MASTER

# Using data of fillet inspection camera to design efficient trimming and logistic processes in a customer-specific manner

Teunesen, Mark J.W.

*Award date:*
2022

Department of Industrial Engineering & Innovation Sciences

Operations, Planning, Accounting, and Control Group

# Master Thesis

## *Using data of fillet inspection camera to design efficient trimming and logistic processes in a customer-specific manner*

M.J.W. (Mark) Teunesen

Student Identity Number: 1014273

March 4, 2022

**Supervisors:**

| | |
|---|---|
| Dr. L. (Lijia) Tan | TU/e |
| Prof. dr. ir. I. (Ivo) Adan | TU/e |
| Ir. R. (Robert) van der Kraan | Marel |

# Abstract

This master thesis project is conducted at Marel Poultry, located in Boxmeer. It describes the opportunities for using the data of fillet inspection cameras to reduce the trim loss and handling cost within the trimming process of broilers' breast fillets at a specific client. Currently, all fillets are sent to human trimmers, who inspect the quality of fillets and are instructed to cut off the defects in terms of fat and blood spots. However, many fillets already meet the quality requirement of customers and therefore do not need to be inspected and trimmed by trimmers. This research proposes four process adjustments to reduce the trim loss and handling cost. Those four process adjustments are: (1) bypassing good quality fillets, (2) bypassing small defected fillets for marinated products, (3) implementing a more efficient distribution algorithm, and (4) distributing the fillets per single fillet instead of pairs. In addition, a data-driven simulation model is built, which could be used to estimate the potential cost-saving of implementing one or several of the before mentioned process adjustments. It has been shown that the process adjustments significantly reduce the trim loss and handling costs. Besides, the data-driven simulation model is robust and adaptable to the processes of other clients.

# Management summary

This master thesis project is performed at Marel, a multi-national food processing company headquartered in Iceland. They are the global leader in transforming the way food is processed. Marel wants to give its clients market advantages through innovations and continuous improvements. This research only focuses on the production line that deals with the breast fillets of broilers. Breast fillets are the most valuable part of broilers and are used within more than twenty different end-products. Each year the quality requirements from retailers and distribution modules became more strict. For the clients of Marel, it is crucial to satisfy the retailers and distribution modules by achieving both the amounts supplied and the quality of the products. Therefore, Marel has to focus on solutions that efficiently guarantee customer quality requirements to satisfy their clients.

### Problem definition

Currently, all fillets are manually inspected and handled by trimmers at the trimming stations. However, Marel found that trimmers trim more from quality B fillets than needed and unnecessarily handle and trim fillets that already meet the quality requirements. However, for some orders, quality B fillets would also be accepted, and therefore there is unnecessary handling cost and depreciation of fillet value due to trimming. Therefore the current design of the trimming process and the corresponding logistic processes around it are not optimal by taking the current development of a fillet inspection camera into account. Therefore the following main research question is formulated:

*How to use the data of the fillet inspection camera to design efficient trimming and logistic processes in a customer-specific manner?*

The following steps are executed to answer the main research question: (1) analyzing the current trimming process, (2) proposing multiple new designs of trimming process which uses camera data, (3) building a data-driven simulation model of the trimming process, (4) testing the proposed new designs in the simulation model, and lastly (5) analyzing the adaptability and robustness of the designs and simulation model.

### Data collection and analysis

The current trim loss at the fillet harvesting line7 is almost 800,000 euros per year, and eight trimmers are currently used at the Trim station. The trimmers at Trim station increase the fillet quality significantly, but
slightly more than 10% of the outgoing fillets still have large defects, which is unfavorable and not accepted by customers. The fraction of good quality incoming fillets is 0.427 before trimming, and therefore, the inflow at the Trim station could be reduced by 42.7% when distributing per single fillet. Currently, fillets are distributed per pair of fillets, which means that the inflow can only be reduced by 18.2%, assuming independence between fillets within a pair. Furthermore, no strong correlations are found between the incoming quality of fillets and the trim loss. Therefore, the trim loss cannot be accurately predicted based on the quality of fillets and therefore is also not modeled as an input parameter with a fixed value or percentage of the fillet weight. In addition, the quality difference between flocks is small. In terms of the trimmers at the Trim station, it is determined that the optimal

utilization is currently 85% and becomes 88% when the fillets are equally distributed based on workload.

## Modeling

A data-driven discrete event simulation model is created within python, in which it is possible to simulate the trimming process. The following four process adjustments are proposed: (1) bypassing good quality fillets, (2) bypassing small defected fillets for marinated products, (3) implementing a more efficient new distribution algorithm, and (4) distributing the fillets per single fillet instead of pairs. The data-driven simulation model determines the potential cost-saving of implementing each relevant combination of the aforementioned process adjustments.

## Model results

For each process adjustment, there are requirements before the adjustment can be implemented. Below, an overview is given of the requirements per adjustment.

| Adjustment | Requirements |
|---|---|
| Bypassing good quality fillets (BA) | Distribution module to bypass fillets (DB)<br>Conveyor belt for bypass lane (CBB)<br>Merger (ME) |
| Bypassing small defected fillets (BB) | Weigher in front of distribution module used for bypass (WB) |
| New distribution algorithm (NDA) | Software update (SU) |
| Distribute per single fillet (DS) | Module to split stream of incoming pairs (MSS) |

It is impossible to give a single cost-saving for implementing each adjustment, since it depends on which other adjustments are implemented. Therefore, the requirements and cost-saving for each possible relevant adjustment combination are shown below. The cost-saving is the aggregated cost reduction in trim loss and handling costs compared to the current yearly cost.

| Implemented adjustments | Requirements | Yearly cost-saving in euros |
|---|---|---|
| BA | DB, CBB, and ME | 118,847 |
| NDA | SU | 118,847 |
| BA and NDA | DB, CBB, ME, and SU | 188,847 |
| BA and DS | DB, CBB, ME, and MSS | 416,828 |
| NDA and DS | SU and MSS | 276,828 |
| BA, BB, and DS | DB, CBB, ME, WB, and MSS | 564,506 |
| BA, NDA, and DS | DB, CBB, ME, SU, and MSS | 416,828 |
| BA, BB, NDA, and DS | DB, CBB, ME, WB, SU, and MSS | 564,506 |

## Robustness of results and adaptability model

Adjusting the incoming quality of fillets can significantly impact the outcomes since the handling times and the possibility to bypass fillets depend on the fillet's quality. Therefore the found cost-savings are not generalizable to other clients. In addition, the required number of trimmers is calculated with a formula using a round-up procedure to an integer. Therefore a small deviation in the handling time or incoming quality percentages could cause a cost-saving difference of 70,000 euros when one trimmer more or less is required. The model can easily be adapted since most variables are modeled as input variables. When the order of modules is different or additional modules need to be added to the model, adjusting the model to other clients' processes requires more effort.

### Conclusion and recommendations

With the help of the simulation model, this research showed that the data generated by the fillet inspection camera could be efficiently used for (1) bypassing good quality fillets, (2) bypassing small defected fillets for marinated products, (3) implementing a more efficient new distribution algorithm, and (4) distributing the fillets per single fillet instead of pairs. All adjustments together could reduce the cost by approximately 564,506 euros per year. In addition, it became clear that the trimming process is client-specific and not the same for multiple clients. Therefore, the simulation model contains many input parameters that can easily be adjusted to simulate the trimming process at other clients when no additional modules are used which are currently not part of the model.

The corresponding recommendations for Marel are:

- Automate data collection
- Implement the process adjustments in the following order:
    1. New distribution algorithm
    2. Distribute per single fillet
    3. Bypass quality A fillets
    4. Bypass small defected fillets
- Assess fillet quality individually
- Investigate the increase in trim performance with the new distribution algorithm

The limitations of this research are:

- Limited available data
- Research focused on single processing line at single client
- Impossible to implement and validate the proposed improvements in real-life
- Increase in trimmers' task performance not validated

# Preface

This master thesis report marks the end of my career as a student. It is the final requirement for the Operations Management and Logistics study at the Eindhoven University of Technology. This report results from an interesting project executed at Marel Poultry within six months. During this period, many people supported me and provided knowledge to complete this thesis. Therefore I would like to thank a few people that have helped me during this thesis.

First of all, I would like to thank my university supervisors Lijia Tan and Ivo Adan for their guidance, valuable feedback, and suggestions during the project. I am grateful for your support during this master thesis project. Moreover, I would like to thank PhD-student Nick Paape, who is currently doing a project at Marel, for discussing and brainstorming regarding the simulation model.

Besides, I am very grateful for Marel Poultry's opportunity to conduct my master thesis project at their Innovation department. You have created a work environment wherein I felt really part of the team and continuously gave me new insights during the project. In particular, I would like to thank Robert van der Kraan for being my company supervisor and sharing your expertise about the topic, helping me understand the process, giving me the opportunity to visit clients, and discussing the findings. In addition, I want to thank all employees at Marel who helped me acquire data and gave me feedback related to the project.

Finally, I would like to thank my parents, girlfriend, and friends for their encouragement and support during my student life.

Mark Teunesen

## Table of contents

# List of Figures



# List of Tables

# List of Abbreviations

| Abbreviation | Definition |
|---|---|
| BA | Bypassing quality A fillets |
| BB | Bypassing small defective fillets for marinated products |
| BPD | Business Process Diagram |
| BPM | Business Process Modelling |
| BPMN | Business Process Modelling Notation |
| CBB | Conveyor Belt for Bypass lane |
| DB | Distribution module for Bypassing fillets |
| DES | Discrete Event Simulation |
| DS | Distribute per Single fillet |
| FEL | Future Event List |
| FES | Future Event Set |
| FQT | Fillet Quality Tool |
| ME | Merger |
| MSS | Module to Split Stream of incoming fillets |
| N | Sample Size |
| NDA | New Distribution Algorithm |
| ROI | Return On Investment |
| SPSS | Statistical Package for the Social Sciences |
| SU | Software Update |
| WB | Weigher in front of Bypass distribution module |
| 7PMG | Seven Process Modelling guidelines |

# 1. Introduction

## 1.1 Company introduction

Marel is a multi-national food processing company headquartered in Iceland. They are the global leader in transforming the way food is processed. Marel supports high-quality, safe, and affordable food production by providing software, services, systems, and solutions to the fish, meat, and poultry processing industries. They have a network of over 7000 people in over 30 countries worldwide. This research is conducted within the business unit Marel Poultry in Boxmeer and focuses on a single client, referred to as client X, for privacy reasons. An overview of the supply chains where Marel Poultry is part of can be found in Figure 1 below.

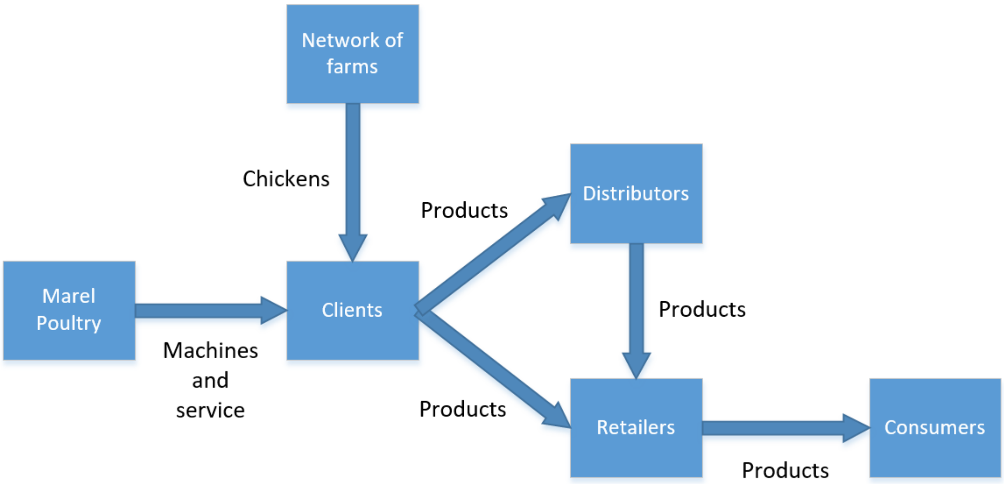



*Figure 1: Supply Chains overview*

Marel Poultry designs, produces, and installs machines for the poultry processing industry and takes care of the service work for these machines. In addition, they build solutions for all sub-processes within poultry processing plants. The fixed process sequence of poultry processing plants is explained in more detail in Appendix A.

Marel wants to give its clients market advantages through innovations and continuous improvements. Most clients of Marel are owners of food processing plants in which the supplied broilers are further processed into end-products that are directly sold to retailers or distribution modules. Via retailers, the end-products are available for consumers within supermarkets and (fast-food) restaurants.

Most clients of Marel produce a large variety of end-products for retailers and distribution modules. Broilers can be sold as whole chicken, but the broilers are cut up into multiple end-products in most cases. The most common parts of broilers sold as consumable goods are wings, thigh fillets, breast fillets, legs, and organs such as the liver and heart. This research only focuses on the production line that deals with the breast fillets of broilers. Breast fillets are the most valuable part of broilers and are used within more than twenty different end-products.

## 1.2 Background information

Food processing industries experience growing logistical demands, growing variety in products, and intense competition (Van Donk, 2001). Besides the increased logistical demands and growing variety, 'GFK Huishoudpanel' found in a research conducted for Vion food group that consumers are more focused on the quality of meat than ever before (Vion food group, 2016). The clients of Marel are therefore also more focused on the visible quality of their end-products since they received feedback from retailers that selling fillets with visible defects is hard. Due to these changing market demands, the quality requirements from retailers and distribution modules became more strict. For the clients of Marel, it is crucial to satisfy the retailers and distribution modules by achieving both the amounts supplied and the quality of the products. Therefore, Marel has to focus on solutions that efficiently guarantee customer quality requirements to satisfy their clients.

Currently, the quality inspection within the trimming process is executed by humans. However, in large manufacturing companies with high daily production quantities, human inspections are very costly, time-consuming and in most cases, humans cannot inspect all units (Weimer et al., 2014). In addition, a limitation of using human inspections is that they have a subjective evaluation of visual quality, while computer-based quality inspections are objective (Laofar & Peansupap, 2012). One of the causes is the anchor effect, which leads to subjective perceptions of humans (Monroe, 1957). Furthermore, each customer could have other threshold values for classifying a fillet as quality A. The difference between those threshold values is just a few square centimeters or even millimeters. Therefore it is hard for humans to execute quality inspection efficiently. Therefore, automated visual inspection is undergoing substantial growth in the food industry because of its cost-effectiveness, consistency, superior speed, and accuracy (Brosnan & Sun, 2004). Also, Marel is now focusing on developing and testing a fillet inspection camera that can overtake (part) of the human quality inspection for processing breast fillets.

## 1.3 Harvesting and processing breast fillets

All clients desire efficient solutions to harvest and process breast fillets, since breast fillets are the most valuable part of broilers. Since Marel has customers worldwide and continuously innovates, the number of unique processing lines sold for harvesting and processing breast fillets is large. However, two common processing lines currently deal with harvesting and trimming breast fillets. Below a short description of both processing lines is given, including the logistic process of distributing the fillets over the different batch processes.

### 1.3.1 Fillet harvesting line + Trim station trimming line

A simplified representation of this processing line can be found in Figure 2. The first module in this processing line is the fillet harvesting line. The fillet harvesting line automatically harvests breast fillets from the carcass and drops both fillets of one carcass side-by-side on a conveyor belt. Since the harvesting of the fillets is automated, the quality of the fillets is worse than at the fillet harvesting line-i trimming line, where trimmers harvest fillets manually. However, the yield of harvesting in terms of fillet weight is higher on the fillet harvesting line than the fillet harvesting line. As shown in Figure 2, all fillets harvested by the fillet harvesting line are transported to the trimming station called the Trim station, where human trimmers inspect the quality and improve the quality of the fillets when possible. The Trim station is called off-line trimming, and the + Trim station is most efficient for large broilers. The trimmers working at the Trim station have to let only quality A fillets pass the station to the automated batching processes, putting quality B fillets on a separate conveyor belt to the external trim station and throwing the trim in a hole in the workstation.

After the fillets left the Trim station, there is, in most cases, a bone detection module that determines if there are still bones left within the fillet. If so, those fillets are sent back to a trimmer working at the Trim station. Afterward, each fillet is distributed to a batching processing line based on their weight and the quantity needed within different orders. For example, an order can be schnitzels, medallions, shawarma, or chicken strips.

X

*Figure 2: A simplified visual representation of the fillet harvesting line + Trim station trimming line and the corresponding logistic process around it*

### 1.3.2 fillet harvesting line-I trimming line

In comparison to the fillet harvesting line + Trim station processing line, harvesting and trimming are combined within a single module called the fillet harvesting line-i. Within the fillet harvesting line-i, the fillets are harvested manually from the carcass, and the trimmers who harvest the fillets immediately do the quality inspection and, if necessary, trim the fillets. The trimmers at the fillet harvesting line-i line have the same three options (let the fillet pass to the bone detection module without trimming, trim the fillet and pass the fillet to the bone detection module, or reject the fillet) for each fillet as the trimmers at the Trim station. The fillet harvesting line-i module is better equipped for small broilers. In Figure 3 below, a simplified schematic representation of the fillet harvesting line-i processing line can be found.

X

*Figure 3: A simplified visual representation of the fillet harvesting line-i trimming line and the corresponding logistic process*

### 1.3.3 Overview trimming process at a client

In practice, both trimming lines can be combined at a single client, and also multiple of the same lines could be used in parallel within the factory. Therefore the trimming process is more complex than the simplified representations in Figures 2 and 3 above. Figure 4 provides a schematic overview of the trimming process at a large retail-focused customer. The color of each arrow indicates the quality of the fillets within each flow. The number of arrows used between machines corresponds to the number of conveyor belts. At the bottom of Figure 4, a legend is given which explains the meaning of each arrow/box.

X

*Figure 4: Overview of trimming process and corresponding logistic processes at retail-focused client*

## 1.4 Problem description

Marel observed that trimmers at the trimming station trim more from quality B fillets than needed and unnecessarily trim quality A fillets. However, for some orders, quality B fillets would also be accepted, and therefore there is unnecessary handling cost and depreciation of fillet value due to trimming. For example, for end-products such as schnitzels and medallions, part of the fillets are marinated, and therefore the defects within quality B fillets are not or less visible in those marinated end-products and therefore accepted by retailers. Furthermore, since the fillet value is around 4 euros per kilogram and the trim is only worth around 2 euros per kilogram, clients' yield can also be increased by using the data of the quality inspection camera to reduce the trim loss. Therefore the current design of the trimming process and the corresponding logistic processes around it are not optimal by taking the current development of a fillet inspection camera into account. Based on the quality assessment of the fillet inspection camera, the fillets can also be distributed based on their quality. There are two possibilities of using the fillet inspection camera. One is to be used in front of the trimming station to determine which fillets can be directly used for end-products without being trimmed. The other is to be used after the trimming station to ensure a fillet's preferred quality within each batching process. Figure 5 visualizes the possibility of using the fillet inspection camera within a single fillet harvesting line + Trim station line, which is based on the first trimming line in Figure 4. It is important to note that the fillet inspection camera can share data regarding the fillet quality with the distribution modules and Trim station, which can use this information to distribute fillets efficiently.

X

Figure 5: *Graphical representation of the possibility of how to use the camera within the trimming process*

The fillet inspection camera is only implemented at one of Marel's clients, referred to as client X, for privacy reasons. The camera is only implemented at a single client, since the fillet inspection camera is currently not available for sale and is still in development. Two fillet inspection cameras are installed on the same fillet harvesting line + Trim station trimming line, one before the Trim station and one after the Trim station. These fillet inspection cameras scan each fillet and generate two types of inspection output. The first output type is a list of all defects detected on a fillet. The second type of output is a quality label per fillet, based on the list of defects. The camera is currently programmed to detect excess skin (yes/no), blood spots (small, medium, and large), and fat spots (small, medium, and large). However, these inspection outputs for filets are currently not used to control the distribution modules and Trim station. Therefore Marel wishes to find out how the data of the fillet inspection cameras can be used to design an efficient trimming and corresponding logistic processes around it. There is no specific design optimal for all clients since Marel has clients worldwide with different processes, requirements, customers, etc.

