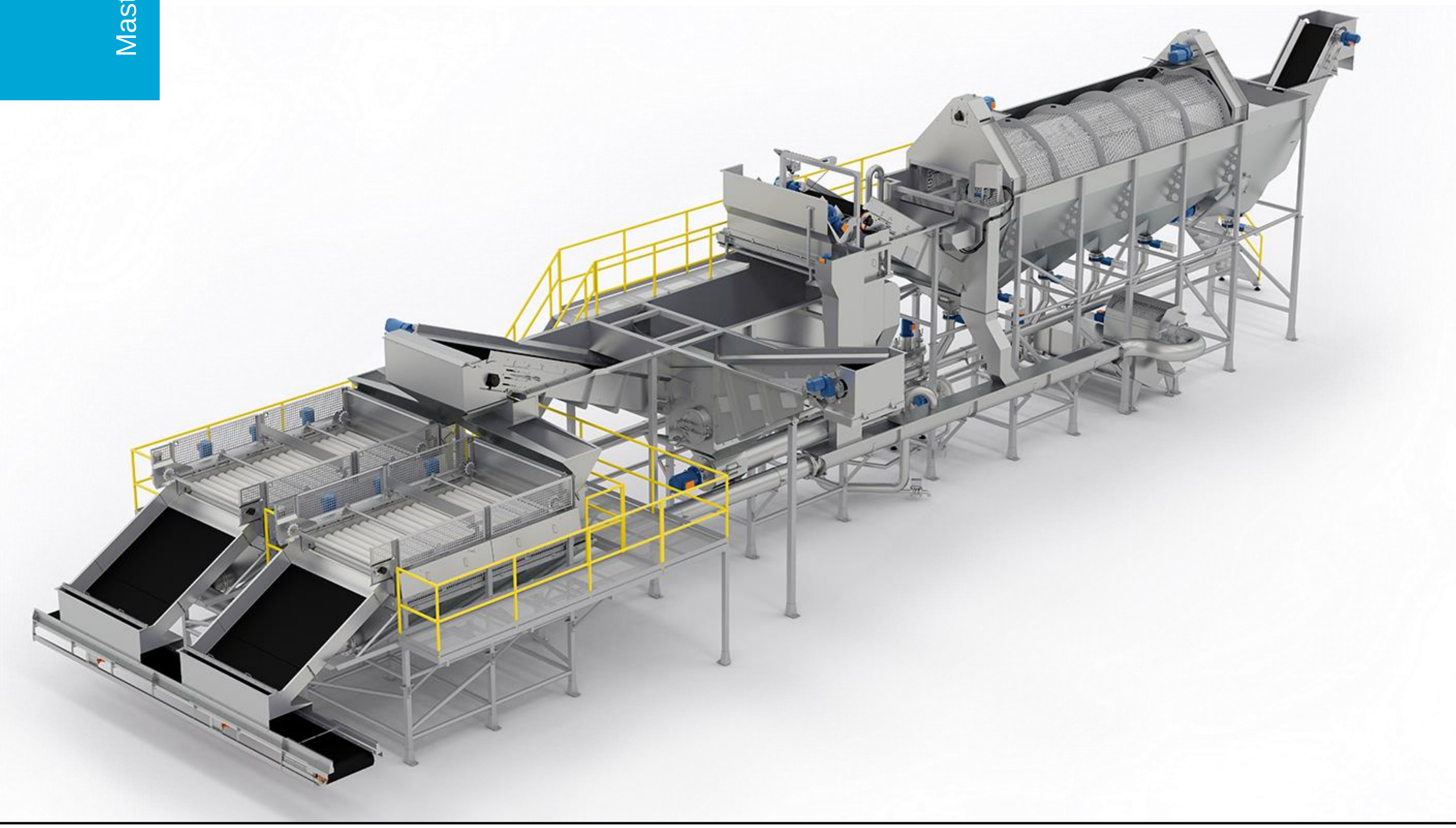
Modular Smart Design of Tuber Washing Lines

A NOVEL DESIGN APPROACH

S. Temmerman

Master of Science Thesis



TUMMERS FOOD PROCESSING SOLUTIONS

TU Delft Delft University of Technology

Modular Smart Design of Tuber Washing Lines

A NOVEL DESIGN APPROACH

by

S. Temmerman

Master of Science Thesis

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Preface

I was raised at a farm where my dad has his own machine line for sorting and packaging potatoes. As a kid I helped him in my summer break by standing alongside the conveyor belt and manually retrieving stones, clods, haulm and other debris from the product stream. During the job I was thinking about ways to make the process more efficient and thought about robots that could take over the job so my dad and I could relax in the sun. When I graduated by bachelor's degree in mechanical engineering I wanted to follow up with a master's degree in agricultural engineering. Because this master's degree does not exist in the Netherlands I chose to study multi-machine engineering and apply the knowledge during a job in agricultural engineering when I graduate. Because of my interest in making machine lines more efficient this thesis is written as a graduation internship at Tummers Food Processing Solutions for the track Multi-Machine Engineering of the MSc Mechanical Engineering at the Delft University of Technology. The project is supervised by daily supervisor Ed van Dolen and secondary supervisor Kees den Boer from the company side and by dr. Jovana Jovanova from the university side, whom I want to thank for their support. During the project continuous contact is maintained with the research group for washing lines and other advisors from the company side for information, counseling and to ensure that the outcome of the project will be backed up by all layers of the company. To get practical insight in the washing lines and customer wants and needs, during the project multiple customers are visited, which are listed in appendix J. Meetings are also held with companies that produce peripheral equipment to the washing lines, sensors or software to gather information and insights on those topics. To prepare for and support this thesis a literature review is performed called: "Modular Smart Processing Lines: Automated Systems and Their Benefits".

Keywords

Modular design, smart design, processing lines, tuber washing, potatoes

Abstract

Tummers Food Processing Solutions is an internationally operating company based in the Netherlands, that sells factory lines for processing tuberous products like potatoes. Before being processed into various products, the incoming tuber batches are always washed and cleaned from waste particles like clods, stones and haulm. For this purpose washing lines consisting out of different machines are used. Every processing application, customer and kind of input product results in different requirements regarding the machines, options and their configuration. Currently for every customer a tailor made machine line is designed, consisting out of customised machines based on the expertise of the corresponding sales agent and the engineer that designs the machines. This results in individually designed machines, friction between different departments and mistakes in drawings, parts lists, manufacturing, documentation and others. Once installed on site, the machine line is controlled by machine operators that keep the factory operational but are not optimising the performance and efficiency of the machine line nor conduct preventive maintenance. To tackle both the issues on the company and the customer side, the strategy for designing these tuber washing lines has to be turned into adaptive machine line design. Adaptive machine line design is a combination of modular design and smart factory engineering. Machine lines are customer specifically configured out of standardised modules and controlled by smart systems to optimize performance and efficiency and predict maintenance.

Because potatoes are by far the most commonly processed product, followed up by carrots, this research focusses on potato washing lines with some specific side notes for processing carrots. Based on sales records and customer preferences, a set of standardised machine models and options is defined as the machine portfolio. This portfolio consists out of ten different machines, each available in different sizes, with waste and product streams to different directions and other standardised options. A jigsaw puzzle model can be made where this machine portfolio is build up as a set of puzzle pieces. For every different application a set of these puzzle pieces can be chosen from the portfolio and connected in different configurations. To determine which machines with which options to choose from the portfolio in which order, a model can be used. This model is based on a set of input- output relations and first set up as a decision scheme after which it is modeled in LabView as a basic machine line configurator. The model is then used to configure machine lines for five different examples. Each example is an existing order with differences in customer specific wishes, input and output characteristics and boundary conditions regarding factory layout and peripheral equipment. With help of these five examples the model is iteratively checked and improved after which the amount of customer specific engineering is determined that still needs to be performed after standardising of the machines.

A first layer of a Digital Twin for smart control of the washing line is designed. This control strategy is based on the Key Performance Indicators of the washing line and their relations between them. Based on open or closed loop control, a set of control schemes is created for each machine that requires smart control.

A thorough analysis of the costs and benefits of implementing a modular design strategy for the tuber washing lines shows that huge amounts of man hours can be saved after implementation. Next to these savings in labour, less mistakes will be made in the design and manufacturing of the machines which improves the professional image of the company and lowers friction between different departments and stress on the workfloor. Due to significant savings in replacing wear sensitive parts, reduced factory downtime, loss of product in waste streams and reduced operator wadges, installing a system for smart control can easily be earned back in the first year of operations. All and all changing the design strategy for tuber washing lines to adaptive machine line design is very promising for both the machine line manufacturer as for the customer.

List of Symbols

a	Input variables	$[various]$
A_d	Drum area	$[m^2]$
A_{filled}	Filled drum area	$[m^2]$
A_p	Product area	$[m^2]$
b	Output variables	$[various]$
c_e	Equipment factor	$[-]$
c_μ	Proportionality coefficient	$[-]$
d_d	Drum diameter	$[m]$
d_p	Perforation size	$[m]$
η	Efficiency	$[\%]$
f_r	Rotational frequency	$[s^{-1}]$
F	Resulting force	$[N]$
F_G	Gravitational force	$[N]$
F_N	Normal force	$[N]$
F_S	Friction force	$[N]$
ϕ	Degree of filling	$[-]$
g	Gravitational constant	$[m/s^2]$
h	Product thickness	$[m]$
l_b	Output belt length	$[m]$
l_d	Drum length	$[m]$
ℓ	Water level	$[-]$
m_a	Potato mass	$[kg]$
m_{tot}	Total mass	$[kg]$
μ_k	Kinematic friction coefficient	$[-]$
μ_k^0	Initial kinematic friction coefficient	$[-]$
n_a	Number of potatoes detected	$[s^{-1}]$
$n_{a,error}$	Potato error	$[s^{-1}]$
$n_{a,max}$	Maximum permissible number of potatoes	$[s^{-1}]$
n_c	Number of clay caps detected	$[s^{-1}]$
$n_{c,error}$	Clay cap error	$[s^{-1}]$
$n_{c,max}$	Maximum permissible number of clay caps	$[s^{-1}]$
n_g	Number of glassed potatoes detected	$[s^{-1}]$
$n_{g,error}$	Glassed potatoes error	$[s^{-1}]$
$n_{g,max}$	Maximum permissible number of glassed potatoes	$[s^{-1}]$
n_h	Number of haulm detected	$[s^{-1}]$
$n_{h,error}$	Haulm error	$[s^{-1}]$
$n_{h,max}$	Maximum permissible number of haulm	$[s^{-1}]$
n_s	Number of stones detected	$[s^{-1}]$
$n_{s,error}$	Stone error	$[s^{-1}]$
$n_{s,max}$	Maximum permissible number of stones	$[s^{-1}]$
n_r	Number of rollers	$[pc.]$
p	Water pollution	$[\%]$
p_{error}	Water pollution error	$[\%]$
p_{max}	Maximum permissible water pollution	$[\%]$
ρ	Weight	$[kg/m^3]$
ρ_a	Potato density	$[kg/m^3]$
$\rho_{a,bulk}$	Potato bulk density	$[kg/m^3]$

Q	Machine capacity	$[TPH]$
Q_{calc}	Calculation capacity	$[TPH]$
Q_C	Corrected machine capacity	$[TPH]$
Q_d	Drainage capacity	$[m^3/h]$
Q_{dr}	Relative drainage capacity	$[m^3/ton]$
Q_{in}	Input capacity	$[m^3/h]$
Q_s	Soil output	$[ton/h]$
r	Radius	$[m]$
SG	Specific gravity	$[-]$
t	Residence time	$[s]$
t_{req}	Minimal required residence time	$[s]$
t_{res}	Resulting residence time	$[s]$
t_d	Discharge time	$[s]$
$t_{d,req}$	Minimal required discharge time	$[s]$
$t_{d,res}$	Resulting discharge time	$[s]$
θ	Belt inclination	$[^\circ]$
θ_b	Boundary angle	$[^\circ]$
θ_{opt}	Optimal angle	$[^\circ]$
θ_{res}	Residual angle	$[^\circ]$
u	Machine type	$[-]$
v	Machine size	$[-]$
v_b	Belt speed	$[m/s]$
v_r	Rolling speed	$[m/s]$
V_p	Product volume	$[m^3]$
w	Waste belt direction	$[-]$
w_b	Belt width	$[m]$
ω	Rotational speed	$[rad/s]$
ω_{opt}	Optimal rotational speed	$[rad/s]$
ω_{res}	Residual rotational speed	$[rad/s]$
x	Motor location	$[-]$
y	FPR type	$[-]$
Y	Young's Modulus	$[Pa]$
z	Machine option	$[-]$

Abbreviations

AI Artificial Intelligence. 13, 15, 21, 79, 152
API Application Programming Interface. 102

CAD Computer Aided Design. 15, 17, 57, 58, 60, 73, 74, 102
CIT Chemical Imaging Technology. 66, 152
CPQ Configure, Price and Quote. 8, 9, 40, 48, 57–60, 73, 76, 80, 81, 102, 103, 121
CPS Cyber-Physical System. 13, 61, 79, 150
CS Cyber Security. 21, 79
CTO Configure To Order. 8, 9, 52–57, 73–75, 79–81, 121

