow-up questions. The interview was not pilot tested.
18. Repeat interviews	Were repeat interviews carried out? If yes, how many?	No repeat interviews were conducted, as there were no further questions after the initial interviews.
19. Audio/visual recording	Did the research use audio or visual recording to collect the data?	Audio recording is used to record the interview and to report the results accurately afterward.
20. Field notes	Were field notes made during and/or after the interview or focus group?	Field notes about the setting and observed behavior are made right after the interview.
21. Duration	What was the duration of the interviews or focus group?	The duration was approximately 15 minutes on average.
22. Data saturation	Was data saturation discussed?	No. There are only three participants, so it is unlikely to observe patterns, thus having data saturation before finishing the three interviews.
23. Transcripts returned	Were transcripts returned to participants for comment and/or correction?	Yes. The results are returned to the participants to be corrected where needed.
Domain 3: analysis and findings		
Data analysis		
24. Number of data coders	How many data coders coded the data?	Initially, the data is coded only by the interviewer herself. However, the data coding is given feedback on by both the external and the UT supervisors.
25. Description of the coding tree	Did authors provide a description of the coding tree?	A coding tree is not provided, but the system that is used to code the data is provided.
26. Derivation of themes	Were themes identified in advance or derived from the data?	The themes for coding the data are identified after the interviews but are not derived from the results.
27. Software	What software, if applicable, was used to manage the data?	None. It is done manually.
28. Participant checking	Did participants provide feedback on the findings?	Yes, after the KPIs are implemented in the dashboard, the dashboard is demon-

		strated to the participants to be evaluat-ed.
Reporting		
29. Quotations presented	Were participant quotations presented to illustrate the themes / findings? Was each quotation identified?	No.
30. Data and findings consistent	Was there consistency between the data presented and the findings?	Yes. The KPIs that were rated as relatively more relevant than others and that were computable with the available data were implemented in the dashboard.
31. Clarity of major themes	Were major themes clearly presented in the findings?	No.
32. Clarity of minor themes	Is there a description of diverse cases or discussion of minor themes?	No.

Table 32: COREQ checklist

8.3. Appendix C: Interview transcripts and field notes

8.3.1. Manager A

This part is removed due to confidentiality issues.

8.3.2. Manager B

This part is removed due to confidentiality issues.

8.3.3. Manager C

This part is removed due to confidentiality issues.

8.4. Appendix D: Steps of data cleaning in Excel

- Freeze top row.
- Remove unnecessary rows. Keep “Sample number”, “Method”, “Instrument”, “Inflow date”, “Inflow time”, and “Workplace”.
- The entire area is formatted as table.
- All spaces are removed from the “Method” and “Instrument” columns with ‘Find and Replace’, as there are unnecessary spaces.
- Create column “Inflow date format” to get the date into the right date format with formula “=RIGHT([@[Inflow date]];2)&"-"&MID([@[Inflow date]];5;2)&"-"&MID([@[Inflow date]];3;2)”. Extend it over the entire column.
- To get the column into the right format, the format is adjusted to date (DD-MM-YY), and the column is copied and pasted as value. After that, the column adjusts to the format with the support of the ‘text to columns’-function.
- Create column “Inflow time format” to get the time into the right time format with formula =IF(LEN([@[Inflow time]])=5;"0"&LEFT([@[Inflow time]];1)&":"&MID([@[Inflow time]];2;2);LEFT(E2;2)&":"&MID([@[Inflow time]];3;2)). The if statement is included as the time in the original column is displayed with either a length of five (H-MM-SS) or six digits (HH-MM-SS). Extend it over the entire column.
- To get the column into the right format, the format is adjusted to time (HH:MM), and the column is copied and pasted as value. After that, the column adjusts to the format with the support of the ‘text to columns’-function.
- There are two different steps of Process C that have the same name for the method and instrument, and the only difference is the workplace. To give those steps an unique instrument name, the column “Instrument+” is created with formula =IF(AND([@Method]="Process C";[@Instrument]="Process CMS";LEFT([@Workplace];3)="XAN");"XAN";IF(AND([@Method]="Process C";[@Instrument]="Process CMS";LEFT([@Workplace];3)="SLP");"SLP";[@Instrument]))
- Create column “Method & instrument” with formula =[@Method]&" "&[@[Instrument+]]
- Create column “Sample & method & instrument” with formula =[@[Sample number]]&" "&[@[Method & instrument]].
- Create column “Inflow date & time” with formula =[@[Inflow date format]]+[@[Inflow time format]].
- Create column “Next method & instrument” with formula =IF([@[Method & instrument]]="Process A WPG";"Process A_DA INWEEG";IF([@[Method & instrument]]="Process A_DA INWEEG";"Process A_DA LABLINK";IF([@[Method & instrument]]="Process A_DA LABLINK";"Process A LABLINK";IF([@[Method & instrument]]="Process A_MS INWEEG";"Process A_MS LABLINK";IF([@[Method & instrument]]="Process A_MS LABLINK";"Process A LABLINK";IF([@[Method & instrument]]="Process B_DA INWEEG";"Process B Process B_DA";IF([@[Method & instrument]]="Process B Process B_DA";"Process B_DA LABLINK";IF([@[Method & instrument]]="Process B_MS INWEEG";"Process B Process B_MS";IF([@[Method & instrument]]="Process B Process B_MS";"Process B_MS LABLINK";IF([@[Method & instrument]]="Process C INWEEG";"Process C XAN";IF([@[Method & instrument]]="Process C XAN";"Process C SLP";IF([@[Method & instrument]]="Process C SLP";"Process CMS LABLINK";"-")))))))))))).
- Create column “Lookup value” with formula =[@[Sample number]]&" "&[@[Next method & instrument]].