## 1.5 Research scope

This research focuses on the fillet harvesting line + Trim station trimming processing line at client X, at which the fillet inspection cameras are currently tested. Client X is a large retail-focused client, for which the trimming process is a crucial part of their business. Retail-focused clients are one of the seven client types classified by Marel. An overview of all seven client types can be found in Appendix B. The retail-focused client type has the most complex logistic processes around trimming since the variety of end-products is high, and customers' requirements are more strict. By focusing on this client, the generated simulation model can easily be simplified to represent the more simple processes of other clients. The project's scope is the trimming process's design from the moment the fillets are harvested from the carcass until the fillets are distributed to one of the batching processes. The trimming process is intermediate between the main processes 'deboning' and ' batching,' explained in more detail in Appendix A. The scope on the process level is represented in Figure 6 below.

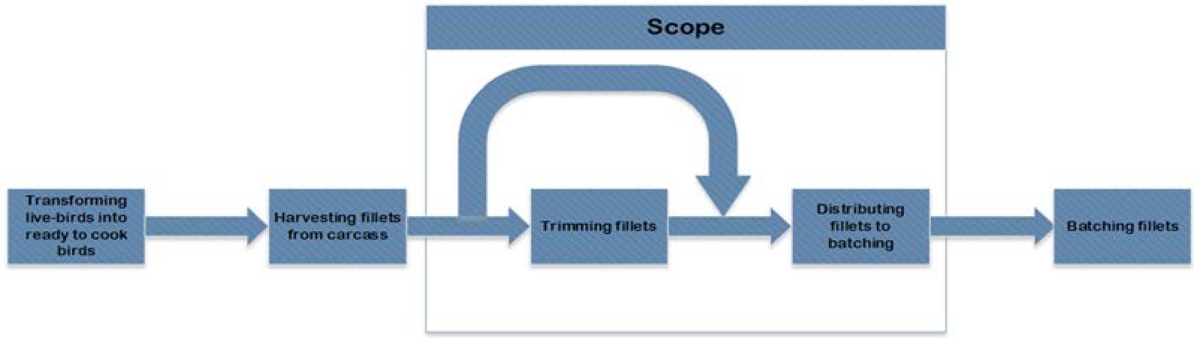



*Figure 6: Graphical representation of the research scope*

Below, two shortlists indicate which parts of the process are in and out-of-scope of the project.

**In-scope:**

- The following modules: fillet inspection cameras, Trim station, bone detection module, distribution modules, and conveyor belts. More information regarding those modules can be found in Appendix C.
- The position of all modules within the process, incoming product flows, product flows in between the different modules, and the product flows leaving the in-scope process.
- The number of trimmers working at the Trim station and the distribution algorithm used to divide the fillets over the trimmers
- The demand of each end-product, since within the proposed design, it needs to be ensured that all demand can be met.

**Out-of-scope**

- The fillet harvesting process of the fillet harvesting line-module.
- Developing/adjusting the complex underlying algorithms used to instruct the modules.
- The batching processes itself that converts (trimmed) fillets into end-products.
- Feasibility of design in terms of currently available modules.

## 1.6 Research questions

The main goal of this research is to get insight into how the data of the fillet inspection camera can be used within the trimming process and logistic processes around it to generate more value for clients. The research is executed for the trimming processing line at client X, but the main research question is as follows:

***How to use the data of the fillet inspection camera to design efficient trimming and logistic processes in a customer-specific manner?***

A set of five sub-questions is formulated and individually explained in more detail below to answer the main research question.

***SQ1. What do the current trimming and corresponding logistic processes look like at client X?***

The current processes at client X will be mapped in terms of locations of all modules and their incoming and outgoing flows, which could be used to determine the current performance of the process. The performance indications in terms of throughput, utilization, trim loss, and handling cost of the current situation are used to determine the potential cost-saving of implementing some improvements. Furthermore, the current situation must be modeled to validate the simulation model and determine the cost-saving of new proposed configurations.

***SQ2. How to evaluate and reduce the trim loss and handling cost at the Trim station?***

One of the main parts of the research is to find a design that reduces the trim loss and handling cost at the Trim station. To compare those values of the old design with the new design, first, the current trim loss at the Trim station needs to be evaluated. Currently, only the total trim loss of all trimmers is measured at the Trim station each hour. However, to measure the reduction in trim loss, when data regarding the fillet quality is known and used, the trim loss needs to be determined per type of incoming quality. Therefore, the expected amount of trim for each incoming fillet will be helpful to determine the reduction in trim loss when bypassing fillets.

***SQ3. What are the suggested designs, in terms of product flows, for the trimming and corresponding logistic processes based on using the data of the fillet inspection camera?***

Based on analyzing the current situation and the data generated by the fillet inspection camera, suggestions for a new design can be proposed. Within these suggestions, each module's capacity and other specifications need to be considered together with the current utilization of each conveyor belt and module. In addition, the demands of each end-product need to be taken into account to ensure that all those demands can be met by sending the right amount of fillets of the desired quality to the corresponding batching processes. Therefore the suggested designs would be specific regarding incoming and outgoing product flows and the modules used, based on client-specific demand and requirements. Finally, all of those suggested designs will be tested within the data-driven simulation model and proposed to employees within Marel to assess each proposed design.

***SQ4. What is the potential value of implementing the new designs?***

A data-driven simulation model will evaluate the proposed designs. The reduction of trim loss and handling cost reflects a proposed design's potential value. In addition to the cost-related performance indicators, the performance of each model will also be measured in terms of average waiting time, the maximum number of fillets waiting, and the utilization of trimmers.

***SQ5. Can these new designs and the data-driven simulation model be adapted to other clients?***

As mentioned before, Marel has clients worldwide with different processes, requirements, customers, etc. Therefore it is essential to determine if the new designs for client X and the simulation model can be adapted to other clients. In addition, the found potential value of implementing the new design is based on a single client's set of input parameters. Therefore, it needs to be determined if the results for this specific client are generalizable.

## 1.7 Research Deliverables

After finishing the research, the following main deliverables will be provided to Marel. First, I will provide Marel with an extensive data analysis regarding found relationships between the fillet quality and other variables such as trim loss and throughput. Second, I will propose new designs for the trimming process and corresponding logistic processes that reduce handling costs and trim loss. New designs will be proposed for both short- and long-term. Finally, these new designs will be tested, and for each model, a list of requirements will be provided in terms of modules and innovations needed. These models will be tested within a discrete-event simulation model. This camera data-driven simulation model will be provided to Marel, in which they can estimate the potential value of implementing new designs in the future for multiple clients.

# 2. Research design

## 2.1 General approach

The design of this thesis is based on the research model of Mitroff et al. (1974), which can be found in Figure 7 below. They developed a research model which covers a research methodology for generating a quantitative model.

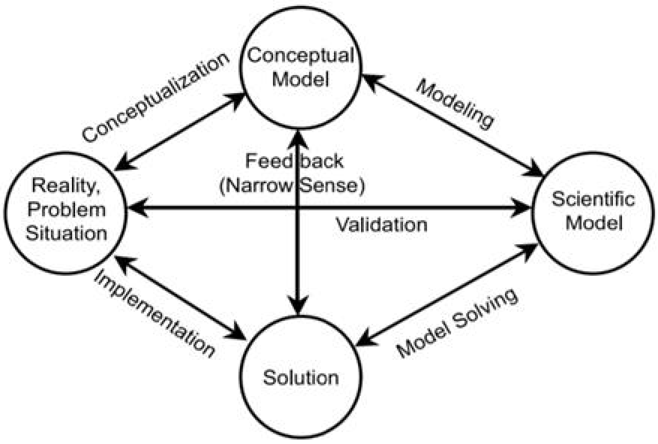



*Figure 7: Research model of Mitroff et al. (1947)*

First of all, the current situation needs to be analyzed. Then, when the current process is known and clear, a conceptual model can be created for determining the relevant variables, parameters, machines, and flows. Then, based on the conceptual model, a scientific model can be developed to determine the cost savings and resources needed for each proposed model. Besides, it is essential to validate if the scientific model represents the actual situation well and if the solution is ready to be implemented.

## 2.2 Research methodology

Figure 8 provides an overview of the research methods used in this project. Below Figure 8, it is explained for each part how the mentioned methods are used and for which purpose.

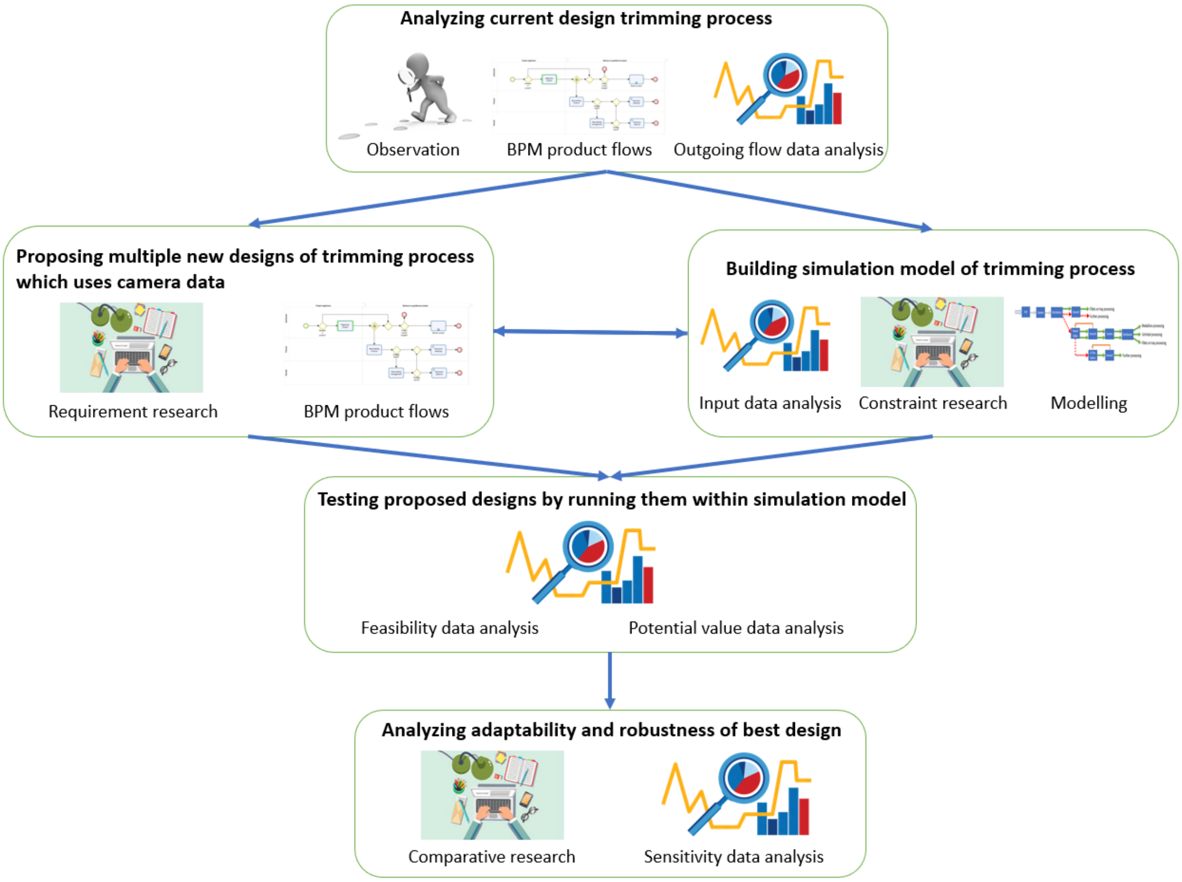



*Figure 8: Diagram of research methodology used within the project.*

### 2.2.1 Analysing current design trimming process

***Observation of current trimming process and logistic processes***

During visits at client X, the trimming process and logistic processes around will be observed. In addition, a schematic overview will be sketched of the location of modules and the incoming and outgoing flows of each module. Furthermore, the trimmers at Trim station will be observed to get insights into those employees' tasks and task performance.

***BPM for product flows within current trimming and logistic processes***

Business Process Modelling (BPM) will be used to convert the sketch of the current processes into a well-known BPM model. All modules and product flow in this BPM model represent client X's current trimming and logistic processes.

***Outgoing flow data analysis on current trimming and logistic processes***

Based on the available data regarding the throughput of fillets per minute at each module and each product flow on a conveyor belt, the current utilization of all modules will be calculated. In addition, there are more outgoing flows than incoming flows at the Trim station, bone detection module, and distribution modules. For those modules, it is essential to analyze each conveyor belt's outgoing probability or rate. Data regarding the daily throughput of fillets through the process is available per day and even per minute for every production day.

### 2.2.2 Proposing multiple new designs of trimming process which uses camera data

***Requirement research***

The research will be conducted to determine the requirements of the proposed new trimming and logistic processes. Requirements that need to be considered are the minimum and maximum amounts of conveyor belts in between modules and the batching processes. In addition, other new design requirements need to be determined based on conversations with employees within Marel and clients.

***BPM for new product flows within proposed design trimming and logistic processes***

BPM will visualize the different proposed new designs for the trimming process. The new proposed designs are based on the current situation analysis results and include the fillet inspection camera. Those new proposed designs shall differ in terms of positioning and amount of modules used within the design and the different ingoing and outgoing product flows of modules.

### 2.2.3 Building simulation model of the trimming process

***Input data analysis***

It is essential to analyze data regarding the important input parameters of the model to build the simulation model. For example, two important input parameters are the quality of the fillets and the trim loss rate at the Trim station.

- **Quality of fillets**

  The quality assessments generated by the post-trim fillet inspection camera (after the Trim station) are available for a couple of months. The data is available for all fillets that passed the fillet inspection camera. The data consist of the amount, type, and sizes of defects on each fillet and the corresponding quality label. This data can be analyzed daily at each customer and flock level. The pre-trim fillet inspection camera (in front of the Trim station) can generate the same data, but this data is currently not stored on a server, but this will be done as soon as possible. In addition, data from the last four months is available regarding the current trim loss at the Trim station per minute in the test-line at client X. This data will be used to determine the ingoing and outgoing quality distribution of fillets at the Trim station.

- **Trim station trim loss rate specified in each type of defect**

  It is essential to determine the expected amount of trim loss within the model when a particular fillet with a specific type of defect should be sent to the Trim station. For the relevant data needed regarding the defect-specific trim loss, Marel can instruct the Trim station so that the data from the fillet inspection camera can be used to manipulate the division of fillets over trimmers at the Trim station. The cut-off trim by each trimmer can be separately collected and weighted within the processing plant during field tests. Such a field test was executed once before. The average current aggregated trim loss was compared with the aggregated trim loss when manipulating the Trim station. During manipulation of the Trim station, one trimmer received only quality A pairs of fillets without trimming those fillets since the knife and scissors were taken away.

***Constraint research***

In addition, research needs to be conducted regarding some constraints within the model. For example, the capacity of the conveyor belts and the corresponding capacity of the modules needs to be determined. Besides, validation needs to occur if the simulation model is appropriate to simulate the actual trimming process. Therefore, the current design of the trimming process will be used within the simulation model to validate the model. In addition, the actual data of incoming fillets at the trimming process will be used within the simulation model and compared to the actual trim loss and throughputs at client X.

***Modeling***

A discrete event simulation model will be used for simulation. The simulation model needs to be easily adaptable between different configurations since multiple proposed designs need to be tested within the simulation model. In addition, the required input parameters need to be easily changeable to make the model flexible to be customer-specific. The simulation model has to deal with input parameters such as the weight and quality distribution of incoming fillets and the demand of each end-product. Furthermore, the model itself needs to visually represent the design of the trimming process and logistic processes around it. The model's output will consist of the resources needed, the utilization of all modules, and the trim loss at the Trim station.

### 2.2.4 Testing proposed designs by running them within a simulation model

***Feasibility data analysis***

The feasibility of the proposed designs needs to be analyzed in terms of module utilization and minimal throughput. Since all conveyor belts within the trimming process and logistic processes around it have a fixed speed, it needs to be taken into account that the capacity will not be exceeded. Furthermore, for the required amount of fillets or fillet weight needed at different batching processes, it needs to be ensured that it is possible to meet these demands within the current design.

***Potential value data analysis***

The potential value of each design needs to be determined and compared to the current situation. First, the number of modules needed in a new design will be compared with the number used in the current design. Secondly, the number of trimmers needed at the Trim station needs to be determined based on this station's peak load and average utilization. Thirdly, the reduction in trim loss needs to be determined within the new design compared to the current design. Lastly, the proposed design results will be compared with the current design results. The ' comparisons with a standard ' method of Law (2015) will be used to determine the potential benefit of each model. Within Law's method, the performance indicators of the current situation are used as input for the variable ' standard '.

### 2.2.5 Analysing adaptability and robustness of best design

***Comparative research regarding input values and design at different clients***

First, it needs to be determined if the (simulation model of the) trimming process at client X can be easily adapted to the trimming process at other clients. The slight change could significantly impact the results since each client is specific in design and product flow. Therefore, designs and data of other clients need to be tested within the model. These differences in product flow and input parameters need to be determined for other relevant retail-focused clients.

***Sensitivity data analysis***

When the range of values for the different input parameters and the different designs at retail-focused clients are determined, a sensitivity analysis will be conducted. These sensitivity analysis results will determine if the found optimal design and feasibility of the design at client X can easily be adapted to the processes at different clients. In addition, the robustness of the potential value of the new design will be analyzed over different sets of input parameters.

# 3. Data collection and analysis

## 3.1 Data collection

Data needs to be collected and analyzed to create a simulation model of the trimming process, which accurately represents the trimming process at client X. First, the current trimming process is analyzed in detail to determine which modules and variables are relevant for the simulation model. Second, for all relevant variables, data is collected to simulate the current trimming process accurately.

### 3.1.1 Process overview

The process overview consists of two parts. The first part is to overview the current configuration of the trimming and logistic processes at client X. The second is to model all decisions and corresponding product flow of fillets through the system in a Business Process Diagram (BPD) using Business Process Modeling Notation (BPMN).

X

*Figure 9: Overview of the current process*

Figure 9 visualizes the configurations of the current trimming process and corresponding logistic processes at client X. Product flows start from the left bottom, where the fillet harvesting line harvesting module constantly supplies fillets to the Trim station. Each pair of breast fillets of each chicken are placed side by side on the conveyor belt. The pre-trim camera scans the fillets and attaches a quality label to each fillet. The quality labels are in range A~H. Quality A is the best quality, and the quality decreases when taking the following letter of the alphabet. For each quality label, there are threshold values regarding the blood area, fat area, and the presence of skin. The blood area and fat area are measured in squared millimeters. The presence of skin is indicated by yes or no. Table 1 provides an overview of each quality label with the corresponding threshold values.

*Table 1: Overview of quality labels and corresponding defect and threshold values*

| Quality label | Defect | Blood area X | Fat area Y | Skin Z |
|---|---|---|---|---|
| A | None | X<=5 | Y<=150 | Z=no |
| B | Small blood spot | 5<X<=10 | Y<=150 | Z=no |
| C | Small fat spot | X<=10 | 150<Y<=300 | Z=no |
| D | Medium blood spot | 10<X<=20 | Y<=300 | Z=no |
| E | Medium fat spot | X<=20 | 300<Y<=550 | Z=no |
| F | Large blood spot | X>20 | Y<=550 | Z=no |
| G | Large fat spot | X=>0 | Y>550 | Z=no |
| H | Skin | X=>0 | Y=>0 | Z=yes |

Note all numbers represent the area in square millimeters

Next, each pair of incoming fillets is distributed over trimmers around the Trim station. The trimmer at the top right receives fewer new incoming fillets than the other trimmers, since this trimmer also receives all fillets sorted out by the bone detection module. The fillets sorted out by the bone detection module contain bones, which need to be removed.

The trimmers at the Trim station inspect the quality of each fillet. The fillets are manually assessed as quality A, quality B and trimmable, quality B and not trimmable or quality X. Quality B in this process represents all quality labels except for label A. The capability of trimming a quality B fillet depends on the defect type and especially the defect's location. Explicitly, if the defect can be trimmed off while maintaining a naturally shaped fillet, the quality B fillet is trimmable. Quality X fillets are those fillets that are not appropriate for human consumption. Some examples of quality X fillets are fillets in which diseases are spotted, and contaminated fillets felt on the floor.