DAC Digital to Analog Converter. 13, 61
DT Digital Twin. 13–15, 17, 19, 20, 61, 64, 67, 71, 79

EIS Electrochemical Impedance Spectroscopy. 82, 156, 161
EMF Electromagnetic Field. 161
ERP Enterprise Resource Planning. 3, 4, 8, 22, 57–60, 75–77, 79, 102
ETO Engineering To Order. 7, 9, 52–58, 73–76, 79–81, 121

FE Finite Element. 20
FEA Finite Element Analysis. 20
FPR Floating Parts Remover. 16, 30, 31, 36, 40, 41, 43, 45–47, 53–57, 62, 63, 66–68, 71, 80, 101, 110, 126, 149–151, 156, 157, 161, 166

IoT Internet of Things. 12, 21, 79
IT Information Technology. 21

KPI Key Performance Indicator. 2, 4, 14, 57, 61, 67, 68, 70, 71, 79, 80, 150

LVDT Linear Variable Differential Transformer. 160, 161, 163, 164

MIMO Multiple Input Multiple Output. 12
MISO Multiple Input Single Output. 79

NIR Near Infrared. 66, 154, 163, 164

PVC polyvinylchloride. 31
PVM Product Variant Master. 59, 80, 104

RFID Radio-Frequency Identification. 14
RGB Red Green Blue. 65, 66, 152
RGBI Red Green Blue Infrared. 65

SCADA Supervisory Control and Data Acquisition. 14

TPH Tons Per Hour. 23–26, 28, 34, 41, 47, 48, 50–55, 57, 77, 118, 155

UV Ultraviolet. 39, 54

VA Variable Area. 158
VPN Virtual Private Network. 61, 76, 80, 155

WLAN Wireless Local Area Network. 12, 62

Contents

1 Introduction

Potatoes are one of the most important vegetables in the diet of the Netherlands but also in the rest of the world. The average Dutchman consumes 72 grams of potato a day. The potato has been part of the classic Dutch diner for ages and even though the multi cultural society has brought new foods like pasta, rice and quinoa to our diner table, the potato is still part of the Dutch diner 3.5 days of the week on average [91]. Next to the classic boiled or fried potatoes, potatoes are processed into an almost infinite list of products found in our supermarkets. Some of the most popular examples are fries, chips and röstis but potato flakes and starch are commonly used in sauces, noodles and for breading but also in less obvious products like wine-gums, frankfurter sausages and wallpaper glue. Even though potatoes are the most popular tuberous vegetable in the Netherlands, other tubers like carrots, parsnips or red beets are also found in our diets.

But before those tubers can be processed into all those various products, they need to be cleaned. Because tubers are grown inside the soil instead of on top of them, product batches contain relatively large amounts of soil, stones, clods, haulm and other waste. Machine lines for cleaning the tubers and removing waste from the product stream are called tuber washing lines. Tuber washing lines are used throughout factories for the production of a multitude of different products. The market for tuber washing lines will be divided into two different categories: fresh packs and industry.

Potatoes and carrots that are processed into fresh packs are only washed, sorted and packaged. Fresh packs are transparent packages of vegetables that are sold in supermarkets. The customer wants fresh and clean vegetables. Breakage, bruising and slicing of vegetables in the washing line needs to be prevented, therefore the machines have to handle the product gently. It is important for the skin to stay intact. This is both for the product to look good in the store as to protect it against viruses and bacteria. Furthermore the vegetables need to be washed thoroughly for the fresh packs not to contain traces of sand or other filth. Discoloured vegetables like green potatoes for example, have to be removed from the stream and the vegetables need to be dried before packaging. Washing lines for fresh packs regularly have lower capacities and are not in continuous operation.

In industry potatoes and carrots are processed into a wide variety of products. Some examples are pre-cut vegetable packages, fries, chips, starch and flakes. After being washed and sorted, the tubers are processed by different lines like peeling, cutting or frying lines for example. Tubers that are peeled have to be washed less thoroughly because sand and filth are removed with the skin. The tubers are immediately processed after being washed. Because the product is often pasteurised, fried and/or packaged in vacuum, bacteria and viruses do not pose a big threat in these production lines. Breakage, bruising and slicing of vegetables in the washing line have less impact on product that is processed for industry. First of all the tubers are often peeled, which cuts takes away all minor damage. Secondly the product goes through an optical sorter after being peeled and cut, this optical sorter removes all pieces that do not meet the requirements. In a factory for potato fries for example, fries with a coloured spot are removed from the product stream. This way if a tuber is damaged, only the damaged part of the product ends up as waste instead of the entire product. In some machine lines for potato fries the fries that do not meet the requirements in the optical sorter are cut in halve and then redirected through the optical sorter. This way only the damaged spot is removed instead of the entire fry. Potatoes that are processed into starch or flakes have even less requirements. Tubers that are damaged do not need to be removed from the product stream, only green or rotten potatoes need to be removed. Tuber washing lines for industry are characterised by high capacities and are in continuous operation of more than 7000 hours per year. Because of this the machines need to be engineered maintenance-free for minimal downtime.

1.1 Need analysis

Adaptive machine lines are based on two core principles: modular design and smart factory engineering. Combining both design principles results in a machine line design that can be configured out of existing modules to fit the machine line application and change its own parameters according to the input and desired output. More theory about adaptive machine lines will be discussed later. Because of these two core principles, the need for both of them needs to be analysed.

Modular design
Deficient communication between different departments within a company is a commonly occurring issue, this is also the case within the organisation of Tummers. Each department looks at the project from a different angle, therefore communication is key in getting a common understanding of the project goal and how to

reach it. A famous cartoon to visualize the problems that occur when different departments work on one project without properly communicating with each other, is the tree swing story, which is visualised in figure 1 below.

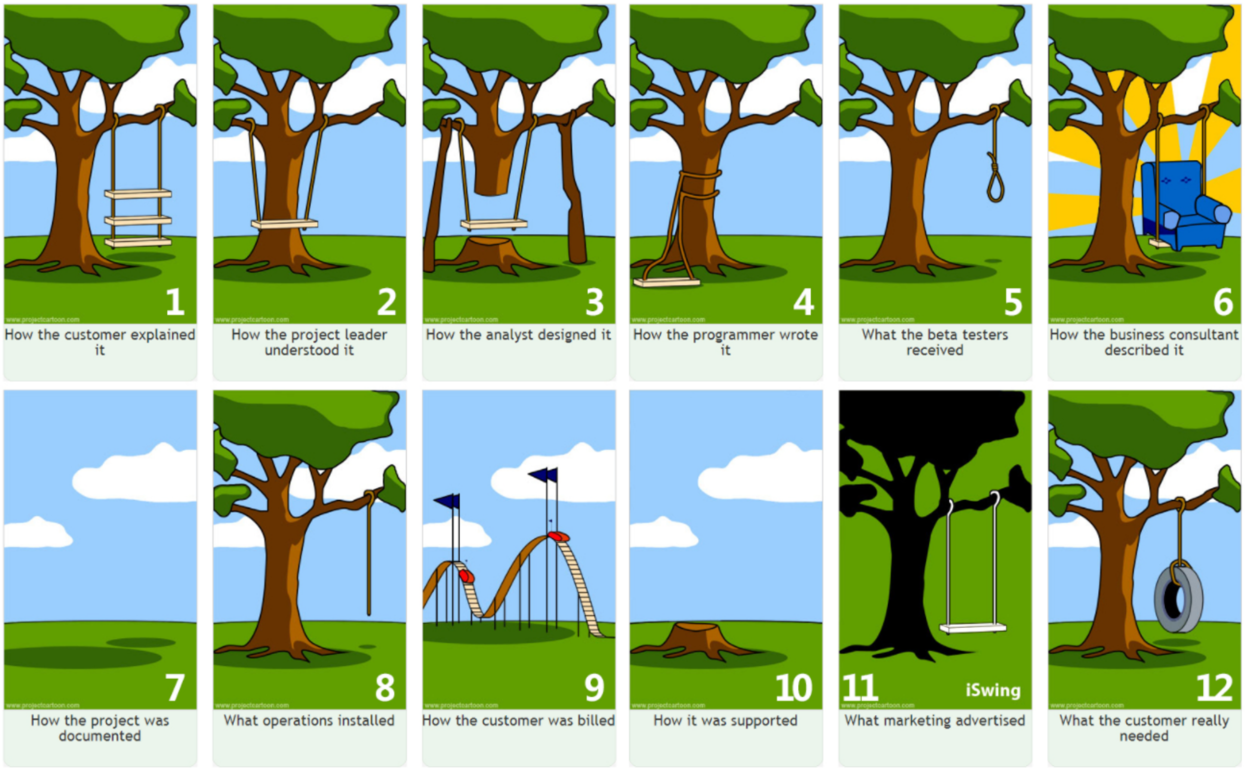


Figure 1: Tree swing analogy cartoon, derived from ref [128].

The project cycle always starts at the customer, which wants to buy a machine line. To explore its preferences the customer gathers information on what machine lines are available to perform the task. The marketing department of the production company has to supply the customer with clear information on the products and services they sell to solve the problem of the customer. Many production companies like Tummers advertise to sell 'custom made solutions'. They show the customer the range of machines they sell and tell them about the options that can be added without specifying exact machine models and their relevant parameters like dimensions and Key Performance Indicator (KPI)s. With this information in mind the customer makes his wish list for the project and then sits down with a sales representative of the company to discuss the project. The salesman writes down the supposed wants and needs of the customer and sets up a first draft of the machine line. After discussion with the customer the draft is adjusted and a final machine line is sold. When sold, the order is sent to the engineering department to engineer a machine line that fits all wants and needs of the customer. The engineers copy existing machine lines that are used for comparable applications and customise them to the specifications that are sold to the customer. Because engineers are very passionate about the technology they work with, they try to improve the machine line for the customer. When engineers have finished their work, the material list is sent to the purchasing department and the drawings are sent to the workshop. Tummers has its own sheet metal production department, the rest of the parts are bought from suppliers. When all parts have come in, the mechanics in the workshop start manufacturing the machines. Most machines are assembled in house. If all machines in the machine line are finished they are send to the customer where the installing team constructs the machine line on site. The machine line is then tested and set to the right settings for optimal performance. The right documentation of the machine line is sent to the customer. When parts of the machine line break of wear out over time, spare parts are ordered from the spare parts department and guided by the manuals, the customer conducts maintenance to the machine line.

During this project cycle a lot of problems are posed by faulty communication between the different departments and the customer. Figure 2 below shows the most important order-related communication streams within the organisation of a machine line manufacturing company. The rectangles are different departments within the organisation, blue arrows indicate communication flows and the dashed brackets around coloured areas indicate responsibility. These communication problems occur throughout the entire organisational structure. The most common communication problems will now be discussed.

The customer bases its wish list on the information supplied by the company. The marketing department presents machine lines they think the customers would like. Sometimes expired machine models or customer specifically made specials for example are presented to the customer, that then orders these products. In this case the customer bases its wish list on the wrong information. Afterwards the customer presents its wish list to the sales department. The sales department sometimes misunderstands the wants and needs of the customer or tries to sell expensive advanced solutions to the problem, which the customer does not really need. It also happens that a salesman agrees with the customer to adjust a machine in a way that is technically hard or even impossible to deliver. When the project is then sold and delivered to the engineering department, the engineers need to adjust the machine designs to the customer specific needs. This can lead to a lot of extra engineering hours and friction between the engineering and sales department. When the design is finished, a new parts list and set of drawings has to be made. Mistakes are often made in this process because a wide set of new parts is needed for the custom made design. For the customer specific machine lines new manuals need to be made. The new parts need to be put in the Enterprise Resource Planning (ERP) software, which is further explained later, afterwards they can be ordered from the suppliers. If current suppliers do not sell these products, a new supplier needs to be found. The new parts are not in stock, which delays the production. Sometimes parts are forgotten to be changed in the drawings, which leads to production errors. The people in the workshop need to produce products they have never made before and work with new parts, which leads to an increased amount of production errors. When the material list is faulty, the wrong components are send to the customer. It is very important for the machines to meet the norms, therefore when customer specific changes are applied to the machines, they have to be checked to do so. When the installing department is building the machine line on site, sometimes on the other side of the world, the absence of some specialised parts leads to a huge increase of installing time. When the machine line is finally set up on site, it sometimes does not represent what the customer ordered because the machine line has changed during the project at different departments. This leads to a dissatisfied customer that will not return to the company for future machine lines and spreads bad words about the company. Due to mistakes when the new products are put in the ERP software, the spare parts list can be faulty. When the customer needs to perform maintenance the parts do not fit the machines and new parts need to be ordered. Also the machines in the documentation differ from the machines that are installed. This leads to increased downtime and extra material costs during maintenance.