- All timestamps from other methods (except Process A, Process B, and Process C) are filtered out.
- The data is copied to another file to store the values properly.
- Some unnecessary columns are removed.
- Create column “Next timestamp” with formula =VLOOKUP([@[Lookup value]];[Sample & method & instrument]:[Inflow date & time];2;FALSE).
- Change format to Custom D-M-YYYY HH:MM.
- Create column “Duration” with formula =[@[Next timestamp]]-[@[Inflow date & time]].
- Change format to Custom [H]:MM.

8.5. Appendix E: Steps of data preparation in Power BI

In the first table called 'timestamps':

- Some columns that are not used as unput for the dashboard are removed.
- Column duration is calculated again, as the one made in Excel could not easily be adjusted to the right data type without having errors. Change the format to duration.
- Rows are sorted on sample number first, then on inflow date & time.
- Remove all rows without a next timestamp by filtering out errors. This concerns the last timestamp that is made per sample (as those do not have a next timestamp to calculate the duration).
- Remove duplicates.
- There are negative durations as sometimes the process is repeated for the same sample number. The rows with negative durations are removed by filtering.
- Z/G/K numbers and blanco samples are removed.

In the second table called 'grouped by sample':

- Use the same Excel file resulting from the steps in Appendix D as input.
- Group by sample number, and create the columns listed in Figure 29. This also results in a relationship between the sample numbers in the 'timestamps'- and 'grouped by sample' table.

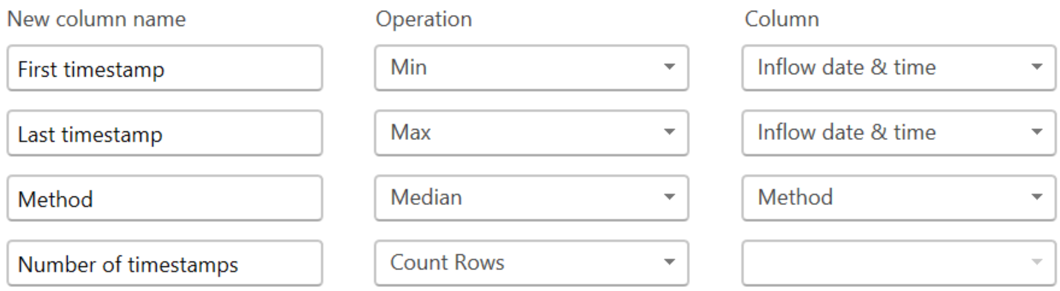

Figure 20: Initial columns created in the 'grouped by sample' table

- Filter out all rows with a number of timestamps that is lower than 3 or higher than 7, as those correspond to incomplete or overcomplete track-and-traces.
- Add a column 'lead time' by subtracting the first timestamp from the last timestamp.
- Change the format of this column to duration.
- Create a column 'analysis method' by using the 'starts with' function, resulting in either Process A, Process B, or Process C.
- Z/G/K numbers and blanco samples are removed.
- As the timestamps only represent a part of the process, the assumed lead time outside of the timestamps is calculated in Table 35 by subtracting the lead time within the timestamps (calculated in Power BI) from the given total lead time (see section 1.2.2).

Method	Lead time within timestamps in days	Given total lead time in days	Assumed lead time outside of timestamps in days
Process A	3.52	20.07	16.55
Process B	0.32	4.44	4.13
Process C	3.11	16.49	13.38

Table 33: Calculation of assumed lead time outside of timestamps

- Create column ‘assumed total lead time’, by adding the previously calculated assumed lead time outside of the timestamps to the led time of each sample within the timestamps, using the code in Figure 30.

This figure is removed due to confidentiality issues.

Figure 21: Code used to calculate assumed total lead time

- Change the type of this column to duration.
- Create column ‘target’ that assign each row a target lead time, based on the analysis method. Those given targets are also displayed in section 1.2.2.
- Change the type of this column to duration.
- Create column ‘Otif’ (on-time-in-full) by assigning ‘yes’ if the assumed total lead time is lower than the target, otherwise assign ‘no’.
- Add column called ‘1’, assigning the number 1 to each row. This is used for the creation of the on-time-in-full chart, as we need to sum some values in that chart.
- Create column ‘lowest lead time possible’ by assigning minimum durations (given by the external supervisor) to the rows, based on the analysis method, see Figure 31.