When a fillet is assessed as quality A or trimmed from quality B to A, the fillet is put on a conveyor belt to the bone detection module within the main process stream. The trim residual is thrown on a conveyor belt through a hole in the work table. This conveyor belt transports the trim residuals of all trimmers at the Trim station to a single weigher, which is measured on an hourly basis. The not trimmable B fillets are sent via a conveyor belt to the Trim Table B, a humanly operated trimming station. This trimming station also receives not trimmable filets from two fillet harvesting line-trimming stations, but this is out of the scope of this research. At Trim Table B, fillets are automatically distributed over trimmers. The trimmers at Trim Table B need to cut off all defects without remaining a natural shape of a fillet. The trim residual at this station is also collected and weighed after being thrown in the holes on the working tables. The remaining quality A parts of the fillets trimmed at Trim Table B are transported to a second bone detection module on a conveyor belt.

Within the bone detection modules, fillets are weighted and scanned in the presence of bones. If the fillet contains bones, the fillet is sorted out and sent back to one of the trimmers at the trimming station before the bone detection module (Trim station or Trim Table B). All fillets passing the bone detection module located after the quality B Trim Table are collected and manually transported to the I-cut batching process, especially for creating Shawarma. All fillets passing the bone detection module located after the Trim station are sent to the distribution modules. Before the fillets are distributed over different batching processes, the quality of half of the fillets is assessed by the post-trim camera. The post-trim camera does the same work as the pre-trim camera and attaches one of Table 1 mentioned quality labels to each fillet. The distribution modules divide the fillets based on their weight and the quantity needed at each batching process. Fillets are weighted at the bone detection module, and due to a tracking system each fillet can be tracked over the conveyor belt, which lets the distribution modules know what action to do at each moment. Distribution modules automatically divide the fillets over four batching processes. These batching processes determine which fillet weight range and quality are most optimal to send to each process. Therefore, the distribution modules can sort out specific fillets that meet the weight and quality of the upcoming batching process. Within the batching processes a large set of different end-products are generated.

The abovementioned information is also represented within an increasingly important standard for process modeling, called a BPMN model (Recker, 2010). Within the BPMN-focused Business Process Diagram, all actions and possible routes of fillets through the system are represented. The BPD can be found in Figure 10 on the next page. Within the BPD, all five relevant modules of interest within each design have their lane with their corresponding processes and decisions.

The seven Process Modeling Guidelines (7PMG) of Mendling et al. (2010) are taken into account to increase the understandability and quality of the BPD. However, some of the guidelines are contradicting, and therefore it needs to be considered which guidelines are more important for this specific process. In Table 2 below, the seven guidelines can be found in ranked order from most important to least important, according to Mendling et al. (2010).

*Table 2: Ranked overview of the 7PMG of Mendling et al. (2010)*

| Guideline ranked on importance | Explanation |
|---|---|
| 1 | Model as structured as possible |
| 2 | Decompose a model with more than 50 elements |
| 3 | Use as few elements in the model as possible |
| 4 | Use verb-object activity labels |
| 5 | Minimize the routing paths per element |
| 6 | Use one start and one end event |
| 7 | Avoid OR routing elements |

All guidelines of Mendling et al. (2010) are used to increase the understandability of the BPD model in Figure 10. However, not all guidelines can be fully complied with since the guidelines are contradicting in some cases. For example, two parts within the process-specific model cannot meet all guidelines. The first one is when a decision needs to be made on dealing with the quality assessment of trimmers since there are three possible decisions with different paths, namely: quality A, quality B, and quality X. According to guidelines 1 and 3, it is better to use a single gateway with all three possible routes for each quality since this is in line with the actual process. However, this contradicts guideline 5, which proposes to minimize the routing paths per element. Because Mendling et al. (2010) concluded based on extensive research that structural modeling and using as few elements as possible are more important than minimizing the routing paths per element, it is decided to use a single gateway with three outgoing flows. Besides, guidelines 3 and 6 contradict guideline 1 regarding the number of end events used for the trimming process. When following guidelines 3 and 6, one end event has to be used. However, not all fillets leave the system to the same final destination within the trimming process. Therefore a lack of information will occur when following guidelines 3 and 6. In addition, since many arrows are going to an end event from different lanes, it is not structured to use only one end event, which is not in line with the most important guideline 1. Combining the most important guideline 1 with the lack of information when using one end event, It is decided to use multiple end events, one for each final destination of a fillet.

*X*

*Figure 10: BPMN model of the trimming and logistic processes around handling breast fillets at client X*

### 3.1.2 Sources of automatically generated data

Marel uses a powerful and comprehensive software tool called Innova, which collects and collates data, allowing food processors to improve performance and productivity. However, for this specific process, Innova only collects data of the bone detection modules. Since the inspection cameras and distribution modules are still in the development phase, the Innova team is still working on creating insights into the fillet quality and the paths of each fillet. For both bone detection modules, Innova shows the total throughput in fillets per day and the number of rejections per day. This data has been available for the last couple of years and could be helpful to determine the average rejection rate of fillets per day.

Since Innova could not give insights into the quality of fillets, the Fillet Quality Tool (FQT) is also used. FQT logs the quality assessments made by both the pre-and post-camera and creates every five minutes a CSV file with all relevant information per (pair of) fillets. The surface of the fillet(s) and the surface of blood and fat defects in mm2 are represented in this CSV file. In addition, the FQT aggregates all 5-minute files into a single CSV file. However, based on research of the camera developers, it is concluded that the camera's performance in detecting defects significantly drops when nobody cleans the camera each morning. Therefore the data used within the FQT tool regarding the quality is only valid when the cameras are correctly cleaned. In addition, the inflow of fillets at the pre-camera and post-camera can be determined by counting the number of scans made within a specific time interval.

At both trimming stations (Trim station and Trim Table B), all trim is collected on a conveyer belt, dropping the trim into a weigher. This weigher measures the total amount of trim per hour collected by client X. Since the weigher is of an external party, only the data regarding the trim per hour can be collected by asking client X for it.

### 3.1.3 Sample tests

Client X is visited several times to observe each part of the process and execute sample tests to get more insights. For example, on January 10 and 11, 2021, the throughput on each conveyer belt, the rejection rate of both bone detection modules, trimmers' handling time and utilization, and the trim loss per five minutes were measured several times.

#### *3.1.3.1 Throughput of the system*

The system throughput is an important measure for the design and continuous improvement of a process (Li, 2004). Analyzing the system throughput can help find bottlenecks (Li, 2004) and determine the line performance (Blumenfeld, 1990). Figure 11 visualizes the product flows in relevant processes. The flows represented by arrows are indexed by 1~18 in Figure 11. Based on 50 sample tests, the average amount of fillets ($\mu_{tp}$) and the corresponding standard deviation ($\sigma_{tp}$), and coefficient of variation ($CV_{tp}$) on each arrow are presented in Table 3 below.

X

*Figure 11: Throughput scheme of the current process*

*Table 3: Average throughput and corresponding standard deviation and coefficient of variation*

| Arrow | μ_tp | σ_tp | CV_tp |
|---|---|---|---|
| 1 | 146 | 1.95 | 0.01 |
| 2 | 146 | 1.95 | 0.01 |
| 3 | 146 | 6.34 | 0.04 |
| 4 | <1 | <1 | - |
| 5 | 15 | 5.12 | 0.34 |
| 6 | 15 | 2.87 | 0.19 |
| 7 | 131 | 12.36 | 0.09 |
| 8 | 13 | 3.23 | 0.25 |
| 9 | 118 | 13.42 | 0.11 |

| Arrow | μ_tp | σ_tp | CV_tp |
|---|---|---|---|
| 10 | 31 | 16.12 | 0.52 |
| 11 | 87 | 19.39 | 0.22 |
| 12 | 52 | 20.98 | 0.40 |
| 13 | 35 | 18.62 | 0.53 |
| 14 | 45 | 10.64 | 0.24 |
| 15 | <1 | <1 | - |
| 16 | 65 | 12.97 | 0.20 |
| 17 | 5 | 1.54 | 0.31 |
| 18 | 60 | 14.88 | 0.25 |

The standard deviations presented in Table 3 show that the product flows are not steady over time. Only the inflow of fillets at the pre-camera and Trim station is quite constant. From the Trim station (arrows 3 and 5) onwards, the variance sharply increases when there is no longer a single product flow. Since the trimmers at the Trim station determine which path a product follows based on the fillet's quality, there may be a correlation between the incoming quality and the throughput. The large CV at the distribution modules (arrows 8, 10, 12, and 13) is caused by the fact that demand depends heavily on the time of the year. In addition, some paths are disabled when demand is already met, or there is a priority at other batching processes, leading to a throughput of zero fillets per minute.

#### *3.1.3.2 Trim loss*

Besides sample tests regarding the throughput, also sample tests are executed to get insight into the trim loss within a smaller interval. Since only the trim loss is known per hour, sample tests are executed to determine the trim loss per five minutes at the Trim station and B Trim Table (both N=11). During the sample tests, the trim loss of all trimmers is collected and weighed before falling into the weigher and afterward inspected and weighed. The sample test is repeated over different days, flocks, and within the same flock to get insight into the variation over time and flocks. A flock is a group of broilers bred in the same period at a single farm. In addition to the trim loss per interval of five minutes, the number of fillets trimmed is counted since the number of fillets trimmed at both trim stations is not steady every minute. This makes it possible to calculate the average trim loss per fillet in grams. This metric (trim loss per fillet in grams) reduces the variability in trim loss caused by the different number of fillets trimmed during each sample test. The average trim loss per fillet is determined at the fillet harvesting line7 ($\mu_{Trim\_1}$) and B-ware ($\mu_{Trim\_2}$). The results of this sample test can be found in Table 4 below.

*Table 4: Average trim loss in grams per fillet within a specific flock based on sample tests of 5 minutes each*

| Sample | Flock | $\mu_{Trim\_1}$ in grams/fillet | $\mu_{Trim\_2}$ in grams/fillet |
|---|---|---|---|
| 1 | 004 | 17.26 | 35.14 |
| 2 | 006 | 18.68 | 64.72 |
| 3 | 007 | 23.21 | 58.55 |
| 4 | 009 | 15.71 | 58.46 |
| 5 | 010 | 14.32 | 83.48 |

| | | | |
|---|---|---|---|
| 6 | 102 | 12.64 | 66.60 |
| 7 | 102 | 13.48 | 69.65 |
| 8 | 103 | 11.88 | 72.47 |
| 9 | 105 | 13.14 | 79.63 |
| 10 | 106 | 15.84 | 69.01 |
| 11 | 106 | 16.06 | 87.36 |

As can be concluded from Table 4, the variability of the average trim loss per fillet per flock is quite large. The total amount of trim per year at the fillet harvesting line7 costs client X just below 800,000 euros in value depreciation each year. An average reduction in trim loss of just one gram per fillet saves around 50,000 euros in value depreciation. Therefore it is essential to get more insight into the trim loss.

#### *3.1.3.3 Fillet trim and handle time*

Another essential variable is the maximum workload that trimmers can handle at the Trim station and Trim Table B. The maximum workload of trimmers depends on the total handling time of fillets. The total handling time per fillet consists of the inspection time, trim time, and the time required to lay down a fillet on the appropriate conveyor belt. The total handling time per fillet depends on the incoming qualities of fillets since, for example, large defects are more challenging to trim than small defects, and some fillets are not trimmed at all. Therefore, the inspection time and time required to lay down a fillet are determined based on a sample test (N=50). The easiest way to measure the time required to inspect and lay down the fillet is to measure the total handling time of fillets that were not trimmed (i.e., the trim time is equal to 0). The handling time is measured with a stopwatch. After measuring the handling time of 50 untrimmed fillets, it became clear that the handling time was quite constant. The average handling time of 50 untrimmed fillets was 2.0 seconds per fillet, rounded to 1 decimal place. It is concluded that in terms of the inspection time and time required to lay down a fillet, there is no significant difference between the fillet qualities, since the corresponding standard deviation was just below 0.1 seconds. This 2.0 second represents the sum of the inspection time and time required to lay down a fillet.

In addition, the trim time of trimmed fillets is determined to get a complete overview of the total handling time per quality of fillets. Based on a sample test (N=50), the average trim time equals 1.2 seconds with a standard deviation of  0.4 seconds. Since the standard deviation is quite large compared to the mean (CV=0.33), it is decided to determine if the trim time is different between the types of quality. The problem with measuring the trim time for each quality type was that it was impossible to see if trimmers were trimming a small or medium defect. Only the large defects were easy to observe, and for the large defects, the average trim time was equal to 2.0 seconds with a standard deviation of 0.2 seconds (N=50). When comparing those values with the average trim time and corresponding standard deviation, it is found that the trim time of large defects is significantly larger than the average trim time and also more constant. Based on these results, it is assumed that the trim time becomes larger when the size of the defect increases. Therefore it is assumed that the trim time for medium defects is larger than for small defects but lower than for large defects. The average trim time of small and medium defects together equals 1.2 seconds (N=50). Based on the pre-camera, the proportion of small defects was slightly larger than for medium defects. Therefore the average trim time of small defects is estimated at 1.0 seconds and the trim time of medium defects at 1.5 seconds. The total handling time per quality type results can be found in Table 5 below.

*Table 5: Total average handling time per fillet*

| Quality type | Inspection time + time lay down fillet in sec. | Trim time in seconds | Total handling time in seconds |
|---|---|---|---|
| Quality A (untrimmed) | 2.0 | 0.0 | 2.0 |
| Small defect | 2.0 | 1.0 | 3.0 |
| Medium defect | 2.0 | 1.5 | 3.5 |
| Large defect (trimmed) | 2.0 | 2.0 | 4.0 |
| Large defect (untrimmed) | 2.0 | 0.0 | 2.0 |

## 3.2 Data analysis

In this section, the collected data will be analyzed to determine how each part of the trimming process can be modeled (i.e., as input parameter, constant, or another way). In the throughput analysis and during sample tests, the volatilities of the trim loss per minute and the number of fillets sent to the B-ware cannot be ignored. The incoming quality of fillets might cause these volatilities and thus influence the outgoing quality. Therefore within 3.2.1, the quality of fillets is analyzed, and in 3.2.2, the trim loss. The unity of these two variables is per hour, since the trim loss is only known per hour.

Furthermore, since flock changes do not always occur at the start of a new hour, in 3.2.3, the quality difference between flocks is analyzed. After that, sections 3.2.4, 3.2.5, and 3.2.6 analyze if the trim loss and amount of fillets sent to the B-ware can be accurately predicted based on the incoming fillet quality. Lastly, in 3.2.7, a discrepancy in the rejection rate at the bone detection module is analyzed.

### 3.2.1 Quality of fillets

In practice, the pre-camera measures for each pair of fillets the total mm2 fillet area, total mm2 blood spots, and total mm2 fat spots, respectively. A small sample test (N=200) is executed to determine how the mm2 blood and fat are divided over a pair of fillets. A set of 200 scans are stored and analyzed, in which 100 scans corresponds to fat defects and 100 scans to blood defects. Based on the blood and fat defects, respectively, each pair of filets is classified into one of the following five categories: the left fillet has all of the mm2 defects (1), the left fillet has significantly more mm2 defects (2), both fillets have an approximately equal amount of mm2 defects (3), the right fillet has significantly more mm2 (4), and the right fillet has all of the mm2 defects (5). The results of the 200 pairs of filets classification into one of the five categories can be found in Table 6 below.

*Table 6: Results of determining the division of defects over 100 defective pairs of fillets*

| Defect: | All left (1) | More left (2) | Relatively equal (3) | More right (4) | All right (5) |
|---|---|---|---|---|---|
| Fat | 0 | 20 | 59 | 21 | 0 |
| Blood | 50 | 4 | 1 | 2 | 43 |

In Table 6, it can be found that in 93% of the cases, all blood was on one of both fillets. Therefore it is assumed that the total mm2 blood on a pair of fillets is entirely assignable to one out of both fillets.

For the fat defects, it became clear that the proportion of defects in both fillets is in most cases relatively equal (59%), in quite a lot cases more in one fillet than the other (41%) and no cases all in a single fillet. However, since the actual mm2 of the total defects in mm2 on the left and right fillet is very hard to estimate, it is challenging to find a function that describes how much of the total mm2 fat is individually on the left and right fillets.

The individual fillet qualities and corresponding total quality percentages are determined for multiple 'proportion allocating rules.' The 'proportion allocating rules' indicate how the total amount of fat is distributed over both fillets within each pair. Since fat is relatively equally distributed over the fillets within a pair, the simple 50/50 proportion rule is tested first. This rule assigns half of the total mm2 fat detected by the pre-camera on a pair of fillets to the left and half to the right fillet. Therefore, applying the 50/50 rule on the same dataset will always result in the same quality percentages. In addition, several uniformly distributed proportion rules are tested since, in quite a lot of cases, the amount of fat was more located on one out of two fillets. The uniformly distributed proportion rules (Uni[X, Y]) generate a random number R between X and Y for each fillet. The random number (R) represents the percentage of the total fat assigned to the left fillet. The corresponding amount of mm2 fat assigned to the right fillet equals 100 minus the R percentage of the total mm2 fat. Important to notice is that the quality assessments of the camera are transformed into four main groups of qualities. The quality profiles given in Table 1 are converted into the categories good (A), small defects (B and C), medium defects (D and E), and large defects (F, G, and H) to create larger subsets and make it more understandable.

*Table 7: Quality distribution in terms of percentages for different division rules fat over pairs*

| Division rule for fat within a pair | Proportion good quality fillets | Proportion small defected fillets | Proportion medium defected fillets | Proportion large defected fillets |
|---|---|---|---|---|
| 50/50 | 42.7% | 21.5% | 16.7% | 19.1% |
| Uniform[0,100] | 47.5% | 17.5% | 13.9% | 21.1% |
| Uniform[10,90] | 46.0% | 19.0% | 14.4% | 20.6% |
| Uniform[20,80] | 44.3% | 20.3% | 15.2% | 20.3% |
| Uniform[30,70] | 43.3% | 21.0% | 15.7% | 20.0% |
| Uniform[40,60] | 42.6% | 21.6% | 16.8% | 19.0% |

Since it was already concluded that the fat spots were never located on only one out of both fillets, it is more reasonable to look at Uni[30,70] and Uni[40,60] instead of the first three uniform proportion rules. As you can see in Table 7 above, the fixed 50/50 proportion lay in between Uni[30,70] and Uni[40,60]. Since it is hard to find the actual lower- and upper-bound of the best uniform distribution, it is decided to assume the simple 50/50 proportion rule. In addition, the post-quality of fillets is given in Table 8, for which no assumptions were needed since this inflow at this camera exists of single fillets.

*Table 8: Quality distribution of fillets at post-trim inspection camera*

| Fillet quality | Proportion good quality fillets | Proportion small defected fillets | Proportion medium defected fillets | Proportion large defected fillets |
|---|---|---|---|---|
| Pre-trim quality | 42.7% | 21.5% | 16.7% | 19.1% |
| Post-trim quality | 65.2% | 14.9% | 9.6% | 10.3% |

Note the proportions of the pre-trim quality are represented for the assumed 50/50 fat division rule.

As shown in Table 8, the post-trim quality improved significantly compared to the pre-trim quality. However, since the trimmers' task is to trim all fillets to good quality, many fillets still have defects (34.8%) after trimming. In most cases, small and medium defects are still accepted by customers, but the 10.3% large defects are not allowed within end-products. Therefore, the incoming percentage of large defects (19.1%) is less than halved by the trimmers, which is considered as poor performance of the trimmers.

### 3.2.2 Relation between trim loss and fillet quality

The relation between the trim loss and fillet quality is split into four parts. For the fillet harvesting line7, there is data available regarding both the pre-and post-quality in terms of blood and fat.

Therefore, to represent the relation between all these variables, it is decided to split this analysis into fat defects versus trim loss in part one and blood defects versus trim loss in part two. On the other hand, only data regarding the pre-quality blood and fat for the B-ware is available. Therefore the data analysis regarding the relationship between the trim loss at B-ware and the quality does not need to be split up and is combined within part three. Lastly, a correlation analysis is executed in section four to determine other unexpected significant correlations between the variables.

#### *3.2.2.1 Relation between fat defects and trim loss fillet harvesting line7*

Since the throughput per hour is not constant due to breaks and production stops, it is decided to transform the trim loss per hour in kilogram into the average trim loss per fillet in grams. For the same reason, the total mm2 fat detected at both cameras is transformed into the average mm2 fat per fillet. Unfortunately, the cameras' data is only valid when the cameras are cleaned in the morning. Therefore the amount of data used within the analysis is limited, and therefore the results found in this data analysis need to be reinvestigated when more data is available. In Figure 12 below, the production hours on November 11, 2021, are plotted against the average mm2 pre-fat and post-fat per minute and the average trim loss per fillet at the fillet harvesting line7.