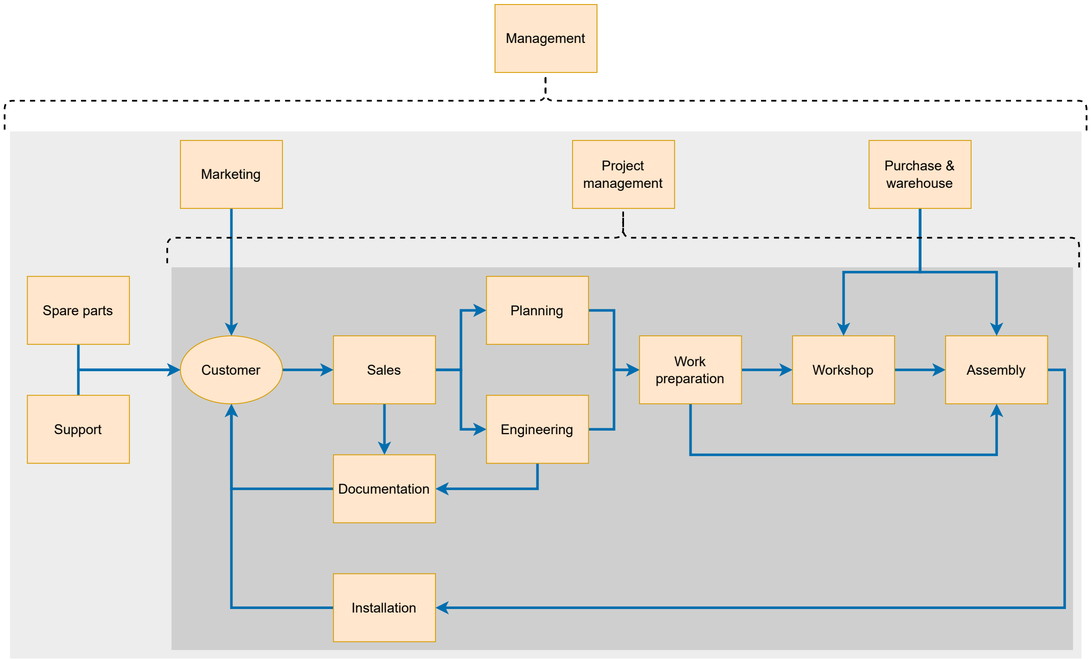


Figure 2: Overview of the most important order-related communication streams throughout the organisation of a machine line manufacturing company, inspired by [92].

In many machine line production companies like Tummers, this deficient communication between the different departments poses a problem. Standardisation, for example through modular design, helps to solve these problems. The portfolio of the company is then standardised into a predefined set of machines and options. Each module comes with a standardised set of KPIs, dimensions, price, parts list, workshop instructions, drawings and documentation. When the standard machines and options are clearly structured and advertised on the website and in brochures, the customer is able to form his wish list based on this information and does not receive a product that differs from what is sold to him. The standards are defined in the ERP system so that all departments are enabled to posses this information at all times. Next to that the ERP system is used for all departments to document their work so that other departments working at the same project further down the line can see the work that is done by their colleagues. This way the problems mentioned above can be prevented from occurring. By preventing these problems huge amounts of labour, time and material costs can be saved. Next to that also secondary benefits are realised: the company builds up a good name for itself, employees experience less stress during their work and there is less friction between different departments. The company is also enabled to improve the standardised machines and to develop new machines instead of focusing on customer specific engineering. Altogether it is clear that there is a huge need for Tummers to work with standardised modular designs to stay ahead of competition and secure or even increase its market share.

Smart design

Smart design is the future of multi machine engineering. A lot of technical knowledge is available on how to optimise the functioning of the machine line by changing the settings. This knowledge lays in the combined expertise of the different departments within the machine line production company. The field employees, service mechanics and engineers have gathered lots of information throughout a multitude of projects over the years. Retirees that now act as external advisors and employees that have worked for the company for many years hold valuable information about how to optimally run a machine line for different applications and under different circumstances. Nowadays a Tummers project manager coaches the machine operators for a few days after the machine line is installed on site. During this short period the basics of operations and maintenance for this specific line are explained. The project manager stays a few days while the machine line is running to cure teething problems in the factory. Machine operators are often low educated and have to work under harsh circumstances in the factories. Generally a machine operator is not specialised in the washing line alone, but takes care of the whole factory. This factory can contain up to sixty machines for a machine line that produces french fries. The washer is only one out of these sixty machines and comes with a multitude of settings that can be changed for different applications, as will be described later in this report. Because the machine operators do not have the knowledge to perfectly operate the whole factory, they focus solely on keeping the machine lines running. They only fix machines when they are jammed or if parts are broken and generally do not focus on preventive maintenance. Maintenance is conducted when the machine line is down due to an error or during periodic maintenance shifts during scheduled downtime. Also the operators do not focus on optimal performance and efficiency of the machine line, they only conduct repairs when parts of the machine line are broken. As one of the managers at a french fries factory wisely said: "There is a huge difference between keeping a washing line operational and making sure a washing line will keep staying operational." (Peter Buffel, 2021).

During a company visit the responsible machine operator was asked what settings of the washing line he changed under which circumstances. He answered that he did not change any setting at all. According to him the machines were set to the right settings when they were installed and the only things he changed afterwards were setting the water level in the washer to the maximum, supposedly to maximise the washing quality, and shutting down all spray bars because they consumed too much expensive fresh water. The problems that occurred partly due to these settings were the drains beneath the washer getting clogged and haulm gathering in dead corners of the washer. In this report it will be made clear that the machines in the washing line are quite complex and that with the right settings they are able to process higher capacities with a higher washing quality at improved efficiency [59].

Partly due to the Covid crisis throughout the whole world, parts nowadays have extremely long delivery times. When a machine line is down due to a broken part which needs to be replaced, but which is currently out of stock, factory owners experience a big problem. Smart systems are able to predict maintenance and automatically order the right parts beforehand so that when maintenance has to be performed, the right parts are always available. Today when a factory experiences a broken part in their washing line without Tummers or themselves having it directly available in stock, they call around befriended factory owners if they have the specific part laying on their shelves. Many factory owners do not want to hand over the parts because the delivery times are very long and when their machine breaks down before the part is delivered, they are saddled up with the problem themselves.

When installing sensors throughout the machine line and controlling it in a smart way by a computer system, the problems of which only a tip of the iceberg is shown above can be solved. With a smart system installed, the machine line will experience less downtime, less maintenance is needed and higher capacities of product can be washed with a higher washing quality for less operating costs. A big reason to control the washing line in a smart way is to limit wear in the machines. If the machine settings like for example the rotational speed of output belts can be lowered, this leads to reduced wear. Because of the high costs of replacement parts and the even bigger costs of factory downtime, wear in the machines has to be limited at all times. All together smart factory engineering poses a great opportunity to be used for improving control of tuber washing lines.

1.2 Gaps in literature

There is no specific literature available on tuber washing lines. The most recent and most specific literature that is available online comes from 1999. This is unexpected because technology has experienced an exponential development rate since the turn of the century and online publication of research has increased likewise. The available literature gives vague descriptions of washing technology like:

> After quality evaluation, potatoes are unloaded and transported in different ways, mostly by flume movement, which allows to remove stones via two-step traps, and removal of floating impurities such as coke, lava, pumice, rotted and hollow hearted potatoes, straw etc., each in specific devices. (Bergthaller et al., 1999, p. 237).

The fact that there is insufficient online literature on tuber washing lines does not mean that the knowledge is not there yet. Manufacturers of tuber processing lines like Tummers, Kiremko or DT Dijkstra for example hold precious knowledge on this subject. Tummers, who is world leader on the market of industrial processing of tuberous products with a market share between 60 and 70%, has been working with this technology since 1967 [101]. Tummers does not only focus on innovation, they also work closely together with their customers and companies that produce peripheral equipment like water treatment systems or optical sorters, which makes them act as a project integrator. Unlike some of their competitors, Tummers does not only work in close contact with their customers while designing the machine line. After the line is sold and installed Tummers educates the machine operators, assists during maintenance and provides spare parts. Because Tummers is not only providing machine lines for the market but also working as a part of it, they have gathered in depth practical knowledge of the washing technology. The point of shortcoming for Tummers is that their machine line configurations are based on experience rather than on science. There is no literature available on this subject which makes it an interesting research topic, therefore this report will be the first to describe design of tuber washing lines from a scientific angle.

For research on modular machine lines and smart factory engineering it is the other way around. Lots of theoretical research is performed on modular design and smart engineering is currently a hot topic. Industry 4.0, which is an engineering philosophy that is all about smart factory design has become the standard rather than the exception. The first sections of this report will go over the currently available literature on these subjects. Even though there is an abundance of research available on these topics, it is all theoretical speculations on hypothetical applications. There is no applied research available on modular or smart engineering of machine lines. It would be a valuable addition to the state of the art to take a company that engineers machine lines customer specifically without clear standards and which is mainly manually operated and change that design strategy to modular and smart design. This practical research can set a clear example for machine line manufacturers in other markets. Therefore the research question of this report will be:

> How to optimally design a smart tuber washing line based on theoretical concepts, customer inputs and a modular approach?

To answer this research question, a set of sub questions is formulated that are answered consecutively throughout this report.

1. What is the state of the art regarding adaptive machine lines?
2. How to compose the machine portfolio?
3. How to model the modular design approach?
4. How to model a smart washing line?
5. What are the benefits of such an adaptive tuber washing line?

Each of the five sub questions is answered in a corresponding chapter. This report ends in a conclusion with recommendations for further research. These corresponding chapters are:

- State of the art regarding adaptive machine lines
- Machine portfolio composition
- Jigsaw puzzle model
- Smart washing line control
- Benefits of an adaptive tuber washing line

2 State of the art regarding adaptive machine lines

Adaptive machine lines are the future for production and processing lines. Factory lines were formerly engineered customer specifically from scratch and individual unique machines were made in series of one and controlled by machine operators. Adaptive machine lines are configured customer and application specifically out of existing machines that are made in multiples and controlled by smart systems. Adaptive machine line design can therefore be divided in two core principles. Which will be addressed in this section in two respective subsections.

Adaptive machine line design = Modular design + Smart factory engineering

2.1 State of the art regarding modular design

Engineering of modular machine lines is a principle where a system is divided into smaller modules. Each module can be independently designed, modified, replaced or exchanged with other modules [49]. A standard portfolio of machines is made that fit together in different configurations. For each specific machine line design, a set of machines can be chosen from the portfolio and combined into a production or processing line.

Ito (2008, p. 37) states the following aspects to be considered for modular design [49].

1. Each module has meaningful functionality and/or structural configuration.
2. Each module must have the dimensional and configuration specifications to be joined to other modules.
3. The alternative designs and combinations must cover the full range of requirements.
4. The performance must meet the specifications.

A modular design is built up out of parts in a hierarchical structure. Each machine line consists out of different function groups. The function groups exist out of different machines working together to fulfill that common function. The machines on their part are made out of different combined modules. The modules are assembled out of different parts [49]. A fresh packs processing line for vegetables is shown as an example in figure 3 below. From each level one component is set out further on the level below it.

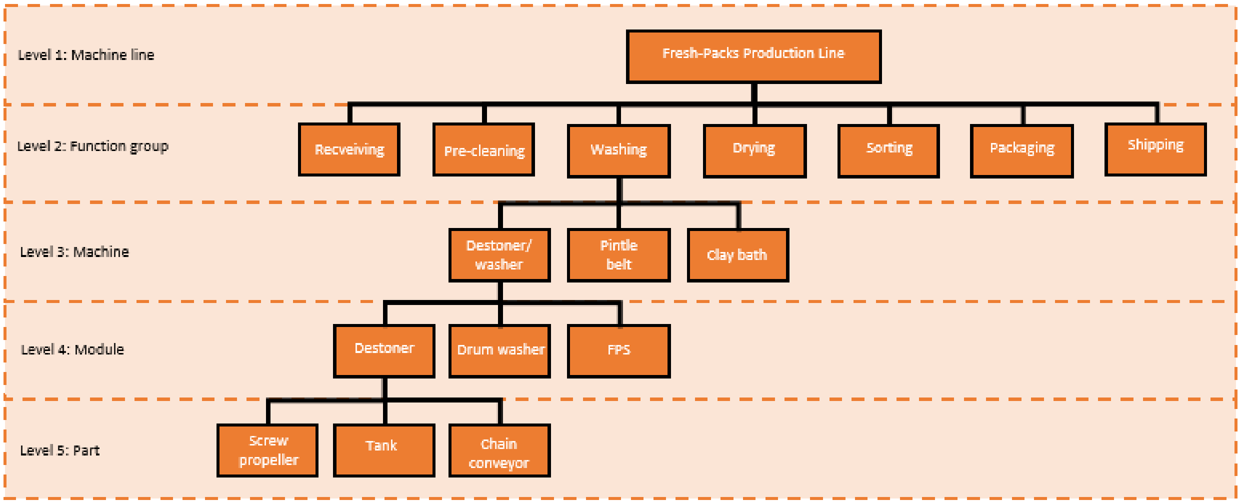


Figure 3: Example of a modular design with hierarchical structure.