This figure is removed due to confidentiality issues.

Figure 22: Minimum durations assigned to the ‘lowest lead time possible’ column

- Change the type of this column to duration.
- Create column ‘Value-added ratio within timestamps’ by dividing the lowest lead time possible by the lead time.
- Change the type of this column to percentage.
- Filter out all percentages higher than 100%, as the process cannot be that faster than the lowest lead time possible.

In the third table called ‘Sort order and benchmarks’.

- The data in this table is put in manually, see Figure 32. The ‘instrument’ column corresponds with the ‘method & instrument’ column in the timestamps table. A relationship between those in the model view is created, to connect them. The sort order column is used to sort the x-as in this order, as they will be sorted in alphabetical order without a sorting order. The instruments are ordered like they are in the process, and clustered by analysis method (Process A/Process B/Process C). The lower- and upper limits are given by the external supervisor and filled into this table. The lower limit corresponds to the lowest lead time possible per step. The upper limit corresponds to the maximum time a step should take. However, note that the steps often take longer than they should, thus take longer than the upper limit. Finally, the column ‘instrument name’ assigns a name to each step that is describing it in a more understandable way. They are based on the process flows in section 2.6.

This figure is removed due to confidentiality issues.

Figure 23: Input for ‘Sort order and benchmarks’ table

8.6. Appendix F: Steps of dashboard design

Lead time chart:

- Put the Average of Lead time on the y-axis, and the analysis method in the legend of a column chart. This data is from the ‘grouped by sample’ table.
- Adjust the title of the chart to ‘Lead time within timestamps’.
- Adjust the title of the y-axis to ‘Average lead time in days’.
- Remove the title of the legend.
- Increase the width of the columns by reducing the inner padding to the minimum.
- Add data labels with the lead times to the columns.

Average time per step chart:

- Put the ‘Instrument name’ and ‘Instrument’ (from the ‘sort order and benchmarks’ table) on the x-as in this order, and the Average of Duration (from the ‘timestamps’ table) on the y-axis. Add the lower limits and upper limits (from the ‘sort order and benchmarks’ table) as line y-axis.
- Change the title of the y-axis to ‘Time in days’.
- Remove the secondary y-axis.
- Remove the title of the legend.
- Rename ‘Average of Lower limit’ to ‘Lowest lead time possible’ and rename ‘Average of Upper limit’ to ‘Maximum time the step should take’.
- Make the colors of the column corresponding to those in the previous chart, so that the steps of one analysis method correspond to the color of that analysis method.
- Change the color of the upper limit to red and the color of the lower limit to green.
- Add markers to the lines.
- Click ‘Instrument’. Sort this variable on sort order. Do the same for ‘Instrument name’.

On-time-in-full chart:

- Create a doughnut chart with the ‘Otif’ and ‘1’ column.
- Change the position of the legend to top left.
- Change the colors of the slices to red for no and green for yes.
- Change the value decimal places to 0.
- Change the chart title to ‘Assumed on-time-in-full’.

Value-added ratio chart:

- Create a card with the average of the value-added ratio.

Slicer:

- Add a slicer with the analysis methods.
- Remove the slicer header.
- Add title: Analysis method.
- Add subtitle: Applies on three lower visuals.

Other:

- Click edit interactions. Edit the interaction between the slicer and the lead time chart such that the slicer does not influence the lead time chart.
- Add the Company X logo by inserting an image.

- Add the title ‘Dashboard on lead time’ by inserting a text box.

Add a filter that applies on the entire page with the analysis methods. Click all the analysis methods (Process A, Process B, Process C), except [Blank]. This prevents this [Blank] category that is caused by a bug to appear in the slicer on the dashboard.

8.7. Appendix G: Overview of the dashboard

This figure is removed due to confidentiality issues.

Figure 24: Overview dashboard

8.8. Appendix H: Evaluation form

Perceived usefulness:

1. Using this product at work would help me complete tasks faster.
2. Using this product would improve my job performance.
3. Using this product would increase my productivity. (Is about the quality of being able to bring forth any services (Dictionary, n.d.))
4. Using this product would increase my effectiveness at work. (Is about the quality of being able to bring forth an intended effect (Vocabulary, n.d.))
5. Using this product would make it easier to do my job.
6. I would find this product useful at work.

Perceived ease of use:

1. I think I would like to use this product frequently.
2. I found the product unnecessarily complicated.
3. I found the product easy to use.
4. I think I need technical support to use the product.
5. I found the different functions of the product well integrated with each other.
6. I thought there were too many contradictions in the product.
7. I can imagine that most people can quickly get to grips with the product.
8. I found the product inconvenient to use.
9. I felt confident while using the product.
10. I had to learn a lot about the product before I could use it properly.

Each question is asked to be answered on the Likert scale:

- Strongly agree
- Agree
- Neutral
- Disagree
- Strongly disagree

After each question, there is space to add a comment.

At the end of the questionnaire, there is space to add any remaining comments.