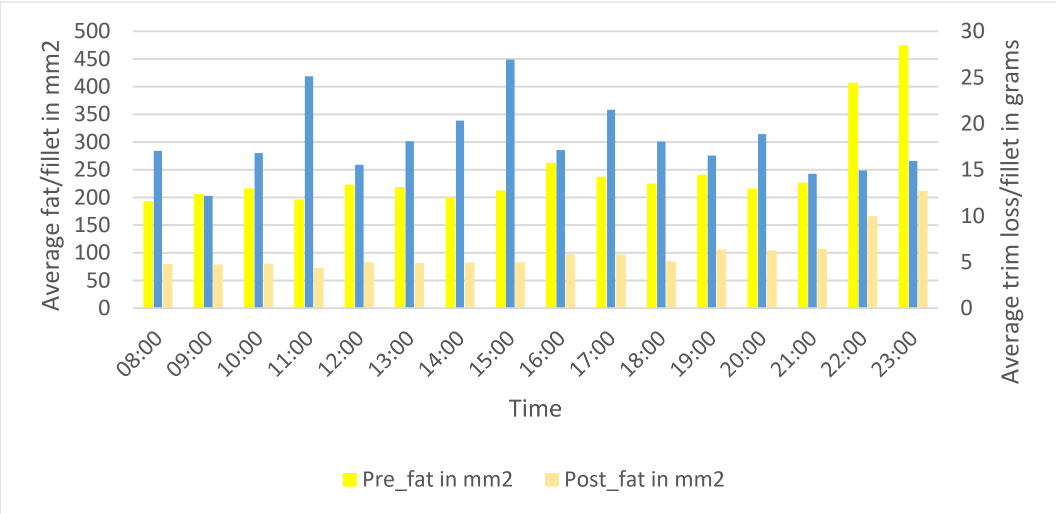



*Figure 12: Average pre and post fat per fillet and the corresponding trim loss at the fillet harvesting line7*

As you can see in Figure 12 above, the trim loss at the fillet harvesting line7 fluctuates a lot, while the pre-and post-fat is steady except for the last two bars. Based on this observation, there is no significant correlation between the pre-fat and post-fat per fillet versus the trim loss fillet harvesting line7. This is also statistically supported by calculating the Pearson correlation score within IBM's Statistical Package for the Social Sciences (SPSS). Both p-values are above 0.5, and the Pearson correlation scores are below 0.2. However, there is a significant correlation between the variables pre-fat and post-fat. As expected, the post-fat is significantly smaller than the pre-fat. The Pearson correlation score between those variables is 0.97**, indicating a very strong correlation significant at $p<0.01$ level (Schober, Boer, & Schwarte, 2018). The subjective quality assessment of humans could explain this strong correlation in combination with the anchor effect. It seems that the trimmers trim a fixed percentage of the incoming fat.

#### *3.2.2.2 Relation between blood defects and trim loss fillet harvesting line7*

The same analysis and figure are created in which the production hours on November 11, 2021, are plotted against the average mm2 pre-blood and post-blood per minute and the average trim loss per fillet at the fillet harvesting line7 (Figure 13). As explained in the previous section, the variables are transformed to the average value per fillet for the same reason.

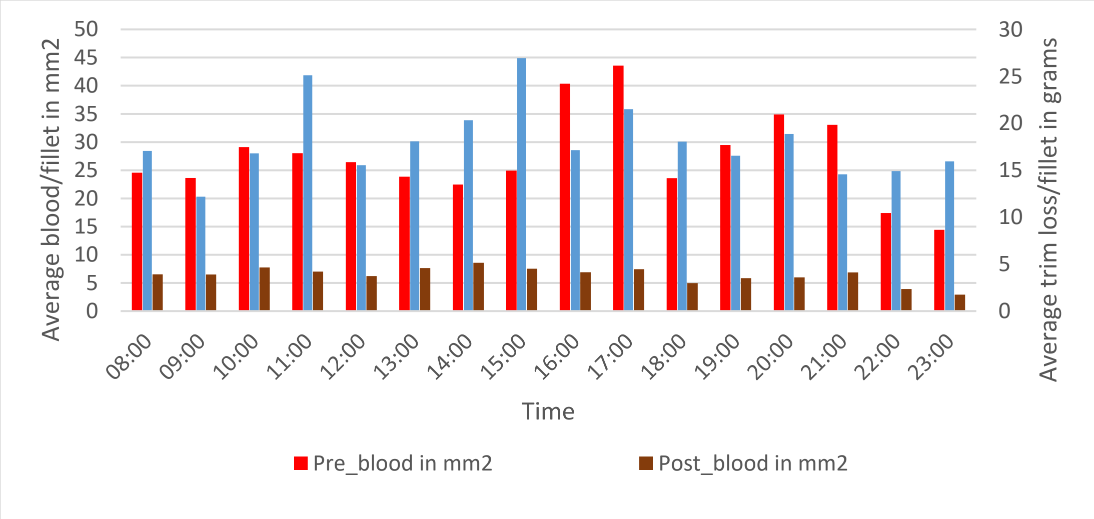



*Figure 13: Average pre and post blood per fillet and the corresponding trim loss at the fillet harvesting line7*

As shown in Figure 13, the average blood per fillet fluctuates way more than the average fat per fillet. However, the relatively higher trim loss bars do not match the relatively higher blood per fillet bars. In addition, it is statistically supported that there is no significant correlation (p-value = 0.76) between the presence of blood and the trim loss on the fillet harvesting line7. No correlation was expected since blood defects are hard to trim while retaining the natural shape since blood defects are in most cases spread over the fillet. Therefore in most cases, blood defects are sent to the B-ware. While on the other hand, fat defects are, in most cases, at the sides of a fillet and therefore easier trimmable.

#### *3.2.2.3 Relation between pre-defects and trim loss B-ware*

For the B-ware, the post-quality is irrelevant since this quality is only measured for fillets at the fillet harvesting line7. Therefore in Figure 14, the production hours on November 11, 2021, are plotted against the average mm2 pre-blood, mm2 pre-fat, and grams trim loss per fillet at the B-ware.

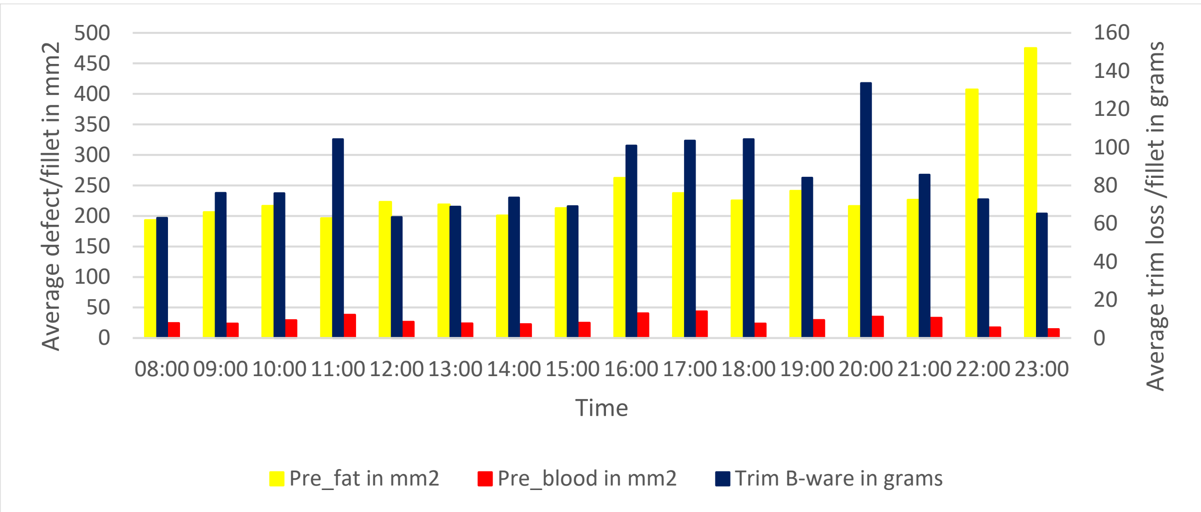



*Figure 14: Average pre-fat and pre blood per fillet plotted against the corresponding trim loss at the B-ware*

As expected, there is no correlation between the variables pre-fat and trim B-ware. However, as expected, there is a statistically proven correlation between the variables pre-blood and trim B-ware. Furthermore, the corresponding Pearson correlation score is 0.73**, which indicates a strong correlation that is significant at <0.01 level (Schober, Boer, & Schwarte, 2018).

#### *3.2.2.4 Correlation analysis*

Until now, four possible correlations have not been tested yet: pre-fat and post-blood, pre-blood and post-fat, post-fat and post-blood, and trim fillet harvesting line7 and trim B-ware. When different flocks cause large deviations in trim loss, there was expected to be a significant correlation between the trim-loss at the fillet harvesting line7 and B-ware. However, there is no statistically significant correlation (p-value = 0.65) between these variables. In addition, the correlation between pre-blood and post-fat is not significant. Surprisingly, there was a strong negative significant correlation between pre-fat and post-blood (-0.82**) and between post-fat and post-blood (-0.82**).

As you can see, the strength of the correlation scores are very close to each other, which could be declared by the fact that pre-fat and post-fat were also very strong correlated (0.97**). The strong negative correlation between pre-fat and post-blood could be explained as follows. Since the trimmers at the Trim station mainly handle the more easy fat defects, their workload is higher when more fat defects are incoming. Therefore, when they are busy with trimming fat, they could send them more difficult blood defects more often to the B-ware than when their workload is low, and they start trimming blood defects themselves.

### 3.2.3 Quality difference between flocks

Since there are no correlations between the fillet quality and trim loss, it is tested if the analysis unit 'per hour' could cause it. Therefore it is decided to analyze the quality difference between flocks. A flock is a group of birds bred together at a single farm. For each fillet arriving at the trimming process, it is known which flock it belongs to. The size of a flock is not constant. Some flocks are processed within two or more consecutive production hours, while others can be processed within less than half an hour. Since the trim loss is only known per hour, and there are many flock changes, it is impossible to estimate/determine the average trim loss per fillet within each flock. The only data available regarding the average trim loss within a specific flock is the data gathered by the executed sample tests (N=11) for five-minute intervals. Since the sample size is limited, it is considered that the data obtained per flock is not sufficient to conclude. Therefore it is decided to first look at the incoming quality differences between flocks. Within the FQT, it is possible to accurately determine the quality per flock. For all different flocks (N=20) processed during the sample tests executed at client X, each fillet is divided into one of the abovementioned quality groups based on the camera's quality assessment. A box plot is created in Figure 15 below to represent the variation in the percentages of incoming qualities.

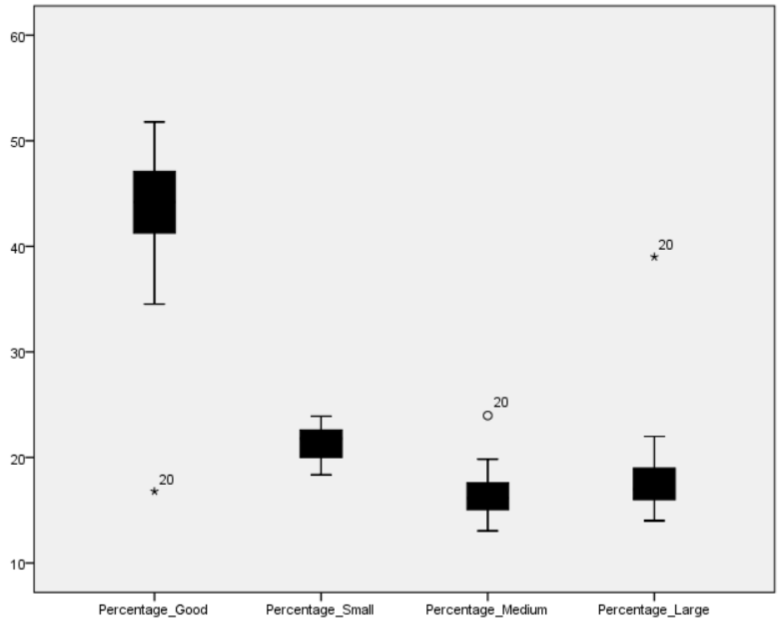



*Figure 15: Boxplot of the percentages of each quality group for 20 different flocks*

Note a circle represents an outlier and a star an extreme outlier

You can find the four quality groups on the X-axis, while the corresponding percentages are displayed on the Y-axis. As you can see, there are three points located outside the whiskers of the boxes. All three outliers correspond to flock 20. Therefore, it is concluded that flock 20 is an outlier, even when the percentage of small defects of flock 20 are within the whiskers. This flock causes that within Figure 12, the last two bars were significantly larger than the others. Furthermore, except for the outlying flock, the variation within the incoming quality is relatively small, especially for the percentage of the small, medium, and large defects.

In addition, it is determined if the percentages of ingoing quality variates on a daily level. During the sample test days on 10-11-2021 and 11-11-2021, it was concluded that the daily ingoing quality was very constant over those two days. For both days, the rounded percentage of each quality group was equal or only differed one percent.

### 3.2.4 Predicting trim loss based on fillet quality

It is concluded within the correlation analysis part that there were no significant correlations between the trim loss and fillet quality when looking at a single variable at a time. Therefore, it is tested if combining all available data regarding the incoming quality could predict the trim loss. A linear regression model is used for both the trim loss at the fillet harvesting line7 and trim loss at the B-ware to test if the trim loss is predictable based on the incoming quality. The estimators used within the linear regression model are the surface of blood and fat in mm2, the number of fillets in each quality group, and the percentage of fillets in each quality group. When the total trim loss can accurately be predicted based on the fillet quality, the potential cost-savings in trim loss reduction can easily be calculated.

#### *3.2.4.1 Predicting total trim loss per hour at fillet harvesting line7*

The first step is to use all the abovementioned variables as predictors for the total trim loss per hour at the fillet harvesting line7. To determine to which extent the amount of variance in the trim loss can be explained using all predictors. The amount of variance explained in the dependent variable (total trim loss per hour at the fillet harvesting line7) is represented by the value of $R^2$. $R^2$ is also known as a measurement for the goodness of fit. $R^2$ will always increase when adding new predicting variables to the model (Harel, 2009). However, when using many predicting variables, you could overfit the model. Therefore, when executing multiple linear regression, you have to look at the adjusted $R^2$ value, compensating for the number of predicting variables used in the model (Leach & Henson, 2007).

However, in this case, when using all predictors regarding the incoming quality of fillets, $R^2$ is only 0.66, which indicates that the predictors can explain only 66.2% of the variance in trim loss fillet harvesting line7. The corresponding adjusted $R^2$ is 0.29, which could be increased to 0.43 when dropping the variables per_small, per_medium, and amount_large. However, an adjusted $R^2$ of 0.43 is way too small to predict accurately. The corresponding standard error of the estimates for the trim loss fillet harvesting line7 is 23.48 kg. Since the mean trim loss at the fillet harvesting line7 is 110 kg/hour, the standard error of the estimate is 21.3% of the mean. In addition, this performance is based on the training set. When using a new test set of values on which the model is not built, it is expected that the performance of the estimation is even worse. Therefore it can be concluded that the trim loss at the fillet harvesting line7 cannot be accurately predicted by the available data regarding the incoming quality of fillets. An overview of the linear regression model results can be found in Appendix F.

#### *3.2.4.2 Predicting total trim loss per hour at B-ware*

The same approach as described above is used to predict the total trim loss at the B-ware. When using all predictors regarding the incoming quality of fillets to predict the trim loss at the B-ware, the $R^2$ is 0.86. The corresponding adjusted $R^2$ value is 0.71. The adjusted $R^2$ value could be increased to 0.78 when dropping the variables per_good, amount_small, and amount_large. However, the standard error in this model is 34.94 kg, which is still 16.6% of the mean trim loss of 210 kg/hour. Therefore it can be concluded that the trim loss at the B-ware cannot be accurately predicted by the available data regarding the incoming quality of fillets. An overview of the linear regression model results can be found in Appendix F.

### 3.2.5 Predicting amount of fillets send to B-ware per minute

Based on the large CV for fillets sent from the Trim station to the B-ware, it is analyzed if this amount is correlated with the incoming quality of fillets. First, the correlation scores must be determined between the number of fillets sent to the B-ware and the incoming quality. The variables total mm2 fat (aggregated mm2 fat detected by pre-camera per minute), total mm2 blood (aggregated mm2 blood detected by pre-camera per minute), and the number of fillets of each quality represent the incoming quality. For this specific analysis, the quality letters are used instead of the aggregated quality groups since it is expected that blood defects are sent more often to the B-ware than fat defects. The Pearson correlation scores between these variables and the dependent variable (number of fillets sent from the fillet harvesting line7 to the B-ware per minute) can be found in Table 9 below.

*Table 9: Pearson correlation scores for incoming quality versus the number of fillets sent to B-ware*

| Variable | Pearson correlation score |
|---|---|
| Amount_A | 0.23 |
| Amount_B | 0.68** |
| Amount_C | 0.50** |
| Amount_D | 0.64** |
| Amount_E | 0.12 |
| Amount_F | 0.59* |
| Amount_G_and_H | -0.14 |
| Total_mm2_fat | -0.40 |
| Total_mm2_blood | 0.13 |

As you can find in Table 9, there are significant positive medium correlations with the number of fillets sent to the B-ware and the amount of B, C, D, and F fillets. B, D, and F fillets represent respectively small, medium, and large defects, and therefore it was expected to find correlations between those variables. Surprisingly, there is also a significant medium correlation with the amount of C fillets, representing the amount of small fat spots.

Since several significant medium correlations are found for the number of fillets of a specific quality, it is tested how accurately the number of fillets sent to the B-ware can be predicted based on a linear regression model. The same procedure in this linear regression model is used, as explained before, when predicting the trim loss. The variables used as predictors are all variables represented in Table 9. When using all predictors regarding the incoming quality of fillets to predict the number of fillets send to the B-ware, the $R^2$ value is 0.68. The corresponding adjusted $R^2$ is 0.19. The adjusted $R^2$ value could be increased to 0.51 when dropping the variables amount_d, amount_e, amount_f, amount g_and_h, and the total_mm2_blood. However, the average standard error for estimating the number of fillets sent from the fillet harvesting line7 to the B-ware per minute is 5.26. Because the mean amount of fillets sent to the B-ware equals 15.2 fillets per minute, the standard error equals 34.6% of the mean. Therefore it can be concluded that the number of fillets sent to the B-ware cannot be accurately predicted by the available data regarding the incoming quality of fillets. An overview of the linear regression model results can be found in Appendix F.

### 3.2.6 Alternative analysis with data reduction

When analyzing the quality assessments of the pre-inspection camera, it is observed that the camera assesses an unskinned fillet as a huge fat spot and a wing still attached to a fillet as a huge blood spot. Since the harvesting of fillets is automated, it is possible that in some cases, a deskinned fillet or a wing of a broiler is sent to the pre-camera. When the skin remover module or wing remover module is malfunctioning within a certain period, the quality assessments of the pre-camera could be inaccurate. When a fillet is unskinned or a wing is detected next to a fillet, the camera assesses the fillet as a large defected fillet. In contrast, the actual quality of the fillet will follow the general quality distribution. Therefore, it is decided to remove all fillets from the dataset of which the individual total surface of blood or fat is larger than 2500 mm2 to test the impact of removing the huge unsure defects. When the surface of a defect is larger than 2500 mm2, it is most likely caused by a wing or skin, not a normal fat or blood spot. In Table 10 below, the impact of removing those fillets on the average defects per fillet is represented.

*Table 10: Impact of removing defects >2500 mm2 on average defects per fillet*

| Data size | Number of fillets | Avg fat per fillet in mm2 | Avg blood per fillet in mm2 |
|---|---|---|---|
| Entire dataset | 106,878 | 248.83 | 27.84 |
| Fat < 2500 | 105,108 | 111.47 | - |
| Blood < 2500 | 106,737 | - | 16.40 |

As you can see in Table 10, in terms of removing fat defects above 2500 mm2, only 1.6% of the fillets are removed, but the average fat per fillet is reduced by 55.2%. On the other hand, only 0.1% of the fillets are removed in terms of blood, and the average blood per fillet is reduced by 41.0%. The impact of the huge blood and fat defects can therefore be seen as very large. However, it will only significantly impact the earlier executed analysis when the number of occurrences fluctuates over time. To determine if the accuracy of the prediction increases, in Table 11 below, the model results of the reduced data set are compared to the original linear regression models. An overview of the linear regression model's results can be found in Appendix F.