2.1.1 Configuration to order

Many companies that sell custom made machine lines to their customers design a totally new line for every individual order, this is called Engineering To Order (ETO). This design strategy takes a lot of engineering hours, which raise the price of the machine line and the time the customer needs to wait for his machine line to be delivered. Furthermore engineers are saddled with complex adjustments to their machines, sold to the customer by the sales department without consulting them if these adjustments are even possible. This often leads to extremely long delivery times, customers that do not exactly receive what they ordered and lots of stress in the engineering office [14].

To solve these issues, the designing strategy has to be changed to Configure To Order (CTO). With CTO engineering, the machine line is configured out of a choice of different modules. For each module a standard design is defined, accompanied with standardised documentation which includes a set of construction drawings, calculations, parts lists, quotation and information about previous sales. This standard is applied throughout all departments and levels of the organisation to ensure optimal collaboration and to prevent miscommunications.

Modular design though CTO engineering can be digitised with Configure, Price and Quote (CPQ) software. All available modules are described in this CPQ software so that the user can configure a machine line out of these modules in the digital environment. CPQ software can be combined with ERP software for an optimal result. According to Mabert et al. (2003, p. 302) ERP systems are enterprise-wide on-line interactive systems that support cross-functional processes using a common database [66]. ERP systems help integrate all parts of the company-wide process through sharing data and workflow standardisation . ERP systems contain both real-time data and data collected over the years. All the orders that are ever produced by the company can for example be retrieved through the ERP system. CPQ software can automatically read out ERP software to get all this (real-time) data. This way only the right product and customer numbers need to be filled into the CPQ software, which will then retrieve all details from the ERP system [14]. If an ERP system is implemented the right way it can be quite beneficial to the company by gaining competitive advantage, streamlining operations and reducing waste time. Never the less, implementing an ERP system is very expensive and takes a lot of time, therefore a company has to do a thorough cost-benefit-analysis before committing to installing an ERP system. Tummers has Ridder IQ ERP software installed throughout the company [14, 66].

2.1.2 Benefits of modular design

In the late 1960s, the strategy of modular design was already assumed to be advantageous for both the manufacturer and the user. For the manufacturer the strategy of modular design is able to reduce both the manufacturing costs and the manufacturing time [13]. Furthermore modular design can increase the production volume and be quite beneficial to the inventory. The latter is caused by the fact that the amount of different parts used in manufacturing is significantly reduced and the volume per part is increased. This way the turnaround time for each part in inventory is reduced [49].

Clarity throughout all organisational levels
Modular design brings a standard way of designing the individual machines in the machine lines, these standards bring clarity to every level in the organisation as previously described in section 1.1. If all organisational levels use the same standards, lots of wasted time and money due to miscommunications can be saved.

Decreased manufacturing time
Because the machine lines are standardised and consist out of less different parts, manufacturing and assembly in the workshop are easier and consume less time for the workshop personnel. This way less manufacturing and assembly errors are made. The installing time at location also decreases [58].

Less different parts
Because less different parts are needed in the warehouse, the investment in inventory has decreased [49]. The total turnover per individual part increases, therefore bigger batches can be ordered per product. Economy of scale leads to a lower price and faster turnaround time per part, which is beneficial for the warehouse. The decrease in variety of parts also makes it easier for the workshop, assembly and installing personnel, for example to locate or identify different parts. The chances of the wrong parts being ordered, shipped or installed are also decreased, which leads to less material costs and reduced waiting times.

Simultaneous production of the same module
When the machine lines that are ordered consist of similar modules, multiple parts of similar modules can be manufactured in the workshop at the same time, this can lead to a significant decrease in manufacturing time of these modules. Furthermore this eases the production planning.

Less customer specific engineering
The customer chooses a machine line that is built out of a combination of standard modules, therefore the machine line does not have to be engineered customer specifically. This not only reduces a lot of engineering

costs for the manufacturer, it also decreases the manufacturing time for the customer. Furthermore the engineers are enabled to spend more time at R&D of the standardised machines to stay ahead of competition. It is also easier to train new personnel in the workshop because of the decreased complexity.

Standardised documentation
Because the machine lines consist out of a combination of standard modules, documentation can easily be standardised. This leads to standardised brochures, manuals, assembly drawings etc., but also makes it easy to develop an online help tool for customers that have malfunctioning equipment. Furthermore customers can be assisted in real-time by professionals of the manufacturing company when they have a problem with their machine line. This reduces a lot of work that is now done by engineers at the drawing board, mechanics that solve malfunctioning and people at the sales office. Because the documentation is standardised it contains less mistakes, which leads to faster repairs by the customer.

Order cancellations have less impact
Because the machine lines are not engineered customer specifically, the modules can be resold to other customers if the original customer cancels his order. This takes away a lot of financial damage when this event takes place.

More sales options
Because of the modular design a CPQ web tool can be made where users are able to fill in their wants and needs into a configurator and the web-tool will show them the combination of modules that is the best fit for their situation. This way the user can browse through the technical specifics of the machine line, have a visualisation of the system and have an approximation of the quotation in real-time. The user can tweak certain parameters to change the machine line in the web-tool and see what the possibilities are. This web-tool can boost sales and reduce time spent by salesmen. Also the users are enabled to watch video's of exactly the machine line they are to order, recorded on site from a previous order. This reduces the chance of disappointments. The strategy for implementing CPQ software will be explained in further depth in section 4.11.

Modules fit together more easily
The modules fit together in a better way because they are specifically designed to do so. This reduces the risk of leakage, wear and downtime due to malfunctioning. Furthermore the machines are all designed with the same capacity which reduces unnecessary costs for capacity that is never used due to limitations up- or downstream.

The beneficial effects of implementing modular design strategies listed above do not only bring down costs for the manufacturer significantly, they also lower the price of the product and are therefore cutting costs for the customer too. This way a company like Tummers can be made able to stay ahead of competition and conquer a bigger market share. Next to that the delivery times for the washing lines, stress under workers and friction between departments will decrease.

2.1.3 Customer specific constraints

In the designing of modular machine lines, customised machine systems are the rule rather than the exception. Every factory requires it's own unique machine line due to a set of customer specific constraints. Machine lines most of the time need to be installed in an existing, or already designed building. This brings a few constraints to the table while designing the factory line.

Because the available factory floor size is predetermined, the machines need to be installed in a configuration that will fit inside the factory. While designing a fitting machine line in a modular way, the different modules can be connected in an efficient way by using advanced transport systems. This way for example machines that are regularly configured in a straight line can be designed around a corner or multiple machines can be placed above each other to save space. The available floor size can also influence the choice between installing two machines with a smaller capacity alongside each other and installing one big machine. A way of taking the best out of the available floor size that needs to be prevented unless absolutely necessary is adjusting the modules to fit into the building. While designing in a modular way, the modules should not be adjusted customer specifically. Customer specific adjustment of modules changes the designing strategy from CTO to ETO, which raises the cost price of the machine line significantly through extra hours spent on engineering and construction.

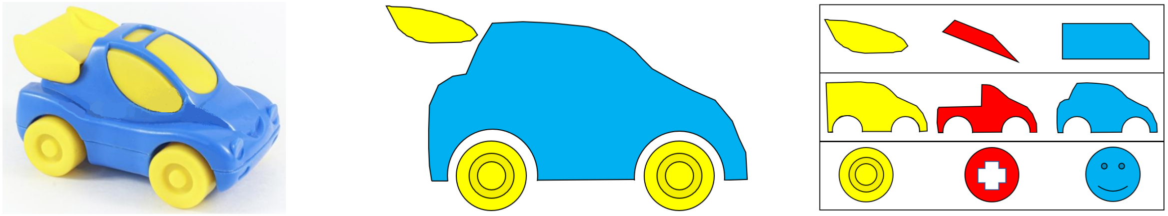
The presence of locally existing machines can also influence the design of a machine line. Some customers already have older machines or machines from competitors that they want to re-use in the new machine line. To handle this issue, again, the modules do not need to be adjusted. The preferable way to handle this is to add efficient transitions between the new modules and the existing machines. These transitions require some extra engineering but prevent the modules from needing to be adjusted.

The biggest factors to influence the factory design are the desired output product to come out of the machine line an the input product fed into the system. The input stream determines the throughput capacity that all the machines in the line are designed to. Furthermore the difference between the quality of the input stream and the desired output product determines the choice between different modules to be implemented into the factory line.

Another constraint can be working together with different external parties to build a factory line. While designing a machine line, some parts need to be outsourced. Not only the dimensions of the machines produced by those parties need to fit those of the machines that are produced in-house to be attached in an efficient way, the maximum capacities also need to match to prevent overloading of a machine. Input streams like water, power or gas need to match the requirements of the machines. Periodic meetings with those external companies during the designing of the factory line will help prevent problems with mismatching equipment from occurring. The software that controls the machine lines can be made by a partner that is involved with the design of the modules and has standard software to control them, there however are also customers that already have their own software throughout the rest of the factory and want that same software to control the new machine line. To make sure the software works with the machines, meetings can be held with the software designer. Furthermore working with international norms like ISO standards facilitate general standards that ease collaboration with companies on an international level [48].

2.1.4 Jigsaw puzzle model

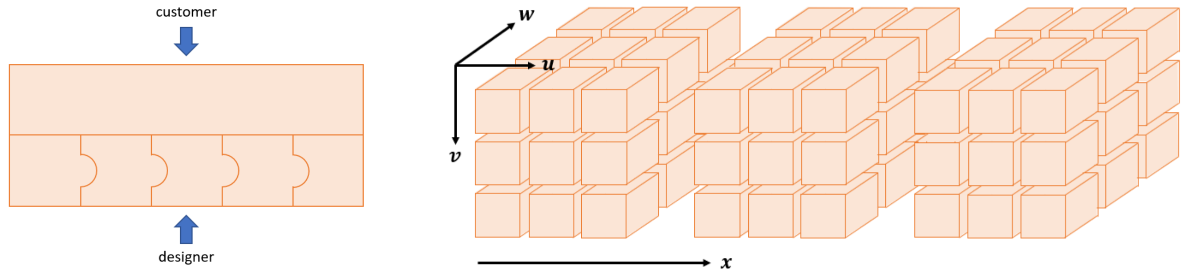
A popular way to model modular design is through a modular kit model. For this model, according to Albers et al. (2019, p.10), the domain is understood as a modular kit so the individual products can be deductively derived from the modular system which inductively describes the modular kit. This is based on the modular kit reference model, which can be generated inductively from the reference product models [3]. An example to illustrate this modelling method can be made for a modular design of a toy car. The modular kit model is a model that describes which parts need to be installed in which toy car. The modular kit contains all different options for the different car parts. These can for example be different chassis, wheels and spoilers. Based on the logic in the modular kit model, a tailor made reference product model can be configured out of these parts that represents the physical product model. Figure 4 below illustrates this example and the terminology of the different stages in this modular design method.



(a) Physical product model. (b) Reference product model. (c) Modular kit.

Figure 4: Modular kit design example.

There are various different ways to visualise the modular kit reference model. Some examples are visualisation through block diagrams or two dimensional physical representations like in figure 4. Based on the modular kit model, a new modelling method is created in this research project, which will be called the jigsaw puzzle model. This modelling method will be used for designing modular machine lines in this report but can also be used for other modular design applications. The basis of the jigsaw puzzle model is that the design is a single specialised tailor made product in the eyes of the customer but in the eyes of the designer this specialised product is a combination of existing standardised modules taken from the module portfolio. This perspective is visualised in figure 5a below. The set of modules which Albers et al. named the modular kit will be referred to as the machine portfolio. In contrast to the two dimensional modular kit, this portfolio can be structured in more than two dimensions. These dimensions represent different machine parameters. The first dimension, u, sets out the different machines that can be placed in the line. The second dimension, v, is the set of available sizes for each specific machine. The other dimensions, $w, x...$, can be machine options, for example the power supply method [24V or 400V] or the height of the frame [300mm, 400mm, 500mm]. Combining these different dimensions in a multi dimensional matrix sets out all the possible modules and represents the machine portfolio. Figure 5b shows a visualisation of a four dimensional machine portfolio matrix.



(a) Two ways of looking at modular design. (b) Multi dimensional structure of the machine portfolio matrix.

Figure 5: Visualisation of the jigsaw puzzle model.

The different machines chosen from the portfolio can then be combined in different machine line configurations. This machine line is then put together like a jigsaw puzzle, which is illustrated in figure 6 below. The different modules, visualised as puzzle pieces can be configured in different orders and exchanged with other pieces from the portfolio, visualised as the puzzle box, as long as the rules are obeyed. Just like with an actual jigsaw puzzle there are a few rules to make a complete configuration. The rules that come with this jigsaw puzzle model are as follows.

- Pieces can only be translated, not rotated.
- Pieces can only be connected to other pieces if their slots fit together.
- The puzzle always has to be completed, no empty slots can be left.

During the designing process machine lines can contain as many machines following up on each other as the designer desires. Also multiple machine lines can be designed to be installed in parallel, therefore this also applies to the puzzle pieces.