*Table 11: Results of linear regression models for different models*

| Model | $R^2$ all variables included | Adjusted $R^2$ best model | Lowest std. Error of the estimate |
|---|---|---|---|
| Trim fillet harvesting line7 (original) | 0.66 | 0.43 | 23.48 |
| Trim fillet harvesting line7 (reduced) | 0.43 | 0.18 | 24.94 |
| Trim B-ware (original) | 0.86 | 0.78 | 34.94 |
| Trim B-ware (reduced) | 0.93 | 0.87 | 29.37 |

In Table 11, it can be observed that reducing the dataset through removing the defects larger than 2500 mm2 has no significant impact on the standard error of the estimate. However, surprisingly for predicting the trim loss at the fillet harvesting line7, the best model is even worse than before. The decrease in $R^2$ and adjusted $R^2$ could be caused by trimmers at the Trim station, who throw the wings on the same conveyor belt as the trim loss, but this is not further investigated. The adjusted $R^2$ predicting the trim loss at the B-ware is significantly larger than the old adjusted $R^2$. However, the standard error of the estimate is still too large to predict the amount of trim-loss accurately.

### 3.2.7 Discrepancy in rejection rate bone detection module

As observed during the sample tests on-site at client X, there was a discrepancy between the number of rejections of the bone detection module and the number of fillets rejected. During observation, it became clear that in case of fillets lay on top of each other or too close after each other, the bone detection module could see multiple fillets as one fillet. Therefore, when the machine thinks he rejects one fillet, it is sometimes multiple fillets in practice. Therefore, the actual amount of rejected fillets are counted and, at the same time, the number of rejections of the corresponding bone detection module to determine the discrepancy between the number of rejections counted by the bone detection modules and the actual amount of fillets rejected. For the bone detection module after the Trim station, on average, 10.4% of the fillets were rejected, while the machine counted on average 9.0% rejections. Therefore the best guess for the discrepancy is 1.4%. For the bone detection module after the B-Trim Table, the same procedure is followed. The probability of fillets laying on top of each other is smaller since the throughput on this bone detection module is smaller and the speed of the belts is the same. Therefore, the same conclusion could be drafted when analyzing the discrepancy at this bone detection module. During the sample tests (N=20), the average percentage of fillets rejected was 8.3%, while the average number of rejections was 8.0%. Therefore the discrepancy on the bone detection module after the B-Trim Table is expected to be 0.3%.

## 3.3 Short summary of main findings data analysis

- The detected amount of blood by the pre-camera for a pair of fillets is in most cases entirely assignable to one out of two fillets.
- The detected amount of fat by the pre-camera for a pair of fillets is never entirely assignable to one out of two fillets, but in most cases, quite evenly distributed.
- The trimmers at the fillet harvesting line7 improve the outgoing fillet quality significantly compared to the incoming quality; however, slightly more than 10% of the outgoing fillets still have large defects.
- A very strong significant correlation was found between the variables pre-fat and post-fat, with a Pearson correlation score of 0.97 and significant at <0.01 level.
- A strong significant correlation was found between the variables pre-blood and trim loss at B-ware, with a Pearson correlation score of 0.73 and significant at <0.01 level.
- Strong negative significant Pearson correlations were found between the variables pre-fat and post-blood (-0.82) and post-fat and post-blood (-0.82), both significant at <0.01 level.
- Medium significant correlations are found between the number of fillets sent to the B-ware and the number of incoming fillets with quality labels B, C, D, and F. The quality letters B, D, and F fillets represent small, medium, and large blood defects, while C represents small fat spots.
- The incoming quality of fillets does not differ much between flocks, except for flock number 20, which is considered an outlier.
- The average incoming quality of fillets is strongly affected by detecting wings and skin still attached to the fillet as large blood and fat spots.
- The amount of trim loss and the number of fillets sent to the B-ware cannot be accurately predicted with a linear regression model including all available data regarding the fillet quality.
- A list of all input parameters which are required within the simulation model:
  - ➢ The arrival time of each fillet
  - ➢ The quality assessment of each fillet
  - ➢ The handling times for each quality of fillets
  - ➢ The length and speed of each conveyor belt
  - ➢ The mean and standard deviation of the fillet weights
  - ➢ The rejection percentages at both bone detection modules
  - ➢ The total demand at each batching process
  - ➢ The marinated demand at each batching process
  - ➢ The desired weight and quality ranges at each batching process

# 4. Modelling

## 4.1 Modelling method: DES

In industry, discrete event simulation (DES) is an extensively used modeling method. It quantitively represents the real world and simulates its dynamics on an event-by-event basis (Babulak & Wang, 2007). Therefore, DES is an ideal platform to support managers in making decisions on the resource deployment and analyzing the process's performance on a detailed level (Babulak & Wang, 2007). There are two main approaches for building DES: the event-scheduling approach and the process-interaction approach (Fishman, 2001). The event-scheduling approach is more helpful for this research since each decision made by trimmers and modules could be seen as an event.

Within the event-scheduling approach of DES, a Future Event List (FEL), also known as a Future Event Set (FES), is commonly used. FES is a sorted list of scheduled future events, which should be employed by all efficient simulations of complicated discrete-event systems (Boon et al., 2020). All events within the simulation are added to the FEL, sorted by the time of occurrence. However, removing and adding items to a list could take a lot of time, and therefore it is essential to use a suitable data structure. Therefore, the Python package 'heapq' is used since this data structure ensures the efficient insertion of new events within a simulation model. (Boon et al., 2020).

## 4.2 Set of models

First, the current situation is modeled to determine to what extent the simulation model behaves the same as the actual process. Then, as explained in sections 3.2.3 and 3.2.4, it is concluded that there was no clear relationship between the incoming quality of fillets and both the trim loss and the number of fillets sent to the B-ware. Therefore the simulation model cannot predict the trim loss for each fillet.

Currently, the inspection cameras are only used to determine the quality of fillets in terms of the pre- and post-trim quality. Besides, the post-trim quality is currently used at the first distribution module to filter out large defects, which are not desirable within (most of) the upcoming batching processes. However, the generated data, especially the pre-trim camera, could make the process more efficient. The data of the pre-trim camera can be used to reduce the inflow of fillets at the Trim station. As observed, many fillets are already of quality A and therefore do not need to be inspected and trimmed. If the data of the pre-trim camera is used to bypass those fillets, those fillets do not need to be inspected and trimmed. This could be beneficial for the company in two crucial aspects. Firstly, the yield could increase since the trim loss should be reduced when trimmers cannot trim the quality A fillets. Based on observations and previous research within Marel, it is found that almost half of the quality A fillets are still trimmed. Secondly, suppose the inflow of fillets at the Trim station is lowered. In that case, less time is needed to inspect and trim all incoming fillets, potentially reducing the number of trimmers needed within the process.

The yield could be increased even more when matching the post-quality of fillets to the quality requirements of specific retailers, orders, or products. Currently, the trimmers are instructed to trim all fillets to quality A, while small defects would also be tolerated for some specific orders. Especially for marinated products, small blood and fat spots are hard to observe within the final product, and therefore, small defective fillets could also be bypassed. Based on the production overview of client X, it is found that the demand for marinated products depends on the time of the year. In summer, 36% and 75% of the total production on respectively the I-cut and SmartSplitter is marinated, while in winter those proportions are only 6% and 46%. Therefore, bypassing small defects for marinated products could reduce the trim loss, and trimmers needed even more than only bypassing quality A fillets.

In addition, the data of the pre-camera could also be used to improve the distribution algorithm at the Trim station. Currently, the fillets are distributed following a fixed pattern to equal the arrival rate of fillets at each trimmer. However, it would make more sense if trimmers' workload was equalized instead of the number of incoming fillets. High and especially fluctuating workloads can harm employees' task performance (Munander et al., 2019). During previous research within Marel, it is observed that trimmers rush when the amount of fillets on their workstation is large. When rushing, the task performance of trimmers will drop, which could lead to accepting also defected fillets or not trimming accurately. When the distributing algorithm focuses on equalizing workload, the peak load at trimmers can be prevented or reduced compared to equalizing the number of incoming fillets. In addition, when data regarding the fillet quality is used within the distribution algorithm, it is also possible to send certain defects always to the same trimmer(s). This should be beneficial for client X since high task-repetitiveness should increase the work performance (Häusser et al., 2014). When not bypassing quality A fillets, those fillets can be sent to trimmers who only receive quality A fillets and are instructed only to inspect the fillets and not trim, which could also reduce the trim loss. In addition, when trimmers' task performance increases, it could also be beneficial to reduce trim loss and lead to a better outgoing quality.

The abovementioned cases could already significantly improve the process in terms of efficiency. However, since currently the fillets are distributed per pair of fillets, all three of those implementations would be less effective than when fillets can be distributed per individual fillet. For example, 42.7% of the fillets could be bypassed when you can distribute per single fillet when bypassing good quality fillets. Currently, in the case of distributing pairs of fillets, both fillets within the pair need quality A to be allowed to bypass those fillets. When assuming that the quality of an individual fillet within a pair is independent of the fillet's quality next to it, only 18.2% (squared value of 42.7%) of the fillets can be bypassed. A new distribution algorithm will also be more effective when individually distributed fillets. When not, combinations of a quality A fillet and large defects must be sent and handled by the same trimmer.

To summarize the abovementioned information, four process adjustments are modeled: (1) bypass quality A fillets, (2) bypass small defected fillets for marinated products, (3) the new distributing algorithm at Trim station, and (4) distribute individual fillets instead of pairs. When considering all possible combinations of those process adjustments, there are 16 different models whose potential value can be determined within the simulation model. Those 16 models can be found in Table 12 below.

*Table 12: Set of simulated models*

| Model number | Bypass quality A? | Bypass defects? | New distributing algorithm Trim station? | Distribute per individual fillet? |
|---|---|---|---|---|
| 1 | No | No | No | No |
| 2 | Yes | No | No | No |
| 3 | No | Yes | No | No |
| 4 | No | No | Yes | No |
| 5 | No | No | No | Yes |
| 6 | Yes | Yes | No | No |
| 7 | Yes | No | Yes | No |
| 8 | Yes | No | No | Yes |
| 9 | No | Yes | Yes | No |
| 10 | No | Yes | No | Yes |
| 11 | No | No | Yes | Yes |
| 12 | Yes | Yes | Yes | No |
| 13 | Yes | Yes | No | Yes |
| 14 | Yes | No | Yes | Yes |
| 15 | No | Yes | Yes | Yes |
| 16 | Yes | Yes | Yes | Yes |

Note the rows highlighted in orange are not modeled since those models are irrelevant

Before modeling and testing all 16 models given in Table 12 above, the list of models is shortened since some models are not relevant to the test. Model 1 represents the current situation and is therefore very important to model first since the outcome of this model needs to be compared to the outcomes of other models to determine the potential value of each model. The models that are removed from the list since they are not considered relevant and value-adding are models 3, 5, 6, 9, 10, 12, and 15. Bypassing defects and not bypassing quality A is not likely to happen in real life, and therefore those models will not be simulated (3,9,10,15). Besides, it is impossible to bypass small defects for specific orders if you cannot distribute per single fillet. When bypassing small defects for specific orders, the weight of an individual incoming fillet is needed and therefore models 3, 6, 9, and 12 will not be simulated. Lastly, model 5 will not be simulated since it has no added value to distribute individual fillets while not bypassing any fillets nor using a new algorithm within the distribution of fillets.

## 4.3 Sub-processes

*The entire trimming process explained in section 3.1.1 is modeled with DES. The entire process is divided into the following sub-processes: (1) the arrival of fillets, (2) quality assessment by cameras, (3) distribution algorithm Trim station, (4) quality assessment trimmers, (5) trim process trimmers, (6) bone rejection bone detection module, and (7) distributing rules for different batching processes. These sub-processes will explain how the process is modeled within the simulation model and which assumptions were needed.*

### 4.3.1 Arrival of fillets

The arrival process of fillets to the pre-camera is relatively constant. The data analysis indicated that, on average, 146 fillets per minute arrived at the pre-camera with only a small coefficient of variation of 0.01. Since the CV is minimal, it is decided to model the arrival process of fillets as a constant process of 146 fillets per minute. The incoming 146 fillets per minute can be translated into 73 pairs of fillets per minute, which can be modeled as a fixed interarrival time between each pair of fillets of 60/73 seconds. In practice, the time of arrival of a pair of fillets is determined, which means that both fillets within a pair have the same arriving time. Therefore the interarrival times of incoming fillets are alternately 0 and 60/73 seconds. The arrival times of fillets are read from an Excel file, making it easy to insert the actual arrival time of each pair of filets derived by the pre-camera. The only data transformation that needs to be made is that each arrival time must be duplicated since the pre-camera only represents one arrival time for each pair of fillets. In comparison, the model needs to have one arrival time per individual fillet.

### 4.3.2 Quality assessment by pre-camera

For the quality assessment of incoming fillets, the distribution of quality percentages given in Table 7, with the 50/50 fat and 100/0 blood proportion rule within each pair of fillets, is used. The quality of each incoming fillet is determined within the input Excel file since, in this way, it is also possible to use the actual quality data of the cameras. The percentages given in Table 7 are converted to the cumulative probabilities. Then, for each fillet, a random number is generated between 1 and 100. When the number is below the cumulative probability of a quality type, starting with the good fillets and ending with the large defects, this defect type is attached to the fillet. In this way, the total percentage of incoming qualities is equal to the values given in Table 7. However, the order of incoming qualities can be easily changed to test the robustness of the model.

### 4.3.3 Handling time of fillets at Trim station and B trim-table

Since it is currently impossible to distribute the same quality of fillets to a single trimmer, it is difficult to determine the trim time of each fillet more accurately. Therefore, the model's hard guesses in section 3.1.3.3 are modeled as constants. When the trimming times can be more accurately determined in the future, those constants can easily be adjusted or changed into random variables following certain distributions. Based on sample tests, the rough estimates are an average handling time of 2 seconds for quality A fillets and fillets sent to the B-ware, 3 seconds for small defects, 3.5 seconds for medium defects, and 4 seconds for large defects.

### 4.3.4 Distribution of fillets over trimmers at Trim station

Within the simulation models, two types of distribution algorithms are used. The first one is focused on the current algorithm, which focuses on an equal number of fillets per trimmer. The second algorithm will focus on an equal workload for all trimmers and as much as possible the same quality per trimmer. In addition, the optimal number of trimmers can be calculated with the same formula (Formula 1 on page 36) for both algorithms.

#### *4.3.4.1 Equal number of fillets algorithm*

Currently, the fixed pattern used within the distribution of fillets at the Trim station is focused on an equal amount of fillets to each trimmer. The pairs of fillets are distributed in a fixed order over all trimmers. Since trimmer number eight also receives the rejected bone containing fillets, this trimmer is only included within one of four cycles. Since currently no fillets are bypassed, it is known for each incoming fillet to which trimmer it is sent to, independent of the quality.

The same fixed order pattern as described above is used in the case of single distribution of fillets. The only minor difference is that the number of distributions has doubled since the distribution quantity has halved from two to one. This situation is still known for each incoming fillet to which trimmer it is sent. The same distribution pattern is used within models where fillets are bypassed, but the interarrival time of receiving fillets is not constant within each cycle.

#### *4.3.4.2 Equal workload and quality based distribution algorithm*

Within the equal workload and quality-based distribution algorithm, the data of the pre-camera is used for distribution. When quality A fillets are not bypassed, the quality A fillets are sent to a trimmer without a knife. In the case of single distribution, all quality A fillets are sent to this trimmer(s). Still, in the case of pair distribution, only pairs of which both fillets have quality A are sent to this trimmer. In addition, the trimmers can be classified into small, medium, or large defect trimmers. This does not mean that the trimmers only receive this quality type of fillets, but as much as possible while keeping the workload equal over trimmers. When a trimmer needs to be supplied with another quality type of fillets, the algorithm will send the trimmer quality types closest to the trimmer's specialty. Unfortunately, there was insufficient time to develop such a complex algorithm in this research period. Therefore within the simulation model, the working of the algorithm is imitated by using the mean trim time for each incoming fillet in combination with the fixed pattern of distributing as explained in 4.3.3.1. In this way, the peak loads at trimmers are reduced as much as possible, while the overall utilization of trimmers remains the same. Next, it needs to be determined how many fillets are trimmed at the Trim station and which quality the fillets are. These values variate per model, and therefore for each of the five models which use the equal workload algorithm, the constant workload trim time needs to be recalculated. The detailed calculations of the constant workload trim time can be found in Appendix D.

#### *4.3.4.3 Amount of trimmers needed*

Another critical input parameter within the simulation model is the number of trimmers used at the Trim station. It first needs to be determined what the optimal utilization of trimmers is to determine the optimal amount of trimmers needed. The optimal utilization of trimmers depends strongly on the process. When determining the optimal utilization, consideration needs to be made between a steady system in terms of throughput times and queue lengths versus the employee cost. Since the optimal utilization is process-specific, the optimal utilization has to be determined for the trimming process of fillets. First of all, the system's behavior is determined with both the old distribution algorithm and the new distribution algorithm. The system's behavior can be found for both the current and new distribution algorithm can be found in Figure 16 below. The mean waiting time of fillets before being trimmed is plotted within these figures against the corresponding utilization rate of trimmers. In addition, the utilization rate of trimmers is calculated by dividing the trimmer's total trim time by the model's corresponding simulation time.

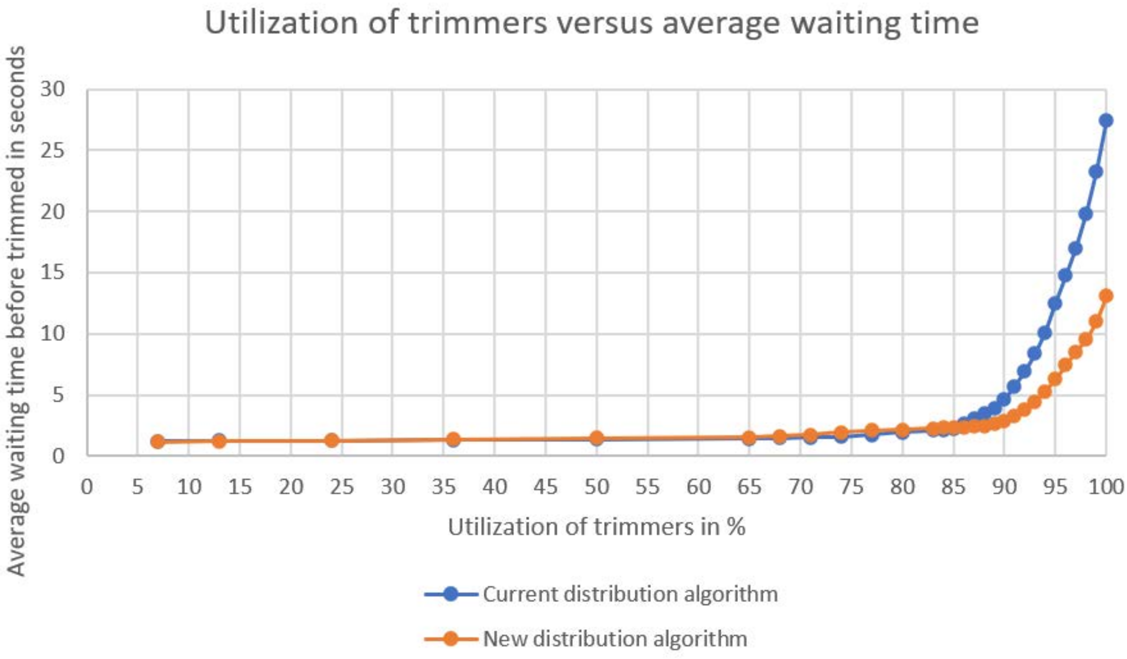



*Figure 16: Utilization of trimmers versus average waiting time while distributing based on quantity*

As you can see in Figure 16 for the old distribution algorithm, the turning point from a steady average waiting time to an exponentially increasing waiting time is around the utilization of 85%. At that point, you have both a steady system in terms of waiting time, and you efficiently use the working time of trimmers. For the new distribution algorithm, it can be seen in Figure 1 that the turning point, and thus the optimal utilization, is slightly higher at approximately 88%.

The generic formula (1) is built to estimate the optimal amount of trimmers needed within all simulation models. The numerator of this formula is the total amount of fillets arriving at the Trim station per minute multiplied by the expected mean handling time of those fillets. The denominator is the capacity of a trimmer per minute without exceeding the optimal utilization rates mentioned before. Therefore within the denominator, the capacity per minute (60 seconds) needs to be multiplied with the optimal utilization rate of trimmers. The outcome of dividing the numerator by the denominator needs to be rounded up since the number of trimmers needed must be an integer.

$$\#Trimmers = \left\lceil \frac{\lambda_{FHF} * (1 - E[\alpha_{by}] + \mu_{rej}) * E[\mu_{HT}]}{60 * Opt\_U} \right\rceil \quad (1)$$

The used variables within formula (1) are shortly explained below:

$\lambda_{FHF}$ = Arrival rate of new fillets at fillet harvesting line per minute

$E[\alpha_{by}]$ = Expected fraction of new incoming fillets that are bypassed

$\mu_{rej}$ = Mean fraction of fillets that bone detection module will reject at fillet harvesting line7

$E[\mu_{HT}]$ = Expected mean handling time at Trim station (new and rejected) for each filet

$Opt_U$ = Optimal utilization rate of trimmer

For this specific client, $\lambda_{FHF}$ and $\mu_{rej}$, can be seen as a constant of respectively 146 fillets per minute and 0.101 as determined within the data analysis. The variable $Opt_U$ takes the constant value of 85% for the models in which the old distribution algorithm is used and 88% when the new distribution algorithm is used. The remaining variables, $E[\alpha_{by}]$ and $E[\mu_{HT}]$ are expectations and need to be estimated for each model. The estimation for $E[\alpha_{by}]$ is separated into two formulas since it depends heavily on the distribution quantity. Formula (2) represents the estimation of distributing per pair of fillets, and Formula (3) represents the estimation for models where fillets are distributed per single fillet. When bypassing per pair of fillets, quality A fillets can only be bypassed if both fillets within a pair are of quality A. Therefore, within Formula (2), the variable $\alpha_A$ is squared.

$$E[\alpha_{by}] = X_A * {\alpha_A}^2 \quad (2)$$

$$E[\alpha_{by}] = X_A * \alpha_A + X_s * E[\alpha_{mar}] * \ \alpha_s \quad (3)$$

The used variables within Formula (2) and (3) are shortly described below:

$X_A \in \{0,1\}$ where 1 indicates if quality A fillets are bypassed, 0 when not

$X_s \in \{0,1\}$ where 1 indicates if small defected fillets are bypassed, 0 when not

$\alpha_A$ = Fraction of arriving fillets which are assessed as quality A = 0.427

$\alpha_s$ = Fraction of arriving fillets which are assessed as small defects = 0.215

$E[\alpha_{mar}]$ = Expected fraction of small defects that can be used for marinated products,

0.700 in summer and 0.438 in winter

$X_A$ and $X_s$ are binary variables, which indicate respectively if quality A fillets and small defected fillets are bypassed or not. $\alpha_A$ and $\alpha_s$ are constants for this specific client and are respectively equal to 0.427 and 0.215. Lastly, the variable $E[\alpha_{mar}]$ is not the same for simulating a winter period compared to a summer period. In the summer, the amount of marinated products is higher, and therefore all small defected fillets within the correct weight ranges can be distributed, which is equal to a fraction of 0.700. In winter, the demand for marinated products on the I-cut is limited, and therefore only a quarter of all fillets in the weight range for the I-cut can be bypassed. Therefore $E[\alpha_{mar}]$ is in the winter only 0.438 instead of 0.700 in summer.

The last variable that needs to be estimated to calculate the number of trimmers needed at the Trim station is $E[\mu_{HT}]$. In Formula (4) below, the calculation for $E[\mu_{HT}]$ can be found.

$$E[\mu_{HT}] = \sum_{t=0}^{5} \alpha_t * \mu_{HT_t} \quad (4)$$

In this formula, the two variables used are:

$\mu_{HT_t}$ = Mean handling time of fillets of type t

$\alpha_t$= Fraction of all fillets handled as type t

The values for $\mu_{HT_t}$ are based on the results of the data analysis. An overview of the different types of handled fillets can be found below in Table 13, with the corresponding values for $\mu_{HT_t}$.

*Table 13: Overview of different types of handled fillets and corresponding mean handling time*

| Type | Definition type | $\mu_{HT}$ in seconds |
|---|---|---|
| t=0 | Lay down fillet on B-ware | 2.0 |
| t=1 | Quality A | 2.0 |
| t=2 | Small defect | 3.0 |
| t=3 | Medium defect | 3.5 |
| t=4 | Large defect | 4.0 |
| t=5 | Inspect A + lay down fillet | 1.5 |

Important to notice that t=5 only occurs if the new distribution algorithm is used and quality A fillets are not bypassed but sent to trimmers at the Trim station. In this case, they only inspect quality A fillets without trimming. The results of applying the formulas mentioned above on each model are shown in Table 14. In addition, the extensive calculations can be found in Appendix E.

*Table 14: Results of calculating optimal amount of trimmer needed*

| Model | $E[Fra_{by}]$ | $E[\mu_{HT}]$ | $Opt\_U$ | #Trimmers |
|---|---|---|---|---|
| 1 | 0 | 2.64 | 0.85 | $\lceil 8.33 \rceil$ = 9 |
| 2 | 0.18 | 2.66 | 0.85 | $\lceil 7.01 \rceil$ = 8 |
| 4 | 0 | 2.55 | 0.88 | $\lceil 7.76 \rceil$ = 8 |
| 7 | 0.18 | 2.59 | 0.88 | $\lceil 6.58 \rceil$ = 7 |
| 8 | 0.43 | 3.03 | 0.85 | $\lceil 5.85 \rceil$ = 6 |
| 11 | 0 | 2.43 | 0.88 | $\lceil 7.39 \rceil$ = 8 |
| 13 | Summer: 0.58<br>Winter: 0.52 | 3.16<br>3.14 | 0.85<br>0.85 | $\lceil 4.73 \rceil$ = 5<br>$\lceil 5.22 \rceil$ = 6 |
| 14 | 0.427 | 3.03 | 0.88 | $\lceil 5.64 \rceil$ = 6 |
| 16 | Summer: 0.58<br>Winter: 0.52 | 3.16<br>3.14 | 0.88<br>0.88 | $\lceil 4.57 \rceil$ = 5<br>$\lceil 5.04 \rceil$ = 6 |

As you can see in Table 14 above, in the current situation, nine trimmers are required instead of the currently used eight trimmers without exceeding the optimal utilization level. Furthermore, for model 2 and model 16 in the winter, the number of trimmers is just slightly above respectively 7 and 5. Therefore, for those two models, it is interesting to determine within the simulation model if respectively 7 and 5 trimmers are sufficient without disrupting the steady process since one operator less, saves 70,000 euros per year.

### 4.3.5 Quality assessment by trimmers at Trim station

Currently, the trimmers at Trim station have to inspect the quality of each fillet. In addition, they need to determine if they can trim the fillet to a quality A fillet without losing the natural shape. Based on the data analysis regarding the ingoing and outgoing qualities and quantities at the fillet harvesting line7 and ingoing qualities at the B-ware, the best estimate is that 100% of quality A fillets, 98% of the small defected fillets, 95% of medium defected fillets, and 55% of large defected fillets are handled at the Trim station. The remaining fillets are sent to the B-ware. Within the simulation model, each fillet receives a randomly generated trim result number between 1 and 100. When the randomly generated trim result number is larger than the percentage given above for the corresponding quality of the fillet, the fillet is sent to the B-ware. Since the numbers are randomly generated, the amount of fillets going to the B-ware is not constant per minute but fluctuates quite a bit, just as in real life.

### 4.3.6 Bone rejection at both bone detection modules

As the data analysis section explained, there was a discrepancy between the rejection % generated by the bone detection modules and the number of fillets rejected. The average actual rejection percentages of the bone detection module machine at the fillet harvesting line7 and the bone detection module at the B-ware are respectively estimated to be 10.1 and 8.1%. Within this percentage, the fillets which are rejected once are included since those fillets can be rejected multiple times when the bones are not removed properly. Since the rejection percentage of bone detection modules fluctuates quite a lot over time, this behavior will also be modeled. A method needs to be found to generate the process of bone rejection within the model. This method needs to achieve a mean rejection rate of 10.1%, but not constantly 10.1% each minute. Therefore it is decided to give each fillet a randomly generated bone number between 1 and 1000. When fillets arrive at the bone detection module at the fillet harvesting line7, and its bone number is smaller or equal to 101 (10.1%), the fillet is rejected and sent back to the Trim station. After that, the bone number of the rejected fillet is replaced by a new randomly generated number between 1 and 1000 to prevent those fillets will never leave the loop of bone rejection. For the bone detection module at the B-ware, the same procedure is followed, except that the threshold value of the bone number is 81 (8.1%) instead of 101.

### 4.3.7 Distributing fillets to different batch-processes

In practice, the first distribution module sorts out all fillets which still contain large defects. Information regarding the quality of fillets is sent from the post-trim camera to the first distribution module. The second and third distribution module does not distribute based on the quality but only based on the weight of a fillet. The weight of each fillet is known after entering the bone detection module, which can share this information with the distribution modules. Besides distributing the fillets based on weight, an additional restriction is added: the number of fillets sent to the line 2 and line 3 is not allowed to exceed 70 fillets per minute. This restriction is added to guarantee that all batching processes are supplied with fillets. At the second distribution module, fillets weighing between 220 and 260 grams are sorted out for line 2. At the last distribution module, the heavy fillets above 260 grams are sorted out and sent to line 3. All fillets below 220 grams and heavier fillets when the maximum of 70 fillets per minute is reached at the other batching processes are sent to line 4. The abovementioned values are the default values, but those values can be adjusted easily to meet all demands. Within the simulation model, the default values at each distribution module are used.

# 5. Model results

## 5.1 Simulation approach and results

A valuable method for comparing the performance of more than two different configurations is using confidence intervals (Law, 2015). In addition, the proposed design results are compared with the values of the current design, which can be considered the 'standard' within the 'comparisons with a standard' method of Law (2015). It is decided to use 95% Confidence Intervals (CI) since this is by far the most commonly used confidence interval in the industry (Hazra, 2017). First, the minimal number of simulation runs must be determined for each model. According to Merzifonluoglu (2020), the minimal number of required simulation runs (N) can be calculated with the following Formula (5).

$$N > \left(\frac{z_\alpha * \sigma}{\varepsilon}\right)^2 \quad (5)$$

In this formula, the value for $z_\alpha$ is approximately 1.96 for a two-sided 95% CI. When the standard deviation (σ) of a variable is unknown, a short simulation could be used to estimate σ (Merzifonluoglu, 2020). Epsilon ($\varepsilon$) represents the margin of error. In practice, $\varepsilon$ = 0.05 is most commonly used when dealing with a 95% CI (Moore, 2014). Based on 100 simulation runs (N=100) for all nine models that need to be simulated, the largest σ in terms of the average waiting time is equal to 0.556. The standard deviation of the average waiting time was chosen since this variable can easily be determined for each model and affects most of the other relevant variables. Inserting those values in Formula (5) indicates that the required simulation runs should be larger than 475. Therefore it is decided to use N=500 as the number of simulation runs per model.

For each model, the same performance indicators are determined to compare the models with each other. The performance indicators for each model are (1) the average fillets waiting at the trimmers, (2) the maximum number of fillets waiting at the trimmers, and (3) the average utilization, all of which come directly from the simulation model's output. In addition, the queue length at each trimmer at the Trim station is tracked during the entire simulation, making it possible to refer to the maximum queue length at each trimmer. Besides, the queue length is known for each moment in time, making it possible to take the average number of fillets waiting at each trimmer. Lastly, the utilization of each trimmer is calculated in the same way as explained before, namely dividing the total time that a trimmer is busy by the total length of the simulation run.

In addition, (4) the required number of trimmers, (5) the trim loss reduction, and (6) total yearly cost reduction compared to the current situation are measured for each model. Those performance indicators are all related to the fillet harvesting line7 since none of the tested innovations affect B-ware's performance or costs. Based on a single shift, the yearly cost per trimmer is 35,000 euros. However, each day two shifts are working, which leads to a yearly cost of 70,000 euros per trimmer. Based on information gathered by Marel, the current yearly trim loss at the fillet harvesting line7 at client X is equal to 792,313 euros per year. In Table 15 below, the results of each model are represented. Model 1 represents the current situation, and therefore the trim loss reduction and cost reduction in the last two columns are the reductions compared to the current situation (model 1). The yearly cost reduction is the sum of the reduction in the number of operators required and the trim loss reduction.

*Table 15: Average performance and costs per model based on N=500 simulation runs with a length of 1 day*

| Model number | # fillets waiting | Max fillets waiting | Utilization trimmers | Number of trimmers | Trim loss reduction | Yearly cost reduction in euros |
|---|---|---|---|---|---|---|
| 1 (current) | 1.6 | 5.2 | 90.2% | 8 | - | - |
| 2 | 0.8 | 2.7 | 77.2% | 8 | 15% | 118,847 |
| 4 | 1.2 (2.1) | 3.1 (12.2) | 88.3% (64.4%) | 8 | 15% | 118,847 |
| 7 | 1.2 | 3.2 | 88.3% | 7 | 15% | 188,847 |
| 8 | 1.0 | 3.6 | 84.2% | 6 | 35% | 416,828 |
| 11 | 0.8 (0.6) | 2.7 (3.7) | 84.7% (76.5%) | 8 | 35% | 276,828 |
| 13 | 1.0 {0.8} | 3.8 {3.2} | 79.1% {74.1%} | 5{6} | 49% | 564,506 |
| 14 | 0.8 | 2.6 | 84.6% | 6 | 35% | 416,828 |
| 16 | 0.7 {0.5} | 2.8 {2.4} | 79.2% {74.1%} | 5{6} | 49% | 564,506 |

Note, values in parenthesis represent trimmer(s) that receive only quality A fillets, and values in angle brackets represent the results during winter.

For the first three variables in Table 15, the 95% CI's can be found in Appendix G. However, it is hard to determine 95% CI's for the variables regarding the yearly cost. The number of trimmers is fixed within each run of the simulation model. Therefore the yearly cost of trimmers is fixed. For the yearly cost of trim loss and the total yearly cost reduction, 95% CI's could also not be determined because it is concluded that the reduction in trim loss could only be determined in total and not per individual fillet. Therefore it is decided only to use the actual yearly trim loss found within previous research of Marel and determine the estimated yearly trim reduction based on this single actual yearly trim loss.

In addition to the cost-savings mentioned above, the performance of each scenario could also be compared in terms of the number of fillets waiting and the overall utilization of trimmers. In some models, the overall utilization of (some) trimmers is relatively low, as expected, since the number of trimmers needed in some scenarios was just above an integer number. Furthermore, for model 2 and during winter in models 13 and 16, the model was also simulated with one trimmer less. However, the average fillets waiting before trimmed and the average value of the maximum fillets waiting at a trimmer both increased by more than 300%. In addition, when comparing the average and the maximum number of fillets waiting at a trimmer, both values decrease on average slightly more than 25% when using the new distribution algorithm. Since both the average and the maximum number of fillets waiting are decreased, it could improve trimmers' task performance since the workload becomes more constant (Munander et al., 2019). In addition, the trimmers' task performance could be increased by reducing trim loss and improving the post-quality.

## 5.2 Requirements needed for the four adjustments

The four process adjustments are: (1) bypassing quality A fillets, (2) distributing individual fillets instead of pairs, (3) the new distributing algorithm at Trim station, and (4) bypassing small defected fillets for marinated products. Unfortunately, these process adjustments cannot be directly implemented since additional software and modules are needed for the implementation. Therefore, the requirements for each process adjustment are described below. In Figure 17 below, the current scenario is represented to visualize the process adjustments.

X

*Figure 17: Lay-out and product flow in the current trimming process*

### 5.2.1 Requirements for bypassing quality A fillets (BA)

A distribution module is required in front of the Trim station to sort out quality A fillets. The data generated by the pre-camera will control the distribution module. Besides a distribution module, an additional conveyor belt from the distribution module to the bone detection module is required for the bypass route. Lastly, the bypassed fillets also need to be scanned by the bone detection module. Therefore a merger is required, which merges the bypassed fillets to one of the two outflow belts of the Trim station. It is also possible to replace the dual-lane bone detection module with a triple-lane bone detection module. However, in that case, new distribution modules in front of the batching processes are needed to maintain the flexibility of sending fillets to the different batching processes. In Figure 18 below, the new layout of the trimming process when bypassing quality A fillets is represented.

X

*Figure 18: Lay-out and product flow when bypassing quality A fillets*

### 5.2.2 Requirements for distributing per single fillet (DS)

The most complex improvement is to distribute per single fillet. A module is required to split the incoming stream of pairs of fillets into two single streams of fillets. Currently, the fillet harvesting line automatically drops both fillets on the same conveyor belt. The dropping process of the fillet harvesting line could be adjusted to create two single outgoing streams to the pre-camera, or after the fillet harvesting line, a new module needs to be invented and installed that can split the pairs of fillets accurately. The layout and product flow when distributing per single fillet can be found in Figure 19 below.

X

*Figure 19: Lay-out and product flow when distributing per single fillet*

### 5.2.3 Requirements for a new distribution algorithm at the Trim station (NDA)

No additional modules are required to distribute fillets at the Trim station based on equal workload and a specific quality range instead of on equal quantity. However, a new algorithm needs to be developed, efficiently using the pre-camera data to distribute fillets based on equal workload and a specific quality range over the trimmers. An overview of the current distribution algorithm versus the new distribution algorithm is given in Figure 20.

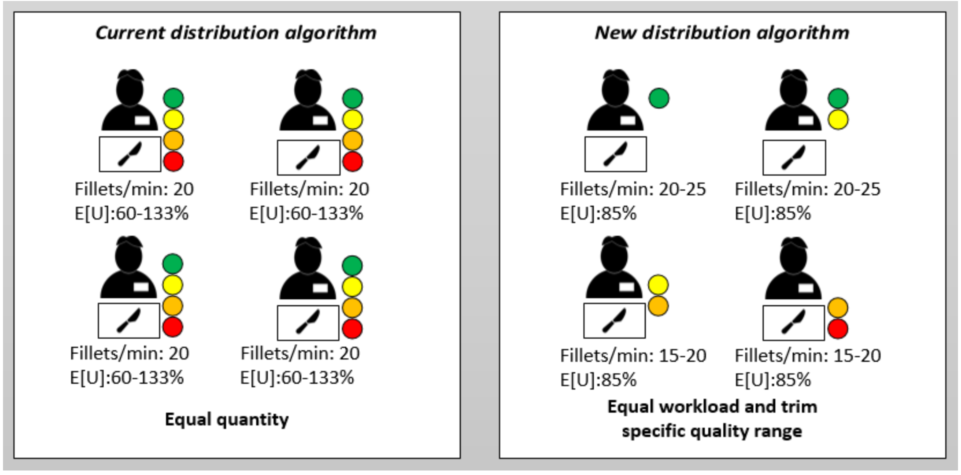



*Figure 20: Comparison of current versus new distribution algorithm*

### 5.2.4 Requirements for bypassing small defected fillets for marinated products (BB)

The same distribution module and conveyor belt could be used as the one that bypasses quality A fillets. However, in addition, a weigher is required in front of the bypass distribution module. This weigher determines for each incoming fillet if the weight is within the weight range of unfilled orders for marinated products. When the demand for marinated products within a specific weight range is met, the distribution module will stop bypassing small defects in the corresponding weight range. When also bypassing small defected fillets, the layout is given in Figure 21.

X

*Figure 21: Lay-out and product flow when bypassing small defected fillets*

### 5.2.5 Summary of requirements per adjustments

In Table 16 below, an overview of the requirements per adjustment can be found. An abbreviation is added at the end of each requirement, referring to each requirement within the summary in part 5.3.