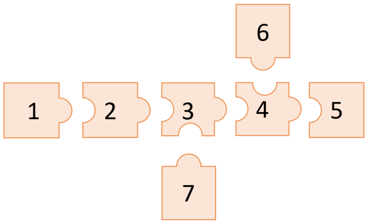
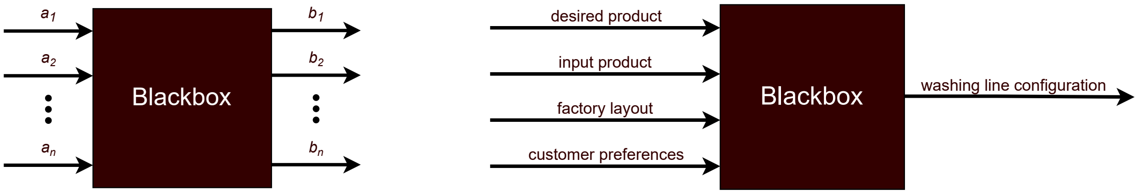


Figure 6: Example of a completed design with the jigsaw puzzle model.

Figure 6 above shows a complete machine line design represented by the jigsaw puzzle model. Other configurations of the pieces could have been made while following the rules. Piece 2 could for example be removed from between 1 and 3, or placed in between piece 3 and 4. Also an extra combination of piece 4 and 6 could be placed in between piece 2 and 3. This emphasizes the scalability and flexibility of modular design.

The jigsaw puzzle model is an advanced version of the modular kit model. It is based on a set of modelling rules and the terminology and visualisation are made easier to understand for a person not skilled in the art of modular design. Furthermore the multi-dimensional machine portfolio matrix expands the configuration options exponentially and makes it easier to define the machine portfolio in modelling software.

But how to determine which specific modules from the portfolio to choose for a customer specific application and in which order to install them? The choice for a specific washing line configuration can be described through a blackbox model. In such a model only the inputs and outputs are known while the decision making process in the blackbox is still undefined [127]. Figure 7a below shows a schematic overview of this black box model. When this model is used for designing modular machine lines, the inputs are parameters of the desired output product, the input product, the factory layout and customer preferences. These four types of inputs are the parameters to determine which machines with which options to implement in the washing line. An overview of a black box model for this application can be found in figure 7b below.



(a) Blackbox model. (b) Blackbox model for machine line configuration.

Figure 7: Visualisation of the blackbox model.

The filling of the blackbox in many companies purely consists of the experience and personal knowledge of salesmen and engineers. This research focuses on changing that strategy to filling in this blackbox with a standardised model for modular design. The difficulty of defining the relations that fill up the blackbox and determine what outputs result from which inputs result from the fact that this single model has multiple inputs and multiple outputs. According to Woolf (2021), Multiple Input Multiple Output (MIMO) systems describe processes with more than one input and more than one output which require multiple control loops. These systems can be complicated through loop interactions that result in variables with unexpected effects [123]. This MIMO model can be defined by a set of relations between certain in- and outputs. To set out these equations in a clear overview for constructing a computer model, a decision scheme can be made.

2.2 State of the art regarding smart factory engineering

The world is now in the middle of the fourth industrial revolution, originating in Germany in 2011 as industry 4.0. Industry being the highly mechanised and automated production of material goods, has been through three other revolutions before. Each revolution has been induced by a disrupting invention. The first industrial revolution was induced by the invention of the steam engine which changed production processes from manual to mechanical. The majority of the labour first was performed manually in houses, but then shifted to industries with the help of machines. In the second industrial revolution steam engines were replaced by the use of electrical energy and iron machines were replaced with steel ones. In the third industrial revolution the widespread digitisation was kick-started by the invention of the computer. This fourth industrial revolution is all about future oriented production through smart machines that are interconnected through the internet. This future oriented production contains efficient, modular systems where products control their own manufacturing processes [60, 84, 61].

While the world is still within the fourth industrial revolution, talking about industry 4.0, the European Commission (2020) is already talking about industry 5.0. The goal of industry 5.0 is for industry to turn digital and green while remaining the engine of prosperity. The wellbeing of workers has to be placed at the core of the production process and new technologies need to be used to provide prosperity, that goes beyond jobs and growth. Key is respecting the production limits of the planet while doing so. This way European industry has to be made sustainable, human-centric and resilient [28].

But what distinguishes such a 'smart' factory? In a smart factory the machines are connected both to each other and to advanced digital technologies. These connections can be formed through for example the internet, Bluetooth or Wireless Local Area Network (WLAN). Through data that is obtained by a multitude of sensors and digital technologies, the manufacturing operations are managed and controlled. People are empowered with information that gives them better visibility into manufacturing processes and operations and therefore it becomes easier to diagnose issues and improve the system in relatively short time. Both productivity and flexibility are improved by smart engineering [95].

A different term to describe the strategy that powers a smart factory is the Internet of Things (IoT). Sufian et al. (2021, p. 13) describe an IoT system as a collection of an ecosystem of combined technology elements that collect, store and exploit data in order to provide information, trigger events and recommend actions. Connecting those machines and controlling them in an IoT system has become more accessible and affordable due to the considerable drop in the cost of sensors and computing and the improvement of the internet in the past few years. This is why smart factory design has become more and more popular [95].

Smart factories contain both classic and adaptive machines, not to be confused with the earlier mentioned 'adaptive machine lines'. What differentiates adaptive machines from classic machines, and makes them a popular choice in smart factories is the ability to change its settings to the product it is processing. Where classic machines are controlled by operators, adaptive machines are controlled by smart control. Adaptive machines contain sensors that measure certain parameters of the incoming product and based on that information change the settings of the machine to process it into the desired product [12]. An example of such an adaptive machine can be a box packing machine in a warehouse. The belt conveyor that feeds the items to the packing robot can be equipped with cameras. The algorithm in the computer connected to the cameras processes the images to determine the size of the objects coming into the box packing machine. The actuators in the machine are then set to cut the cardboard and fold it to the right size to fit the object. This way the machine changes its settings to the product it is processing.

One of the most advanced technologies in smart engineering is Artificial Intelligence (AI). According to Sufian et al. (2021, p. 20) AI is the ability of a computer to think and learn by itself based on using Big Data, intelligent algorithms and computer systems to enhance machines and people through digital capabilities such as perception, reasoning, learning and autonomous decision-making. AI are particularly useful to cut costs, optimize operations and improve customer service and workplace environment. AI can also be used to plan preventive maintenance after analysing data about wear and failure of parts [95].

A special type of AI is machine learning. Machine learning is powered by algorithms that focus on learning from the data that is gathered by sensors in the machine and so improve the performance of the machine by adjusting the control. There are two types of machine learning algorithms: supervised and unsupervised machine learning algorithms. Supervised algorithms are the most commonly used ones. In this case the data scientist acts as a middleman who teaches the algorithm which conclusions need to be drawn. The algorithm is trained by the data scientist through a prelabelled data set with a known output. Unsupervised algorithms act in an independent way. A computer teaches itself to identify complex processes and patterns without a human operator to guide it. The algorithm is trained with a data set that has no labels and an unknown output. Which of these two machine learning types to use depends on the amount of data that is to be processed, how that data is structured and the context of use [78]. A special type of machine learning is deep learning. Deep learning algorithms are self-directed machine learning algorithms that are able to make themselves smarter. What makes deep learning algorithms special is that they, in contrast to regular machine learning algorithms, are able to redirect themselves to fulfill their goal without manual intervention. An example to show the difference between machine learning and deep learning is a self-driving car that recognises stop signs. When this car has a regular machine learning algorithm, the programmer has to supply it with a set of pictures of stop signs and tell the software how to recognise them. For example to look at the colours, the edges of the sign or the symbols on it. A deep learning algorithm only has to be supplied with a set of pictures that are stop signs, the software then compares the signs and finds the similar features itself. Deep learning algorithms can be considered the evolution of machine learning. While the advantage of deep learning is that it takes little human intervention to function properly, it takes huge amounts of data for the software to be able to teach itself [122].

2.2.1 Smart technologies

Essential for a smart factory to work is a central computer system connected to mobile devices that controls the factory with computer-based algorithms, also known as a Cyber-Physical System (CPS). The central computer system is where the data from all the connected machines is gathered. It processes the data, monitors the processes in the factory and makes decisions accordingly [73, 124]. This way a Digital Twin (DT), a virtual representation of the real-life system, is formed. This DT represents both the physical appearance and the behaviour of the simulated system [84]. The operators on the factory floor can log into the central computer system with a mobile device to be equipped with the right information on the spot [130]. Recipes can be programmed on the central computer system. These recipes work the same as for example in a modern oven: to perfectly bake a pizza, it just needs to be placed in the oven and when the pizza button is pushed on the screen, the oven will automatically change the settings to bake it to perfection. This way a processing line in a factory can also be adjusted to produce the right product with just the push of a button. The machines that are connected to the system are then directed with the right commands and set themselves to the right configuration. Also a reset-button can be used to set the machine back to the original settings, this way a machine operator can change back the settings of the machine after they are manually changed. DTs will be described in more detail in section 2.2.2 below.

The machines in the factory can be equipped with multiple sensors to acquire data. These sensors can for example be used to monitor wear, errors, safety issues and other deviations from the optimal functioning of the processing line. The information obtained by the sensors is send to the central computer through a Digital to Analog Converter (DAC) device. In a manufacturing line a dense grid of sensors can be used to make sure that no parts are missing and that every part is in exactly the right location after the final assembly [124].

There are multiple different sensor types for monitoring wear in different parts of the machine line. Vision sensors for example can be used to detect damaged conveyor belts or deviating parts in a product stream. Acoustic sensors are able to detect certain sounds that indicate damaged bearings or motors. Tachometers can be used to monitor the same things but through material vibrations instead of air vibrations. Radiation sensors are used to detect heat produced by for example friction or electrical errors. Strain gauges can be used to detect unintended deflections or loads on structures. Volt and ampere meters can be used to monitor motor power among others [81, 60]. Sensors can also be used for safety systems. They can for example detect when a hatch is opened, exposing parts of the machine that may be hazardous for human contact.

To monitor machine lines in the factory, KPIs are set up. These KPIs are a set of metrics that describe the functioning of the process of manufacturing operations. KPIs are calculated by sets of mathematical formulations and can be used in feedback loops to keep the machine lines producing under optimal conditions. Common KPIs are manufacturing costs per produced unit, factory efficiency, scrap rate and yield, among others. Next to those purposes, KPIs are often set up to asses the progress with respect to goals and objectives [95]. Regularly monitors are set up in factories to show KPIs in real time. Most workers in the factories do not care about the process, as long as the machines keep running. When the machines are made smart and aim for optimal KPIs, the workers that do not take the quality of the product seriously do not have a negative impact anymore because the machines are regulated by the system.

Radio-Frequency Identification (RFID)-technology is one of the basic technologies that enables smart engineering. RFID-tags are cheap devices that can be used for identifying goods. They contain a microchip and therefore can be read out without line of sight, as opposed to barcodes [10].

RFID-technology can for example be used in potato cutting lines for fries factories. Figure 8 below shows a schematic drawing of such a potato cutting line. The numbers in the figure correspond to the part numbers in the text. To cut the potatoes into a specific shape all three parts of the cutting line need to be configured in the right order. The right accelerator tube (1), fin aligner (2) and knife block (3) need to be installed. The accelerator tube regulates the cutting speed of the potatoes, the fin aligner regulates the positioning of the potatoes when they hit the knife block and the knife block sets the size of the fries. The knife blocks are installed in a switch-box that is able to very rapidly change the knife block if an object gets stuck, without interrupting the factory process. RFID chips can be installed onto these three adjustable parts of the machine. When the production is started, scanners in the machine line automatically scan the RFID chips of these three parts for the system to check if the right parts are installed into the configuration. When the right parts are in place, production is started but when one or multiple parts are faulty, a message will pop up on the monitoring system for the operator to change those parts before production can be initiated. This way no potatoes are wasted by cutting them wrongly.

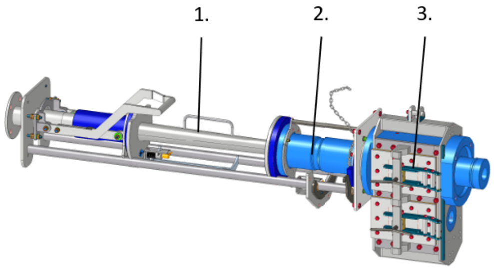


Figure 8: Schematic drawing of part of a potato cutting line.

2.2.2 Digital Twins

The system of software and hardware elements that allows industrial organisations to control industrial processes locally or at remote locations, monitor, gather, and process real-time data are called Supervisory Control and Data Acquisition (SCADA) systems [43]. As previously described DTs are virtual representations of the physical machine line that evaluate functioning of the machine line and recommend appropriate control actions. DTs are composed of three components: the physical part in real space, the virtual part in virtual space and the connections between those two parts that exchange the data and information. There are three main types of DTs: analysing, real-time and predictive DTs. Analysing DTs analyse data regarding functioning of the system in past-history. It can be used to get an insight into how the system has functioned under different circumstances. Real-time DTs show a virtual representation of the system in real-time. They can be used to facilitate real-time monitoring of the system, this way a machine operator can keep an eye on how the system is functioning. Predictive DTs use the data from earlier and present functioning of the system to look for trends, sometimes started by certain events. When comparing the real-time functioning of the system with these trends and events they are able to predict the functioning of the system in the future. This way for example maintenance can be scheduled and production can be planned. Predictive DTs get more and more reliable every year through developments in AI and advanced analytics [63].