*Table 16: Requirements per adjustment*

| Adjustment | Requirements |
|---|---|
| BA | Distribution module to bypass fillets (DB)<br>Conveyor belt for bypass lane (CBB)<br>Merger (ME) |
| BB | Weigher in front of distribution module used for bypass (WB) |
| NDA | Software update (SU) |
| DS | Module to split stream of incoming pairs (MSS) |

## 5.3 Summary of cost-savings versus requirements

In Table 17, an overview combines the yearly cost-savings found in part 5.1 with the corresponding requirements given in part 5.2. It is impossible to give a single cost-saving for implementing each adjustment since it depends on which other adjustments are implemented. Therefore, the requirements and cost-saving for each model are given in Table 17. In addition, this table can be used to determine which of the models has the highest return on investment (ROI) when the costs of all requirements are determined. Determining the cost for each requirement is not part of this research.

*Table 17: Overview of requirements and cost-saving per set of implemented adjustments*

| Implemented adjustments | Requirements | Yearly cost-saving in euros |
|---|---|---|
| BA | DB, CBB, and ME | 118,847 |
| NDA | SU | 118,847 |
| BA and NDA | DB, CBB, ME, and SU | 188,847 |
| BA and DS | DB, CBB, ME, and MSS | 416,828 |
| NDA and DS | SU and MSS | 276,828 |
| BA, BB, and DS | DB, CBB, ME, WB, and MSS | 564,506 |
| BA, NDA, and DS | DB, CBB, ME, SU, and MSS | 416,828 |
| BA, BB, NDA, and DS | DB, CBB, ME, WB, SU, and MSS | 564,506 |

# 6. Robustness of results and adaptability model

## 6.1 Sensitivity analysis

The robustness of the model is determined by executing a sensitivity analysis (Cont et al., 2010). A sensitivity analysis is defined as 'the study of how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input (Saltelli et al., 2004). The sensitivity analysis focuses on model 16 since model 16's design is the most complex and has the highest cost-saving. For the most critical variables handling times and incoming qualities, the available data was limited to the data gathered during the sample tests. Only those two variables are considered since the other input parameters, such as the number of fillets to B-ware and percentage rejection at bone detection module, are relatively small numbers and therefore expected not significantly impact the outcomes. The same number of runs (N=500) is used within the sensitivity analysis.

### 6.1.1 Handling times

The handling times are given in Table 13, but these values were difficult to measure, as already explained. Therefore, determining how the model's outcome changes when variating the handling times per fillet is interesting. Two restrictions that are made within fluctuating handling times are that in the current situation, the overall utilization of trimmers cannot exceed 100% and that the trim time of larger defects cannot be lower than for smaller defects. Variating the handling times could influence the required number of trimmers. Since the currently used handling times are based on an observed overall utilization of 90%, the handling times are adjusted with the same percentual differences to a 100% and 80% overall utilization in the current process. Therefore, each quality-specific handling time is first increased and then decreased by 10%. In addition, the handle times are adjusted so that the trim time is constant, independent of the fillet's quality because it was hard to measure differences in trim times between small and medium defects. The results of the sensitivity analysis can be found below in Table 18.

*Table 18: Sensitivity analysis on handling times*

| Situation | Number of trimmers | Yearly trim loss in euros | Yearly cost-saving in euros |
|---|---|---|---|
| Original model 16 | 5 (6) | 402,807 | 564,506 |
| Handling time -10% | 5 | 402,807 | 599,506 |
| Handling time +10% | 6 | 402,807 | 529,506 |
| Equal trim times | 5 (6) | 402,807 | 564,506 |

Note that the values in parenthesis indicate the required different number of trimmers in winter.

As can be concluded from Table 18 above, adjusting the handling times could only change the number of trimmers required and not the total trim loss. Since the number of trimmers is determined with Formula 1, and it is confirmed that this formula is accurate for all simulated models, it can easily be determined what impact other values for handling times have on the outcome, even without running 500 simulation runs. The size of the cost-saving depends on the handling times used within the model. However, the differences are relatively small since, taking the most extreme but fair values, the number of trimmers required differs at most one trimmer.

### 6.1.2 Incoming quality of fillets

The incoming qualities within the simulation model are based on the average quality of two days with the doubtful 50/50 fat proportion rule over a pair of fillets. Therefore within the sensitivity analysis, it is decided to test the largest deviating proportion rule Uniform[0,100]. In addition, the incoming qualities are adjusted to the flocks with the highest and lowest percentage of quality A fillets, neglecting the outlying flock 20. The sensitivity analysis results on the incoming quality of fillets can be found in Table 19 below.

*Table 19: Sensitivity analysis on incoming quality*

| Situation | Number of trimmers | Yearly trim loss in euros | Yearly cost-saving in euros |
|---|---|---|---|
| Original model 16 | 5 (6) | 402,807 | 564,506 |
| Uniform [0,100] fat | 5 | 362,368 | 639,945 |
| Highest quality flock | 4 (5) | 315,532 | 721,781 |
| Lowest quality flock | 6 | 459,451 | 472,862 |

Note that the values in parenthesis indicate the required number of trimmers in winter.

As can be concluded from Table 19, changing the incoming quality of fillets affects both the number of trimmers required and the total trim loss. When more data is available, and it seems that the worst-case flock out of twenty flocks represents the average quality of fillets the best, the total cost-saving will reduce by almost 100,000 euros per year. Therefore, adjusting the incoming quality of fillets can have quite a significant impact on the outcomes. Therefore, it could be wise to insert a specific client's historical actual fillet quality information into the model instead of simulating an average percentual incoming quality of fillets.

## 6.2 Adaptability of the model

Since Marel has many clients worldwide, the model needs to be flexible to model the trimming process for many clients. Therefore, much of the client-specific information is covered within the input parameters of the simulation model. The input parameters of the model are the arrival times of fillets, incoming quality, handle times, length and speed of the conveyor belts, the weight distribution of fillets, probability of fillets going to B-ware, the trim performance of trimmers, rejection percentages of bone detection modules, and the desired weight at each batching process. Furthermore, the distribution algorithm of fillets at the Trim station can easily be adjusted within the script when the number of trimmers is not correct. In addition, the allocation rules of distributing fillets to each of the batching processes can also be easily adjusted when changing the weight and or the preferred quality.

However, it becomes more complex when adding modules and possible events or changing the order of modules within a client-specific process. Unfortunately, within this modeling technique, the order of modules cannot be easily adjusted. The upcoming destination needs to be indicated for each event at each module. Furthermore, the model and improvements are only applicable on the fillet harvesting line + Trim station trimming line. The model is not appropriate for fillet harvesting line-I trimming lines since fillets are directly trimmed after harvested and therefore cannot be inspected accurately by a camera before being trimmed. Lastly, the model is built for the most complex processes at retail-focused clients. Therefore the model can easily be adapted to the less complex processes if no additional modules are used within those processes.

# 7. Conclusion and Recommendations

## 7.1 Conclusion

This project is performed at the Innovation department of Marel Poultry. Based on the current development of a fillet inspection camera, the importance of improving clients' yield, and the importance of meeting customer's requirements, the following main research question was formulated:

***How to use the data of the fillet inspection camera to design efficient trimming and logistic processes in a customer-specific manner?***

With the help of the simulation model, this research showed that the data generated by the fillet inspection camera could be efficiently used for multiple purposes. First, the camera could instruct a distribution module, bypassing fillets that already meet the quality requirements of orders. It is shown that bypassing fillets could significantly reduce the handling cost and trim loss. Second, the fillet inspection camera data could be used to distribute fillets more efficiently over trimmers at the Trim station. When fillets are distributed more efficiently, it is shown that the peak workload of trimmers can be reduced. This is expected to improve the trimmers' task performance, leading to less trim loss and higher output quality. Third, the fillet inspection camera could instruct the distribution modules before the batching processes to distribute the fillets based on quality requirements. Lastly, it is shown that the efficiency of implementing the abovementioned improvements will increase significantly when the fillets could be distributed per single fillet instead of per pair of fillets.

In addition, it became clear that the trimming process is client-specific and not the same for multiple clients. Therefore, the simulation model contains many input parameters that can easily be adjusted to simulate the trimming process at other clients. The improvements mentioned above are not all applicable to the processes of each client. When a client has, for example, only fillet harvesting line-i trimming lines or not a Trim station, some of the improvements cannot be implemented without changing the entire trimming process.

## 7.2 Recommendations

Given the results of this research, several recommendations are provided to Marel regarding how to use the data of the fillet inspection camera efficiently:

- *Automate data collection.* It was very time-consuming to manually gather all relevant data regarding the throughput at each conveyor belt. In addition, it was impossible to count the number of fillets on each conveyor belt at the same point in time. Therefore I recommend placing sensors on all relevant conveyor belts to know for each moment in time how many fillets are sent to each conveyor belt. Knowing the throughput on each conveyor belt each minute will make it easier to analyze possible relationships between the fillet quality, trim loss, and throughput.

- *Implement the process adjustments in the following order.* Based on all simulated scenarios and the corresponding (additional) cost-savings, it is recommended to implement the process adjustments in the following order: (1) New distribution algorithm, (2) Distribute per single fillet, (3) Bypass quality A fillets, and (4) Bypass small defected fillets.

  1. **New distribution algorithm**
     Only a software update is required to implement the new distribution algorithm at the Trim station, without adjusting the layout of the trimming process. Therefore it is considered the cheapest and easiest way to improve the efficiency of the trimming process. The research shows that a new distribution algorithm at the Trim station, which focuses on equal workload and trimming the same quality, reduces the yearly cost by 118,847 euros. In addition, it is expected that the new distribution algorithm will increase trimmers' task performance, which should increase the yearly cost-saving even more.

  2. **Distribute per single fillet**
     A splitting module is required to split the incoming stream of pairs of fillets into two streams. Unfortunately, this module is currently not available, and therefore I recommend exploring a solution to split the incoming stream of pairs. First, the new distribution algorithm will become more efficient when fillets can be distributed per single fillet. This is because single fillets can be more effectively distributed according to the specialized quality ranges of each trimmer, which increases the yearly cost-saving to 276,828 euros. Second, distributing per single fillet makes it possible to bypass all 42.7% of the quality A fillets instead of the 18.2% when distributing per pair of fillets. Lastly, small defected fillets could be bypassed when fillets are distributed per single fillet since the individual weight and quality of fillets can be measured.

  3. **Bypass quality A fillets**
     An additional distribution module, conveyor belt, and merger are required to automated bypass quality A fillets. The distribution module and conveyor belt are available modules, but a merger is currently unavailable. Therefore it is recommended to investigate if it is possible to develop a merger, which is useful in multiple processing lines. When the new

distribution algorithm is implemented, and fillets can be distributed per single fillet, the cost-saving increases to 416,828 euros per year.

4. **Bypass small defected fillets**
   Lastly, when clients are open to using small defected fillets for marinated products, only a weigher is required in addition to the modules required for bypassing quality A fillets. A weigher is required to determine if the weight fits an order for marinated products for each small defected fillet. Therefore, a yearly cost-saving of 564,506 euros can be obtained when bypassing small defected fillets for marinated products.

- *Assess fillet quality individually.* Currently, the fillet inspection camera determines the quality of each pair of fillets. However, the quality of fillets within a pair could differ. Therefore, an individual quality assessment is recommended to effectively distribute the fillets while meeting the customer's quality requirements.
- *Investigate the increase in trim performance with the new distribution algorithm.* When the new distribution algorithm is developed and implemented, it is recommended to test its impact on the trim performance. When it brings additional value, the potential cost-saving of the proposed process layouts will increase and could win over (new) clients to invest in one of the proposed solutions with the fillet inspection cameras.

## 7.3 Limitations and future research

In this section, the limitations of this research are discussed. In addition, based on these limitations, several options for future research are proposed.

- *Limited available data.* The available data is limited since the fillet inspection cameras, distribution modules, and trim weigher are relatively new modules. Marel is currently working on the automated data generation of the throughput and a solution to keep the cameras clean. Therefore, as mentioned in Chapter 4, most of the data is based on sample tests executed within two consecutive days. Therefore the amount of data used within the analysis is limited and could not cover potential seasonal patterns and trends. In addition, it is suggested that future research will focus on redoing the data analysis when more data is available. In this research, it is important to determine if the trim loss is predictable and if relevant variables, seasonal patterns, or trends are not covered in the simulation model.

- *Research focused on single processing line at single client.* Since the fillet inspection cameras are still in development, they are only installed on this single trimming line at client X. Therefore, only the process-specific parameters of this client could be used and tested within the model. The model is easily adjustable to other processes at other clients, but it is not investigated if the potential cost-savings and process adjustments are feasible and beneficial for multiple clients.

- *Impossible to implement and validate the proposed improvements in real-life.* Since Marel does not own the factories in which their equipment is used, it was unfortunately not possible to implement and test/validate (part of) the proposed improvements in real-life. It is very costly and time-consuming to adjust the trimming process by inserting additional paths and modules. Furthermore, most improvements could not be implemented since not all required modules have been developed yet. When the proposed improvements are ready to be tested, future research is suggested to determine the actual cost-savings in real life and compare them with the model results.

- *Increase in trimmers' task performance not validated.* There was no time left to develop and implement the new distribution algorithm during this project. Therefore, it was unfortunately not possible to test the new distribution algorithm's effectiveness in increasing the trimmers' task performance. Therefore, it is suggested to do future research to determine the increase in trimmers' task performance when distributing the fillets more efficiently based on the quality and constant workload. The research especially needs to focus on determining the reduction of trim loss and the improved outgoing quality of fillets.

# References


Babulak, E., & Wang, M. (2007). Discrete Event Simulation: State of the art. *International Journal of Online Engineering (iJOE), 4*(2), 60.

Blumenfeld, D. E. (1990). A simple formula for estimating throughput of serial production lines with variable processing times and limited buffer capacity. *The International Journal Of Production Research, 28*(6), 1163-1182.

Boon, M., van der Boor, M., van Leeuwarden, J., Mathijsen, B., van der Pol, J., & Resing, J. (2020). *Stochastic Simulation using Python* (Version: February 4, 2020). Eindhoven, The Netherlands: Technical University of Eindhoven.

Cont, R., Deguest, R., & Scandolo, G. (2010). Robustness and sensitivity analysis of risk measurement procedures. *Quantitative finance*, *10*(6), 593-606.

Brosnan, T., & Sun, D. W. (2004). Improving quality inspection of food products by computer vision—a review. *Journal of food engineering, 61*(1), 3-16.

Fishman, G.S. (2001). *Discrete-event simulation: modelling, programming, and analysis* (5th ed.). New York, USA: McGraw Hill Education.

Harel, O. (2009). The estimation of R 2 and adjusted R 2 in incomplete data sets using multiple imputation. *Journal of Applied Statistics, 36*(10), 1109-1118.

Hazra, A. (2017). Using the confidence interval confidently. *Journal of thoracic disease*, *9*(10), 4125.

Häusser, J. A., Schulz-Hardt, S., Schultze, T., Tomaschek, A., & Mojzisch, A. (2014). Experimental evidence for the effects of task repetitiveness on mental strain and objective work performance. *Journal of Organizational Behavior, 35*(5), 705-721.

Laofor, C., & Peansupap, V. (2012). Defect detection and quantification system to support subjective visual quality inspection via a digital image processing: A tiling work case study. *Automation in Construction, 24*, 160-174.

Law, A.M. (2015). *Simulation modelling and analysis* (1st ed.). New York, USA: Springer.

Leach, L. F., & Henson, R. K. (2007). The use and impact of adjusted R2 effects in published regression research. *Multiple Linear Regression Viewpoints, 33*(1), 1-11.

Li, J. (2004). Throughput analysis in automotive paint shops: A case study. *IEEE Transactions on Automation Science and Engineering, 1*(1), 90-98.

Mendling, J., Reijers, H. A., & van der Aalst, W. M. (2010). Seven process modeling guidelines (7PMG). *Information and Software Technology, 52*(2), 127-136.

Merzifonluoglu, Y. (2020). *Decision Making Under Uncertainty* (Version: December 12, 2020). Tilburg, The Netherlands: Tilburg University.

Mitroff, I.I., Betz, F., Pondy, L.R. & Sagasti, F. (1974). On Managing Science in the Systems Age: Two Schemas for the Study of Science as a Whole Systems Phenomenon. *Interfaces, 4(*3), 46-58.

Monroe, K.B. (1973). Buyers' subjective perceptions of price. *Journal of marketing research, 10*(1), 70-80.

Moore, D.S. (2014). *Introduction to the practice of statistics* (8th Ed.). New York, USA: W.H. Freeman and Company, a Macmillan Higher Education Company.

Munander, A., Musnadi, S., Sulaiman, S. (2019). *The effect of work stress, work load and work environment on job satisfaction and it's implication on the employee performance of Aceh Investment and One Stop services agency.* Conference: Proceeding of the First International Graduate Conference (IGC) On Innovation, Creativity, Digital, & Technopreneurship for Sustainable Development, Banda Aceh, Indonesia.

Recker, J. (2010). Opportunities and constraints: the current struggle with BPMN. *Business Process Management Journal, 16(*1), 181-201.

Saltelli, A., Tarantola, S., Campolongo, F., & Ratto, M. (2004). *Sensitivity analysis in practice: a guide to assessing scientific models* (Vol. 1). USA, New York: Wiley.

Schober, P., Boer, C., & Schwarte, L. A. (2018). Correlation coefficients: appropriate use and interpretation. *Anesthesia & Analgesia, 126(*5), 1763-1768.

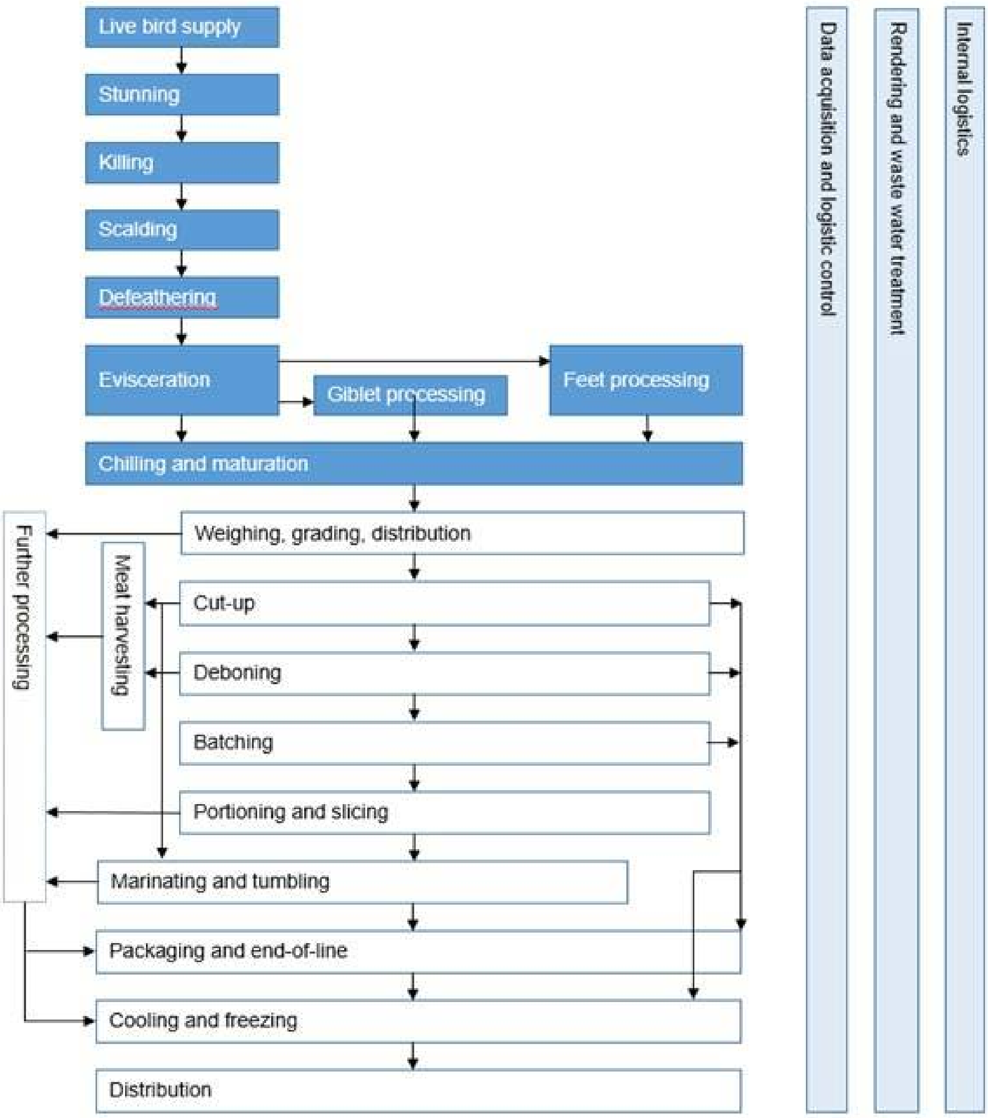
Van Donk, D.P. (2001). Make to stock or make to order: The decoupling point in the food processing industries. *International Journal of Production Economics, 69*(3), 297-306.

Vion Food Group (2016, September 12). *Consument kiest vaker voor dierenwelzijn*. Retrieved from: https://www.vionfoodgroup.com/nl/nieuws-pers/nieuws/post/consument-kiest-vaker-voor-dierenwelzijn/show.html?L=0&cHash=7964f1b02949f5c65d2d176c1975ffc1

Weimer, D., Thamer, H., Fellmann, C., Lütjen, M., Thoben, K. D., & Scholz-Reiter, B. (2014). Towards 100% in-situ 2D/3D quality inspection of metallic micro components using plenoptic cameras. *Procedia CIRP, 17*, 847-852.

# Appendices

## Appendix A – Process overview Marel Poultry




The processes in the dark blue boxes at the top of the figure above represent the primary processes fixed for all incoming broilers. Each incoming broiler must be stunned, killed, scalded, de-feathered, eviscerated, and chilled before the meat is suitable for being transformed into end-products.

The chilled ready-to-cook poultry's first processing step is 'weighing, grading, and distribution.' In this process, the weight and quality of the products can be determined, which makes the distribution of all products over the upcoming processes more manageable and more accurate to achieve the (estimated) demand for each end-product and each product is traceable.

In most cases, the live birds within the cut-up process are cut into three pieces: wings, breast parts, and legs. After cutting up the eviscerated birds, some of them will be deboned, and a small part would again go via the process of meat harvesting to further processing.

The remaining products will be batched based on their properties such as part and weights and, if needed, portioned and sliced to produce the required amount of each end product. After batching, portioning, and slicing and the products produced at further processing, the products will be packaged and afterward cooled or frozen before the products are distributed to the customers.

Besides those processing steps to go from live-bird to end product, the processes ‘internal logistics’, ‘rendering and wastewater treatment, and ‘data acquisition and logistic control’ are vital processes executed in parallel. Internal logistics are focused on bringing the right products to the right places as efficiently as possible. Data acquisition and logistic control focus on the real-time quality data of fillets and the traceability of each fillet within the process.

# Appendix B – Overview and description of client types

***Retail focused***

A processor's plant dealing with a flexible and logistic complex process, with first priority to deliver an assortment of consumer packages to retail customers. Non retail products need to be delivered to other channels.

***Food-service focused***

A processor supplying exact portioned boneless breast and/or (bone in) dark meat to the food service channel and institutions. This type of processor has to deal with a flexible and logistically complex process to deliver a wide assortment of (value added) products.

***Bulk focused***

Processor focuses on costs, delivering a small assortment of products to processors such as deboners, distribution module and to lesser extends to foodservice.

***Boneless meat, further processing supply focused***

Processor's plant focuses mainly on the delivery of raw material for supply to further processing activities. The meat can be sold as it is, but can also be portioned into specific dimensions/weights/shapes. A grading and or batching process often is part of the process. Products can be delivered fresh or frozen (for export) to specific markets with specific product specifications. Customers can be food service, further processors, fast food or specific export markets.

***Quick service bone in focused***

The processor is delivering primarily highly specified cuts of raw material to foodservice, fast-food, institutions and quick service restaurant chains. Aim is a very small weight range. Out of spec products need to be delivered to other channels.

***Whole product focused***

Processing plant delivering whole products fresh or frozen (mainly without giblets), individually packed in plastic bags or in a box. Sometimes fixed weight range and/or fixed number in a box. Products are mainly sold via wholesales.

***Independent / trading focused***

A processor who mainly debones breasts and/or leg products where optimizing process efficiency and raw material supply.

# Appendix C – Description of different in-scope modules

***Fillet inspection camera***

The fillet inspection camera is a module that can be attached to a conveyor belt and scan the top of each fillet. Based on this picture, the fillet inspection camera can detect certain 'defects' on each fillet and, based on this information, give each fillet a quality label within a few milliseconds. The fillet inspection camera is currently programmed to detect blood spots (small, medium, and large), excess skin (yes/no), and fat (small, medium, and large). Besides detecting those 'defects,' it classifies each fillet to a specific quality label based on the size of blood and fat spots and the presence of skin.

***Trim station***

The Trim station is an off-line trimming station commonly placed after an fillet harvesting line module. Within this trimming station, all fillets are distributed over trimmers. Those trimmers inspect and, if necessary, trim the fillets and put all fillets on the right conveyor belt to the corresponding downstream processes.

***Bone detection module***

Based on an X-ray scan, the bone detection module measures if a fillet still has some bones in it and can accurately weigh the fillet. This module is used to guarantee the safety of consumers of fillets. If bones are detected within the fillet, the fillet will be sent (back) to an trimmer at the Trim station, who knows that this fillet contains bones or other unwanted pieces such as metals. The bone detection module is available in a single, double, and triple lane module, but most customers are using the double lane bone detection module.

***Distribution module***

A distribution module is a module used to transform a single conveyor belt, which supplies fillets, into two separate conveyor belts, leading to different modules or batch processes. This module can distribute the incoming fillets over the two outgoing conveyor belts based on the desired weight, quality, and quantity needed within each batching process.

***Merger***

A merger is a module that can do the opposite of a distribution module, combining multiple ingoing conveyor belts with a single outgoing conveyor belt. Unfortunately, this module is not available, but it is expected to become available in a couple of years.

***Conveyor belts***

The fillets are transported on conveyor belts between the modules mentioned above and after the distribution modules.

# Appendix D – Calculations constant workload

The proportion of each incoming quality fillet at the Trim station needs to be multiplied with the corresponding average handling time of that fillet to calculate the constant workload at the Trim station. The constant workload calculations can be found below in a table for every model where the new algorithm is used.

| Model | Calculation constant workload |
|---|---|
| **4** | $0.427 * 2 + 0.215 * 3 + 0.167 * 3.5 + 0.191 * 4 = 2.76$ |
| **7** | $0.196 * 2 + 0.293 * 3 + 0.220 * 3.5 + 0.146 * 4 + 0.145 * 1.5 = 2.84$ |
| **11** | $0.215 * 3 + 0.167 * 3.5 + 0.191 * 4 + 0.427 * 1.5 = 2.64$ |
| **14** | $0.450 * 3 + 0.330 * 3.5 + 0.22 * 4 = 3.39$ |
| **16 summer**<br>**16 winter** | $0.153 * 3 + 0.395 * 3.5 + 0.452 * 4 = 3.65$<br>$0.252 * 3 + 0.349 * 3.5 + 0.399 * 4 = 3.57$ |

# Appendix E – Calculations for number of trimmers needed

***Model 1***

$$E[Per_{by}] = X_A * {Per_A}^2 = 0 * 0.427^2 = 0$$

$$E[\mu_{HT}] = \sum_{t=0}^{5} Prop_t * \mu_{HT_t} = -0.103 * 2 + 0.427 * 2 + 0.215 * 3 + 0.167 * 3.5 + 0.191 * 4 = 2.64$$

***Model 2***

$$E[Per_{by}] = X_A * {Per_A}^2 = 1 * 0.427^2 = 0.18$$

$$E[\mu_{HT}] = \sum_{t=0}^{5} Prop_t * \mu_{HT_t} = -0.103 * \frac{100}{81.8} * 2 + 0.341 * 2 + 0.293 * 3 + 0.220 * 3.5 + 0.146 * 4 = 2.66$$

***Model 4***

$$E[Per_{by}] = X_A * {Per_A}^2 = 0 * 0.427^2 = 0$$

$$E[\mu_{HT}] = \sum_{t=0}^{5} Prop_t * \mu_{HT_t} = -0.103 * 2 + 0.245 * 2 + 0.215 * 3 + 0.167 * 3.5 + 0.191 * 4 + 0.182 * 1.5 = 2.55$$

***Model 7***

$$E[Per_{by}] = X_A * {Per_A}^2 = 1 * 0.427^2 = 0.18$$

$$E[\mu_{HT}] = \sum_{t=0}^{5} Prop_t * \mu_{HT_t} = -0.103 * \frac{100}{81.8} * 2 + 0.196 * 2 + 0.293 * 3 + 0.220 * 3.5 + 0.146 * 4 + 0.145 * 1.5 = 2.59$$

***Model 8 and 14***

$$E[Per_{by}] = X_A * Per_A + X_s * E[Per_{mar}] * Per_s = 1 * 0.427 + 0 * E[Per_{mar}] * 0.215 = 0.43$$

$$E[\mu_{HT}] = \sum_{t=0}^{5} Prop_t * \mu_{HT_t} = -0.103 * \frac{100}{57.3} * 2 + 0.450 * 3 + 0.330 * 3.5 + 0.22 * 4 = 3.03$$

***Model 11***

$$E[Per_{by}] = X_A * Per_A + X_s * E[Per_{mar}] * Per_s = 0 * 0.427 + 0 * E[Per_{mar}] * 0.215 = 0$$

$$E[\mu_{HT}] = \sum_{t=0}^{5} Prop_t * \mu_{HT_t} = -0.103 * 2 + 0.215 * 3 + 0.167 * 3.5 + 0.191 * 4 + 0.427 * 1.5 = 2.43$$

***Model 13 and 16***

$$E[Per_{by}]summer = X_A * Per_A + X_s * E[Per_{mar}] * Per_s = 1 * 0.427 + 1 * 0.7 * 0.215 = 0.58$$

$$E[Per_{by}]winter = X_A * Per_A + X_s * E[Per_{mar}] * Per_s = 1 * 0.427 + 1 * 0.7 * 0.215 = 0.44$$

$$E[\mu_{HT}]summer = \sum_{t=0}^{5} Prop_t * \mu_{HT_t} = -0.103 * \frac{100}{42.2} * 2 + 0.153 * 3 + 0.395 * 3.5 + 0.452 * 4 = 3.16$$

$$E[\mu_{HT}]winter = \sum_{t=0}^{5} Prop_t * \mu_{HT_t} = -0.103 * \frac{100}{47.9} * 2 + 0.252 * 3 + 0.349 * 3.5 + 0.399 * 4 = 3.14$$

# Appendix F – Output linear regression models

Model summary of predicting trim loss fillet harvesting line7 with entire dataset

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | ,814[a] | ,662 | ,286 | 26,259 |
| 2 | ,813[b] | ,661 | ,355 | 24,948 |
| 3 | ,811[c] | ,658 | ,410 | 23,873 |
| 4 | ,800[d] | ,640 | ,429 | 23,477 |
| 5 | ,760[e] | ,578 | ,383 | 24,420 |

a. Predictors: (Constant), Blood_mm2, Fat_mm2, Per_Small, Amount_Good, Per_Medium, Per_Large, Amount_Small, Amount_Large, Amount_Medium, Per_Good

b. Predictors: (Constant), Blood_mm2, Fat_mm2, Amount_Good, Per_Medium, Per_Large, Amount_Small, Amount_Large, Amount_Medium, Per_Good

c. Predictors: (Constant), Blood_mm2, Fat_mm2, Amount_Good, Per_Large, Amount_Small, Amount_Large, Amount_Medium, Per_Good

d. Predictors: (Constant), Blood_mm2, Fat_mm2, Amount_Good, Per_Large, Amount_Small, Amount_Medium, Per_Good

e. Predictors: (Constant), Blood_mm2, Fat_mm2, Per_Large, Amount_Small, Amount_Medium, Per_Good

Model summary of predicting trim loss B-ware with entire dataset

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | ,929[a] | ,864 | ,713 | 39,64898 |
| 2 | ,929[b] | ,863 | ,740 | 37,71822 |
| 3 | ,929[c] | ,863 | ,763 | 36,02857 |
| 4 | ,927[d] | ,859 | ,777 | 34,93803 |
| 5 | ,919[e] | ,845 | ,774 | 35,16899 |

a. Predictors: (Constant), Blood_mm2, Fat_mm2, Per_Small, Amount_Good, Per_Medium, Per_Large, Amount_Small, Amount_Large, Amount_Medium, Per_Good

b. Predictors: (Constant), Blood_mm2, Fat_mm2, Per_Small, Amount_Good, Per_Medium, Per_Large, Amount_Small, Amount_Medium, Per_Good

c. Predictors: (Constant), Blood_mm2, Fat_mm2, Per_Small, Amount_Good, Per_Medium, Per_Large, Amount_Medium, Per_Good

d. Predictors: (Constant), Blood_mm2, Fat_mm2, Per_Small, Per_Medium, Per_Large, Amount_Medium, Per_Good

e. Predictors: (Constant), Blood_mm2, Fat_mm2, Per_Small, Per_Medium, Amount_Medium, Per_Good

Model summary predicting number of fillets to B-ware

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | ,822[a] | ,675 | ,188 | 6,77721 |
| 2 | ,822[b] | ,675 | ,304 | 6,27616 |
| 3 | ,821[c] | ,674 | ,388 | 5,88283 |
| 4 | ,820[d] | ,673 | ,455 | 5,55009 |
| 5 | ,811[e] | ,658 | ,486 | 5,38974 |
| 6 | ,801[f] | ,641 | ,511 | 5,26125 |
| 7 | ,759[g] | ,577 | ,471 | 5,47155 |
| 8 | ,742[h] | ,550 | ,481 | 5,41758 |
| 9 | ,684[i] | ,468 | ,430 | 5,67657 |

a. Predictors: (Constant), Total_mm2_blood, Amount__A, Amount__E, Amount__B, Amount__F, Total_mm2_fat, Amount__C, Amount__D, Amount__G_and_H

b. Predictors: (Constant), Amount__A, Amount__E, Amount__B, Amount__F, Total_mm2_fat, Amount__C, Amount__D, Amount__G_and_H

c. Predictors: (Constant), Amount__A, Amount__E, Amount__B, Amount__F, Total_mm2_fat, Amount__C, Amount__D

d. Predictors: (Constant), Amount__A, Amount__B, Amount__F, Total_mm2_fat, Amount__C, Amount__D

e. Predictors: (Constant), Amount__A, Amount__B, Total_mm2_fat, Amount__C, Amount__D

f. Predictors: (Constant), Amount__A, Amount__B, Total_mm2_fat, Amount__C

g. Predictors: (Constant), Amount__A, Amount__B, Amount__C

h. Predictors: (Constant), Amount__A, Amount__B

i. Predictors: (Constant), Amount__B

Model summary of predicting trim loss fillet harvesting line7 with adjusted dataset (removing defects >2500 mm2)

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | ,654[a] | ,428 | -,715 | 31,67387 |
| 2 | ,652[b] | ,425 | -,438 | 29,00287 |
| 3 | ,646[c] | ,417 | -,249 | 27,72559 |
| 4 | ,629[d] | ,395 | -,134 | 27,05346 |
| 5 | ,604[e] | ,364 | -,059 | 26,89055 |
| 6 | ,575[f] | ,331 | -,004 | 26,22972 |
| 7 | ,545[g] | ,297 | ,041 | 25,77788 |
| 8 | ,538[h] | ,290 | ,112 | 25,68966 |
| 9 | ,498[i] | ,248 | ,133 | 25,52069 |
| 10 | ,482[j] | ,232 | ,177 | 24,93577 |

a. Predictors: (Constant), Total_blood_mm2, Total_fat_mm2, Per_Small, Amount_Good, Per_Medium, Per_Large, Amount_Medium, Amount_Large, Amount_Small, Per_Good

b. Predictors: (Constant), Total_blood_mm2, Total_fat_mm2, Per_Small, Amount_Good, Per_Medium, Per_Large, Amount_Medium, Amount_Small, Per_Good

c. Predictors: (Constant), Total_blood_mm2, Total_fat_mm2, Amount_Good, Per_Medium, Per_Large, Amount_Medium, Amount_Small, Per_Good

d. Predictors: (Constant), Total_fat_mm2, Amount_Good, Per_Medium, Per_Large, Amount_Medium, Amount_Small, Per_Good

e. Predictors: (Constant), Amount_Good, Per_Medium, Per_Large, Amount_Medium, Amount_Small, Per_Good

f. Predictors: (Constant), Per_Medium, Per_Large, Amount_Medium, Amount_Small, Per_Good

g. Predictors: (Constant), Per_Large, Amount_Medium, Amount_Small, Per_Good

h. Predictors: (Constant), Per_Large, Amount_Small, Per_Good

i. Predictors: (Constant), Amount_Small, Per_Good

j. Predictors: (Constant), Amount_Small

Model summary of predicting trim loss B-ware with adjusted dataset (removing defects >2500 mm2)

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | ,965[a] | ,931 | ,792 | 36,55384 |
| 2 | ,965[b] | ,931 | ,826 | 33,44159 |
| 3 | ,964[c] | ,929 | ,849 | 31,19276 |
| 4 | ,961[d] | ,924 | ,857 | 30,31049 |
| 5 | ,959[e] | ,920 | ,866 | 29,36599 |
| 6 | ,944[f] | ,892 | ,838 | 32,32018 |
| 7 | ,939[g] | ,881 | ,838 | 32,28131 |
| 8 | ,937[h] | ,878 | ,848 | 31,33658 |

a. Predictors: (Constant), Total_blood_mm2, Total_fat_mm2, Per_Small, Amount_Good, Per_Medium, Per_Large, Amount_Medium, Amount_Large, Amount_Small, Per_Good

b. Predictors: (Constant), Total_blood_mm2, Total_fat_mm2, Per_Small, Amount_Good, Per_Medium, Amount_Medium, Amount_Large, Amount_Small, Per_Good

c. Predictors: (Constant), Total_blood_mm2, Total_fat_mm2, Per_Small, Amount_Good, Per_Medium, Amount_Medium, Amount_Large, Amount_Small

d. Predictors: (Constant), Total_blood_mm2, Total_fat_mm2, Per_Small, Amount_Good, Per_Medium, Amount_Large, Amount_Small

e. Predictors: (Constant), Total_blood_mm2, Total_fat_mm2, Per_Small, Amount_Good, Per_Medium, Amount_Large

f. Predictors: (Constant), Total_blood_mm2, Total_fat_mm2, Per_Small, Amount_Good, Amount_Large

g. Predictors: (Constant), Total_blood_mm2, Per_Small, Amount_Good, Amount_Large

h. Predictors: (Constant), Total_blood_mm2, Per_Small, Amount_Good

# Appendix G – 95% Confidence intervals of results

| Model number | # fillets waiting | Max fillets waiting | Utilization trimmers |
|---|---|---|---|
| **1** | [1.2, 2.0] | [3.0, 7.4] | [88.7, 91.7] |
| **2** | [0.7, 0.8] | [1.8, 3.6] | [75.6, 78.8] |
| **4** | [0.9, 1.5]* ([1.5, 2.7]) | [2.3, 3.8]* ([6.7, 17.6]) | [86.5, 90.0] * ([60.0, 68.7]) |
| **7** | [1.1, 1.3] | [2.3, 4.0] | [86.6, 90.0] |
| **8** | [0.7, 1.2] | [2.1, 5.0] | [82.3, 86.1] |
| **11** | [0.7, 0.9]* ([0.5, 0.7]) | [1.3, 4.1]* ([2.2, 5.1]) | [82.9, 86.4]* ([74.6, 78.4]) |
| **13** | [0.7, 1.2] ** {[0.5, 1.0]} | [2.1, 5.5]** {[1.7, 4.9]} | [77.0, 81.1]** {[72.6, 75.5]} |
| **14** | [0.7, 0.9] | [1.5. 3.8] | [82.8, 86.4] |
| **16** | [0.6, 0.8]** {[0.3, 0.7]} | [1.7, 3.9]** {[1.5, 3.2]} | [77.1, 81.2]** {[72.7, 75.5]} |

Note, values in parenthesis represent trimmer(s) that receive only quality A fillets, and values in angle brackets represent the results during winter.