DTs enable learning, not only from data obtained by the sensors but also from experiments and comparisons through modelling. Instead of performing the experiment with the physical system, the experiment can be simulated and performed with the DT. The ultimate goal is for DTs to iteratively model, test and optimise a machine line in the virtual space until the model meets the expected performance. At that point the model is ready to be enhanced in the physical world [56]

There are various descriptions of what a DT is throughout literature. It is important to note that not every combination of a physical system and digital representation is in fact a DT. Tekinerdogan and Verdouw (2020) divide those combinations into four categories, which are illustrated below in figure 9. The blue arrows in the drawings represent automatic processes and the grey arrows represent processes that require manual interventions. When the physical system and digital representation are interconnected only through manual intervention, this relation is called 'digital model'. When the physical system is automatically controlled by the digital representation through the use of actuators, but the data flow to the digital representation is only realised by manual intervention this relation is called 'digital generator'. The 'digital shadow' is a relation where the physical system is controlled manually but automatically updates the digital representation with data obtained through sensors. In case both the control of the physical system and the data flow to the digital representation are automated, the relation is called a 'digital twin'. The digital representation of DT systems can be modelled in different ways for different applications, in this section a few examples are described.

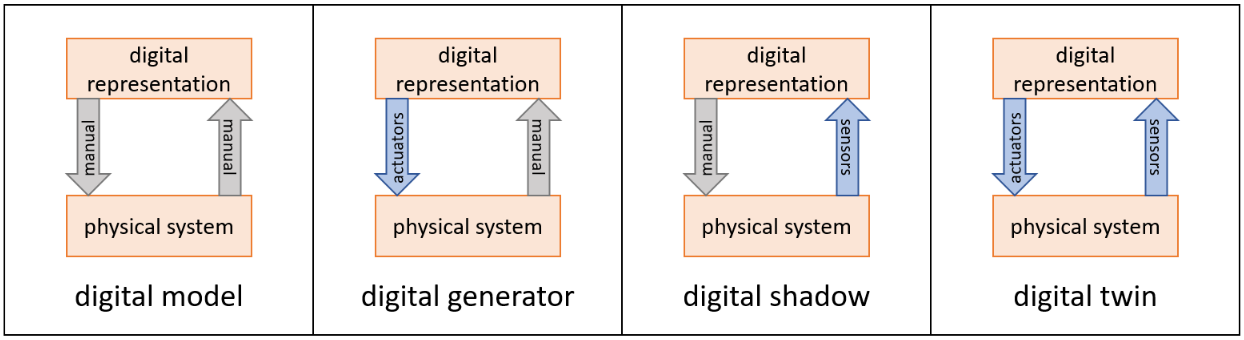


Figure 9: Four types of relations between the physical system and the digital representation, inspired by ref. [97].

Computer Aided Design

A thee dimensional Computer Aided Design (CAD) model can be used to get a clear overview of the functioning of a machine line. Different parts of the machine can be clicked to open a window with real time information coming from the sensors embedded into the machine. If an error occurs, a message will pop up and the part of the machine that experiences the error will be highlighted. This way it is easy for the machine operator to see how all the individual parts of the machine line are functioning. Figure 10 below shows a CAD visualisation example of a simple tuber washing line, the numbers in the figure correspond to the numbers below to show the different parts of the line that can be monitored and/or controlled. The product is fed into the destoner on the right side of the picture and leaves the machine line over the product belt on the left side.

1. **Stone removal belt:** rotary speed and drive power
2. **Destoner propeller:** rotary speed and drive power
3. **First washing drum drive:** rotary speed and drive power
4. **Second washing drum drive:** rotary speed and drive power
5. **Destoner purge valve:** purge time
6. **First washer purge valve:** purge time

7. **Second washer purge valve:** purge time
8. **Third washer purge valve:** purge time
9. **Floating Parts Remover (FPR) purge valve:** purge time
10. **Dosing disk actuator:** actuation angle
11. **Floating parts removal belt:** rotary speed and drive power
12. **Product belt:** rotary speed and drive power
13. **Washer:** water level and degree of pollution

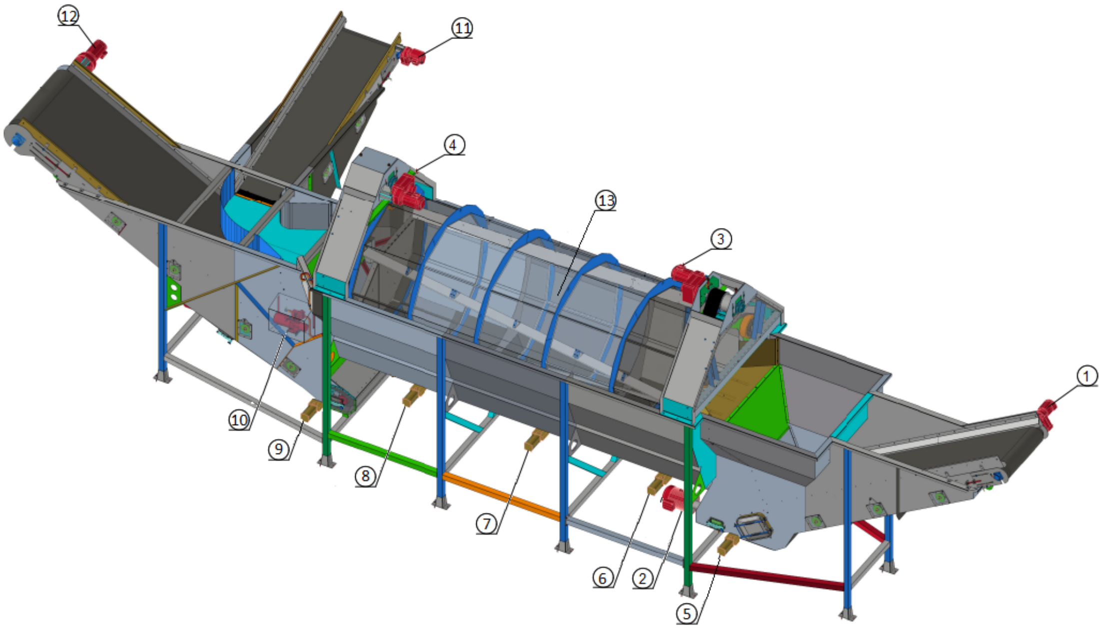


Figure 10: Example of a CAD based DT visualisation.

Simple menu
The cheapest and easiest way to model an interface for a DT system is through a simple menu. The menu shows multiple buttons to choose different parts of the machine. Some buttons can be used to check real-time performance of the system and others can be used to manually change settings or choose a standard recipe.

Figure 11 below shows a simple menu interface to monitor a tuber washing line. With the buttons on the screen the discharge times of the purge valves, water level in the washing drum, rotation of the drives and angle of the dosing disk can be monitored in real-time and changed manually.

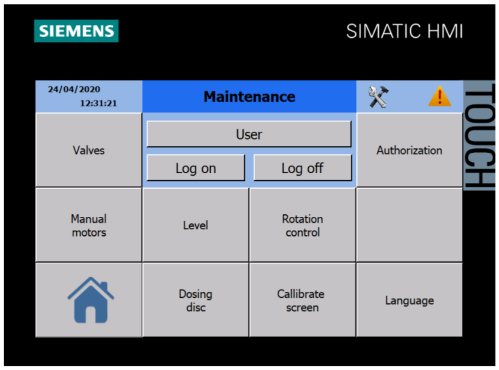
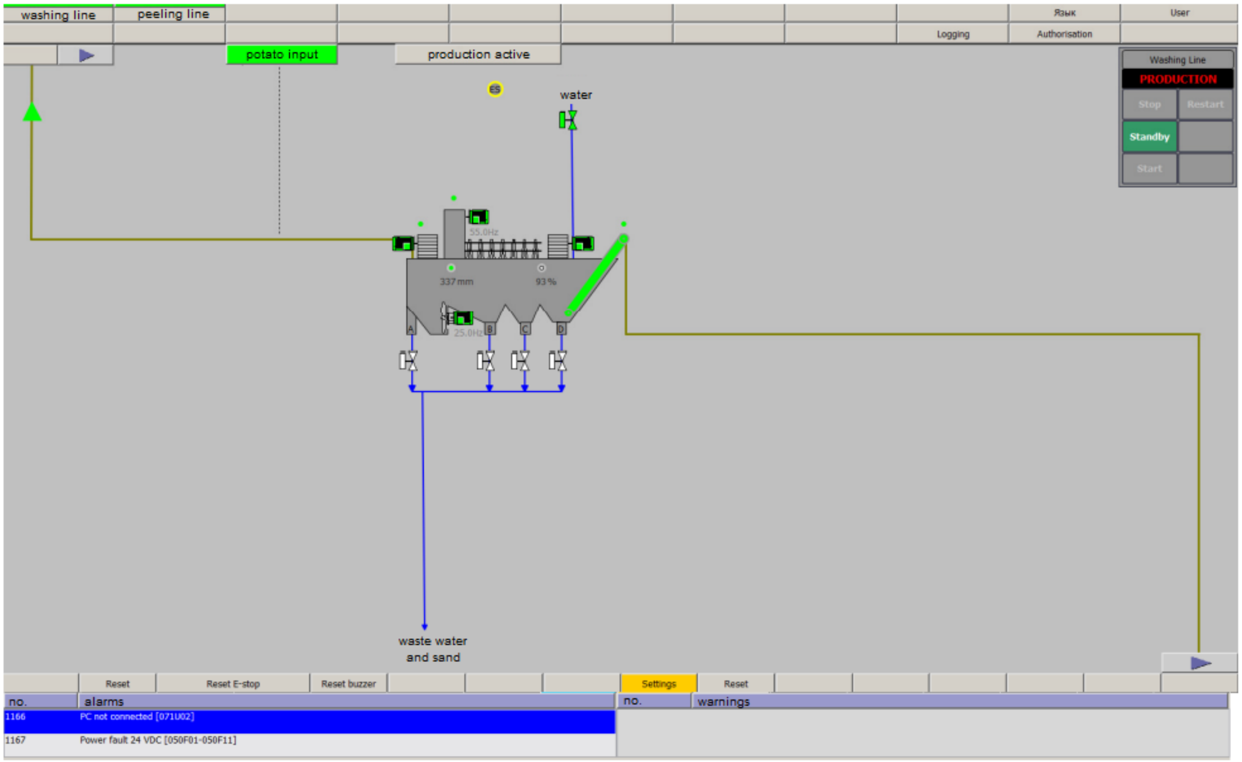


Figure 11: Example of a simple menu based DT visualisation, adapted from [27].

Two dimensional physical
Another commonly used way to design a DT based monitoring system is through a two dimensional physical model. In addition to the simple menu, this model physically represents the machine line. When a part of the machine line experiences an error it will be highlighted and can be clicked by the operator to get all useful information, this makes is easy for machine operators to see where and what the problem is.

Figure 12 below shows a two dimensional physical representation used for monitoring a tuber washing line. When a part of the machine is not actively running or closed, it is coloured white, like for example the purge valves in the bottom of the tank. When a part of the machine is running without errors or open, it is coloured green, like the motor that drives the stone belt. If a part of the machine experiences a fault, it is coloured red and a popup will appear in the window in the left bottom corner that shows the alarms. An example of such an alarm is when a motor experiences a thermal overload or when the water level in the drum is too low. If a machine experiences an active warning, it will be coloured orange. The window in the right bottom corner shows the warnings, these are alarms with low priority, for example when a sensor is forced by a maintenance engineer or when the speed of a motor is manually changed. The 'potato input' tile in the upper part of the screen is green when there are still enough potatoes in the storage bunkers to feed the washing line. The button turns red when the bunkers run out of product. With the buttons in the upper right corner the washing line can be stopped, started or put on standby. The yellow encircled light just underneath the 'production active' tile, is the emergency light. When an emergency stop is activated it will turn red, if not it will stay grey. When the washing line is combined with other factory lines that follow up in the processing of the potatoes, like for example a peeling or cutting line, they will be added as extra tabs in the monitoring system. These tabs for different machine lines in the factory are shown in top of the screen [26].



no.	alarms
1166	PC not connected [071U02]
1167	Power fault 24 VDC [050F01-050F11]

no.	warnings

Figure 12: Example of a 2D physical DT visualisation, adapted from ref [26].

Flowcharts

Flowcharts are another way of modelling a DT system. They can for example be used to get a clear overview of all streams within a machine line. Figure 13 below shows a flowchart visualisation example for a tuber washing line. The ovals represent the different heaps and the blocks represent different machines. The arrows in between them represent the streams: orange arrows show product streams, blue arrows show water streams and black arrows show solid waste streams. Important is for every part of the machine to have an input/output balance that results in zero. A faulty mass balance can for example be caused by leakage, blockage or a broken sensor. When leakage occurs in a part of the machine line, water will disappear from this machine and the measured water input will be bigger than the measured water output. When a blockage is formed, the product and/or water input of a machine is bigger than the output. Product and/or water will then heap up in this part of the machine line. In case of a malfunctioning sensor the measured data will be incorrect. Sometimes a sensor can be re-calibrated to fix it and sometimes the sensor needs to be replaced with a new one. If a mass balance that is not adding up to zero is detected by the monitoring system, a warning will pop up on the screen and the part of the line that is faulty will be highlighted, this way the machine operator is aware of the error. In case of a safety breaching error the whole machine line will be shut down to prevent damage or safety risks until the cause of the error is fixed. Via this overview, the effectiveness of the machines in the line can be calculated. The amounts of pollution in the input product are estimated by samples taken from the batches coming into the storage lines. When the waste coming out of the washing line is lower than the waste coming in, part of the waste is not removed by the washing line and continues to stay in the product stream.

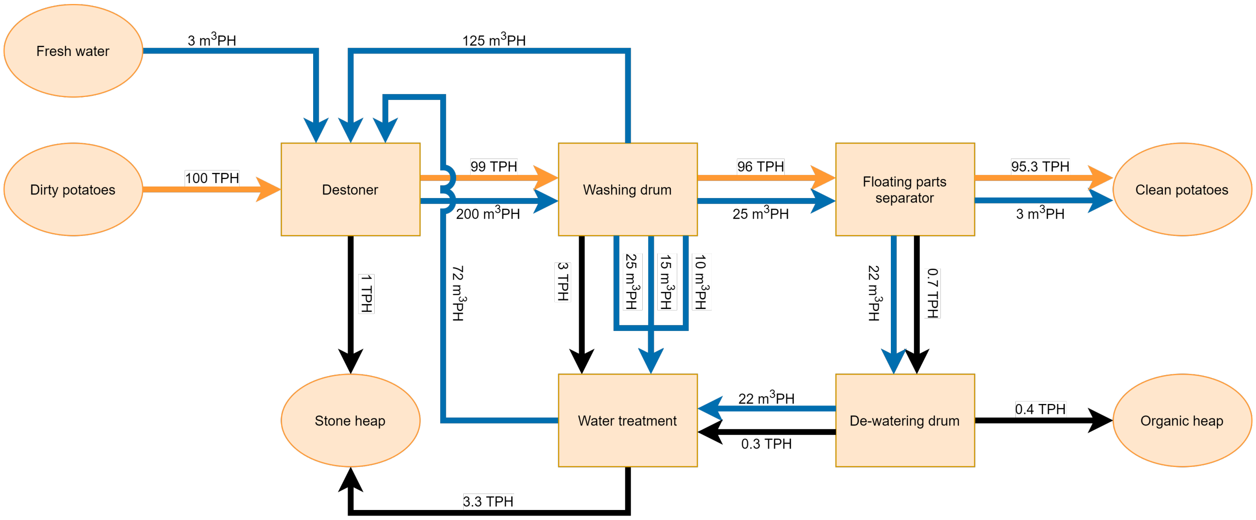


Figure 13: Example of a flowchart based DT visualisation.

Finite Element model

Finite Element (FE) models are a popular calculation method to get an approximate solution for partial differential equations and integrals by dividing a structure into small finite elements, doing the calculations for every individual element and adding them up to get the result for the complete structure. With Finite Element Analysis (FEA), the effects of putting a load on the modelled part can be calculated. For multi machine monitoring though DT systems, FEA can be used to analyse the functioning of parts in the machine line. Through the use of FEA for example the stress, strain and wear of a specific part can be calculated over time. Just like with other DT systems, the input for the FE model will be the data obtained by sensors. Data from the historical past will be combined with real-time data to predict when parts are near the end of their lifetime or deformed too much and need to be replaced.

Because FE models are not currently used in monitoring of tuber washing lines, figure 14 below shows an example of a FE based monitoring system for a ship-to-shore crane. The model in the picture shows the displacement of the crane structure when subjected to certain loads. The loads are caused by wind, braking and lifting of a container. In the image displacements are exaggerated and indexed by a colour scale to make them easily visible for the machine operator. When displacements come close to the elasticity limit of the beams or endanger operation of the crane in another way, a warning will pop up in the system so the machine operator knows to be extra careful or for example to stop operations until the weather has improved.

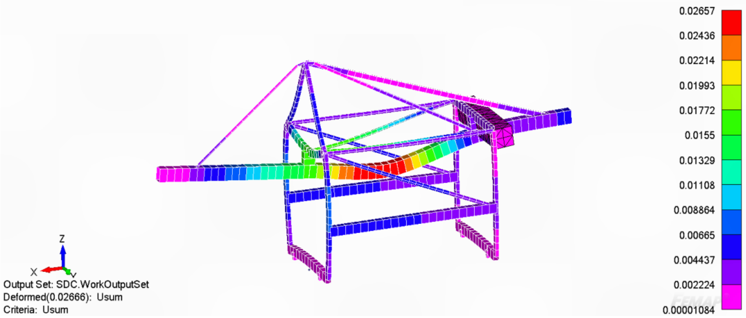


Figure 14: Example of a FE based DT visualisation, adapted from [94].

2.2.3 Dangers and weak spots of a smart factory

Every system has its weak spots and so does a smart factory. Because the whole factory is interconnected through the IoT, malfunctioning of the internet connection can lead to lack of control in the factory. Manual overwrites can empower operators on the work-floor to control the machines but require more manpower to keep the factory running.

Also the abundance of sensors rises the chance of errors to occur. When a sensor is damaged or has an electrical failure, the system has to react accordingly. A difference has to be made between essential and expendable sensors. If an essential sensor is malfunctioning, the system has to be shut down and an operator has to be alerted on his mobile device that the sensor needs to be replaced immediately. To speed up this process the mobile device has to show the exact location and specifics of the sensor that needs to be replaced. After the replacement the machine line can be turned on again. To prevent this downtime, backup sensors can be installed so that if one sensor fails, the machine line can still keep on going. If an expendable sensor fails, the operator has to be alerted on his mobile device that the sensor needs to be replaced soon. In this case the machine line can keep on being operational until the replacement. To keep downtime to a minimum an inventory of sensors has to be kept in the factory which is replenished in time.

Another problem of smart factories is the complexity of the system. The personnel on the work-floor has to be instructed on how to work with the computer system and the mobile devices that control the factory. Especially older or less educated factory workers that are used to manual control of the machines and not accustomed to modern computer technologies might have a hard time acclimating to the new ways of operation. Use of user-friendly interfaces with data visualisation dashboards makes it easier for personnel to get used to the system. Chatbots for example can be implemented as a fast and user friendly tool to direct users to the right information [67].

Cyber Security (CS) forms another big threat to smart factories. The more devices are connected to the internet, the bigger the risk of a CS threat. When the system is not protected well enough, hackers can get into the system, causing the machines to shut down or cause danger to the machine lines, products or the operator. If there is a leak in the CS, the data can also be modified or stolen from the system with the chance of falling into the hands of competitors, causing severe financial damage to the company. In order to keep hackers from entering the system, a CS defence strategy containing encryption and authentication has to be set in place to address the threats. Information Technology (IT) experts can be hired to maintain this defence strategy. Using open-source software can lead to faster discovery and repair of vulnerabilities in the system [95, 67].

The sensors collect a vast amount of data, referred to as Big Data. All this data has to be sorted, categorised and stored in the cloud. Challenges that come with handling Big Data are data complexity, volume, network speed and bandwidth. To be able to overcome these challenges the data needs to be cleaned and compressed to a reasonable size before being processed, stored and analysed [95].

As previously mentioned AI can be used to optimize production processes even further, but it also brings a few challenges to the table. AI based systems need to be trained, monitored and evaluated continuously to protect the system against bias, privacy violations and safety concerns. The AI will do anything to improve itself and optimize up to its goal. It is therefore necessary to set up the AI with the right boundary conditions to keep it from making changes that undermine secondary goals or safety on the workfloor [95].

3 Machine portfolio composition

3.1 Washing line demand

Before setting up a modular design method for the washing lines, the modules or puzzle pieces need to be defined. Most of the designs for the machines in the washing line originate from Botman. Botman was a producer of agricultural washing machines specialised in washing bulbs. When Botman was struggling financially, Tummers bought over the company and all machine designs owned by it in 2005. Through the following years Tummers has improved the machine designs and adapted them to be able to wash other tuberous products like potatoes and carrots. During these developments the capacities of the machines were maintained. An overview of the standard capacities of all machines from the Tummers washing group can be found in appendix H. Next to that, one of the principles of Tummers has been to supply tailored solutions for every customer, therefore next to the machines from the regular portfolio, a lot of unique machines were sold. In the early days Tummers did not only sell high-end stainless steel machines for industrial purposes. To get onto the market they also sold steel machines and mobile washers for agricultural purposes. After a few years on the market, management decided the future of Tummers laid with selling high-end industrial machines because way higher profits could be realised in this market segment and there was less competition. The focus of Tummers therefore was placed on selling industrial machines, afraid of declining orders though, agricultural machines stayed inside the portfolio [88].

3.1.1 Washing line configuration

To set the base for modular design, a choice has to be made which specific machine models and options to include in the standard portfolio. To support this choice, the machines sold by Tummers from January 2007 up to January 2022 are analysed. In this analysis only machines that belong to the washing group are taken into account. Unique tailored machines, steel machines for agriculture and mobile washers are left out of the scope of this research because they are sold in very low quantities and provide relatively low profits when compared to the industrial machines. All orders archived in Ridder IQ, the ERP software used by Tummers, are analysed. The machines that apply to the previously stated conditions are counted per specific machine size. Figure 32 in appendix F shows the amount of machines sold per different model.

Something that immediately strikes out from the data is that the washer with integrated destoner is the most commonly sold machine. The washer/destoner is sold much more than the separate washer. This is because stones need to be removed from the product for the far majority of washing line applications and a set of a separate washer and destoner is more expensive and maintenance-sensitive than a washer with integrated destoner. Some separate washers are sold as a second washer placed in series with a washer/destoner to wash the product more thoroughly. It is also quite remarkable that there are standardised machine models for machines that are only sold once or which are never sold at all, like the drum washer TW-700-2000x6250 and the clay bath FPR-K-320-1000x3500. The reason for this can be explained as follows. The clay bath and brine separator are exactly the same machine, the only difference is the mixture added to the water in the tank since the clay bath is filled with a clay and water mixture and the brine separator works with a salt solution. Because of this the clay bath FPR-K-320-1000x3500 is an exact copy of the brine separator FPR-Z-320-1000x3500 and did not need any engineering to be added to the portfolio of standard machines. This applies also to the drum washer TW-700-2000x6250 which is in practice the same as the washer/destoner KW-700-2000x6250 but without an integrated destoner.

The after washer was previously sold under a unique machine code WTD. Because the after washer is in fact a converted drum washer to wash the product without submerging it in water, it is currently sold under the machine code TW-D that represents the dry drum washer. The dry drum washer is covered in more depth in section 3.3.3.

Something else that stands out from the figure is that every machine has different models to fit to the other machines with the codes 320, 450, 600, 700 and 800, except the pintle belt and the roller spreader. For the roller spreader this is caused by the simple fact that this machine originally comes from the peeling line portfolio. It was first used only for removing moisture and peels from a stream of peeled potatoes. Later it was also used to divide a stream of washed potatoes over two roller spreaders and therefore added to the washing line portfolio. For the pintle belt this does not hold. Pintle belts are commonly sold in two different models, EB-1000x1500 and EB-1500x1500. The sole difference between both of them is the width of the pintle belt, $w_b = 1000mm$ and $w_b = 1500mm$ respectively. There always have been these two different options until a customer asked for a model in between, the EB-1200x1500. The price of this pintle belt is lower than that of the EB-1500x1500 so if it fits the machine line it is a waste of money for the customer to buy the bigger pintle belt model. More and more bigger washing lines are sold over the years and the biggest pintle belt, EB-1500x1500 does not have the required capacity to fit washers bigger than the KW/TW-600 nor does the width of the pintle belt fit the width of the output belt of these bigger washers. The widths of the output belt of the bigger washer models KW/TW-700 and KW/TW-800 are $w_b = 1400$ and $w_b = 1600mm$ respectively. Because the product needs to be spread over the pintle belt for the haulm separation to be effective, a wider pintle belt is needed. Therefore it would be advisory to add a pintle belt model EB-2000x1500 to the machine portfolio. The pintle belts are made with a standard V10 profile. V10 pintle belts with a width of $w_b = 2000mm$ are part of the standard sizes sold by the belt supplier which enables development of a pintle belt in this size [37].

It is also remarkable that the smallest roller dryer, RD-320-1000-10R is only sold once. This is caused by the fact that the product only has to be dried if it is processed into fresh packs or stored in bunkers between being washed and being processed. Different washer models have different popular applications. Table 1 below shows the most common application for each washer size. As can be seen fresh-packs are commonly produced with maximum capacities of 40 to 50 Tons Per Hour (TPH). This explains the fact that the smallest roller dryer model is only sold once and roller dryers bigger than the RD-600 are never developed.

Model	**Capacity**	**Most popular application**
KW/TW-320-1000x2500	$15TPH$	flakes
KW/TW-450-1300x3650	$30TPH$	flakes
KW/TW-450-1300x4800	$40TPH$	fresh packs
KW/TW-600-1650x3750	$50TPH$	fresh packs
KW/TW-600-1650x5000	$70TPH$	fries
KW/TW-700-2000x5000	$100TPH$	fries
KW/TW-700-2000x6250	$125TPH$	fries & starch
KW/TW-800-2400x6200	$180TPH$	starch

Table 1: List of washer models and their most common applications.

Dry desoilers are sold on the Tummers website. In the period of investigation only four copies are sold, the focus of Tummers does not lie on selling dry desoilers. Other companies are able to sell them way cheaper, therefore they are not taken into account in this report.

3.1.2 Capacity demand

To see which capacities are demanded under the washing lines, the sales of different washer models are analysed. Every washing line sold by Tummers includes a washer, this can either be a drum washer with or without integrated destoner (KW or TW). Figure 59 in appendix F shows the amount of washers sold per model. The results show that the KW/TW-800 model is sold way less than the other washers and that the KW/TW-450 is the most popular model.

To see what capacities are most interesting for Tummers to focus on, the price of each model has to be taken into account as well. Because the same profit margins apply to all models, the turnover for the washing lines between January 2007 and January 2022 per washer model shows what models bring in the highest revenue for the company. To estimate this revenue, the amount of washers sold per model are multiplied by the standard sales price and then with an equipment factor c_e. For every washer peripheral equipment has to be installed too, the revenue due to this equipment is therefore taken into account with an equipment factor of $c_e = 1.2$. Peripheral equipment includes waterpipes, frames and platforms for example. Figure 60 in appendix F shows the estimated turnover generated for different washer models in the given time period.

As can be seen in figure 59 in appendix F the smaller washer models are sold more than the bigger washers. The clear favorite is the KW/TW-450 and the least sold model is the KW/TW-800. When the price of the different washer models is taken into account this difference is compensated for because the bigger models are more expensive then the smaller models. Figure 60 in appendix F shows that the middle size washer models generate the biggest revenues. In this figure the revenue generated by selling the three middle size washer models, the KW/TW-450, KW/TW-600 and KW/TW-700, do not differ much. The least profitable washer model is clearly the KW/TW-320. Because each washer model currently sold by Tummers leads to a good share of revenue, all five different sizes will be taken into account in the modular approach.

3.1.3 Product to be processed

Tuber washing lines sold by Tummers all over the world are most commonly used for potatoes. The second largest market for these lines is for carrot processing. Other root vegetables that can be cleaned with these washing lines include beetroots, sugar beets, cassava roots, parsnips, celeriac and other root vegetables. However, not all of these vegetables can be processed with every machine, each machine has specific vegetables it is suitable for. The washer/destoner is the most important and therefore most occurring machine in washing lines sold by Tummers, as can be seen in figure **??** in appendix F. This washer can be used for washing potatoes, carrots, flower bulbs, red beets, cassava and even for seaweed. The washer/destoner models sold between 2007 and 2021 are analysed on the product they are used to wash, the results are shown in figure 61 in appendix F. Figure 62 in appendix F shows the share of washer/destoners that is used to wash potatoes, carrots and other tuberous products. Because the clear majority of tuber washing lines is used to wash potatoes and carrots, only these two applications will be discussed in this report, with the focus on potatoes. Something that stands out of figure 61 in appendix F is that the KW-700-2000x6250 is quite commonly used for washing carrots. This can be explained as follows. Carrots are most commonly processed into fresh packs. As previously shown in table 1 potatoes are most commonly processed into fresh packs with maximum capacities of 40 to 50 TPH. Because washers have lower capacities for washing carrots, which will be explained later on, for washing carrots the KW/TW-700-2000x6250 has a maximum capacity of $Q = 35$ *TPH*. This capacity falls in the range of common capacities for processing potatoes into fresh packs while this capacity range also holds for carrots.

3.2 Machine capacity analysis

As previously described in section 3.1 most machine parameters are derived from the machines designed by Botman. The machines are improved after the company went bankrupt and was bought over by Tummers but the main dimensions and capacities have stayed the same. To see if the capacities still fit the machines, a simplified analysis of the machine parameters is conducted. The most important machine in the washing lines is the drum washer. The washing quality scales linearly to the time the product stays inside the washing drum, called the residence time t. Because a product has to be washed with the same quality for each washer size, the residence time at maximum capacity Q should be the same for each washer model. The residence time is derived from the maximum throughput capacity and the total product mass in the washer m_a. This mass can be derived from the product density that is $\rho_a = 1,300 kg/m^3$ on average and the product volume V_a, which depends on the drum length l_d and diameter d_d. The average degree of filling for the washing drums is $\phi = \frac{V_a}{V_w} = 0.5$ and the average water height is $\ell = \frac{A_{filled}}{A_{tot}} = 0.5$. The rotational speed of the drum also influences the washing time because the cleats in the washing drum are positioned under an angle to be able to empty the drum from product when needed. Because the rotational speed of the drum is set to a constant value for the average customer and the exact relation between this speed and the residence time can only be derived from testing or complex models, it is not specified in this calculation but included in the degree of filling. The residence time can be calculated by equation 1 below. In table 33 in appendix G, the residence time is calculated for each washer.

$$t = \frac{m_a}{Q} = \frac{V_a \rho_a}{Q} = \frac{\phi \ell l_d \frac{1}{4} \pi d_d^2 \rho_a}{Q} = \frac{\phi \ell l_d \pi d_d^2 \rho_a}{4Q} \tag{1}$$

As can be seen in table 33 in appendix G, the residence times vary for the different washer models. The KW-320 has a lower residence time than the others, which means that the washing quality is lower than for the other models when used at maximum capacity. The KW-700 and KW-800 have higher residence times than the others, which means that the washing quality is higher than for the other models when used at maximum capacity. To make sure the washing quality for all models is the same, new maximum capacities have to be calculated. This can be done by filling in a constant residence time of $t = 11.6s$ in formula 1. This is the average time that comes out of table 33. To get a better view on what the average residence time on maximum capacity should be, tests can be conducted with an operational drum washer. Table 34 below shows the corrected maximum capacities, rounded to a multitude of $5TPH$ for commercial purposes.

From table 34 in appendix G can be seen that only the maximum capacities of the KW-320 and KW-450-1300x3650 do not need to be changed, for them the corrected capacity Q_C is the same as the initial machine capacity. The maximum capacities of the KW-450-1300x4800 and KW-600-1650x3750 each have to be lowered with $5TPH$, which makes them slightly less productive. The capacities of the KW-600-1650x5000, KW-700 and KW-800 need to be raised. Except for the washer models to get into line concerning the washing quality, the change in maximum capacity also has commercial benefits. The increase in maximum capacities for the bigger washers makes them more interesting for customers because they are able to process higher amounts of product per time. Therefore it is advised to change the current maximum capacities in the machine specifics sheets and on the website to these corrected capacities. From now on the corrected capacities will be set as the standard for all machines throughout this report.

One of the great qualities of Tummers machines is that they are able to handle overcapacity quite well. Machines made by competitors can break when overloaded. Tummers machines are made of high quality components and designed specifically to operate under rough industrial circumstances. When the machines are set to process over their maximum capacity, the washing quality slowly decreases without damaging the machines. If on the other hand a washing line has to process a very strongly polluted product batch, the washing line can be fed with a lower capacity to ensure a higher washing quality [53]. The quality of Tummers machines to operate above their maximum capacity without breaking can be illustrated with an anecdote.

In 2012 four mobile washers were sold to a German recycling company. This firm bought the machines to wash sugar beets before processing them into bio-fuel. The machines were sold with a maximum capacity of $Q = 60TPH$ and contain a destoner model KS-600. After using the machines for some time, the customer was contacted by Tummers to hear if he was satisfied with his purchase. During the conversation the customer spoke very proudly that he processed up to $Q = 200TPH$ of sugar beets with each machine and that they worked perfectly fine. The only problem the customer encountered was stones bigger than $25cm$ to get stuck in the output of the stone conveyor. This problem was solved by Tummers by making some minor changes to the stone conveyor. In this example damaging of the sugar beets by increasing the throughput does not pose a problem because the beets are not mend for human consumption but processed into bio fuel [54].

3.3 Modular machine design

This section focuses on the modular design of all machines that are part of the washing lines produced by Tummers. The configuration of the machine line out of these machines will be discussed in section 4 afterwards. For each machine first the working principle is explained, illustrated by a schematic drawing. Then the machine dimensions of the different models are set out. Afterwards the different options that can be installed in the machine concerned are discussed. For some more complex machines, different parts and properties of the machine are explained in more detail in individual paragraphs.

3.3.1 Storage lines

Washing lines are always following up on a storage line. Storage lines are the place where the product enters the factory and consist of the next few standard parts: receiving hoppers, dry-desoilers, belt transporters and silos. The configuration and specifications of those parts varies widely depending on the input product and the desired output product. The tubers are brought into the storage line by trucks, that dump the product in a receiving hopper. The receiving hopper contains a roller spreader set to spread out the product stream. This roller spreader set also retrieves a share of the dry soil, haulm and small tubers, stones and clods. The product then goes through a large parts separator. The large parts separator removes bricks, logs and other large debris from the product stream. In some regions in Belgium that are used for growing potatoes, lots of bombs from the first world war are still ending up in the product batch during the harvest. These bombs are often found in the waste heap of the large parts separator in the storage line.

After the receiving hopper and large parts separator the product goes over a dry-desoiler. The two most common dry-desoilers are desoilers that work with a vibrating set of horizontal pins where the product slides down the slope over the pins and the soil falls through the pins, and dry-desoilers that work with desoiler rollers. There are varying kinds of desoiler rollers like for example spiral rollers, star rollers or finger rollers. Each kind of roller has other qualities. Spiral rollers for example are excellent at separating haulm from the product stream and star rollers are specialised in retrieving undersised potatoes [102].

After the dry-desoiler the product is sometimes processed by a pintle belt for haulm removal. The pintle belt is discusses later in section 3.3.5. Afterwards the product is guided to storage silos to build up a buffer. From these storage silos the washing line is fed, which commonly starts with a destoner.

It is important to remove as much of the contamination from the product stream in dry state as possible. This is caused by multiple factors. Firstly haulm has the tendency to get stuck in machines. It can for example get stuck in belts conveyors, clog drums and valves and entangle into clusters in the washer. To prevent machines from getting jammed, clogged or damaged it is important to remove as much haulm as possible in the most early stages. Secondly all dirt that can be removed in dry state, does not need to pass through the water treatment, which saves a lot of costs.

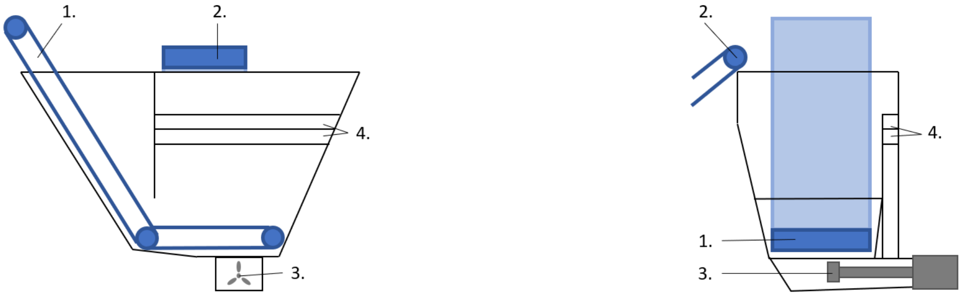
To remove contamination in a dry state, a dry-desoiler and pintle belt can be added in between the bunkers and the washing line. Because Tummers is not specialised in dry-desoilers, they are not taken into account in depth in this research report. Adding a pintle belt in front of the washing line can remove a significant amount of haulm and sand from the product stream, therefore this option is often recommended.

3.3.2 Destoner

Destoners are an important step in the processing of root vegetables. Root vegetables grow in the soil instead of on top of it, therefore stones and clods from the soil come with the product during harvesting. Stones need to be removed from the product stream not only because customers do not want stones to end up in their product but also because stones can damage and obstruct machines in the line and bruise the product.

There are multiple destoners on the market built by a wide range of companies. The most commonly used destoners are the tank destoner, cyclone destoner and auger destoner which all work through the same principle: weight difference. The most basic and robust of these destoners is the tank destoner which is produced by Tummers, among others. Formerly, Tummers also sold cyclone destoners. Because too much of the product ended up on the stone belt, the cyclone destoner had too high of a good-to-bad ratio and therefore Tummers sticked with just the tank destoner. While other companies only sell destoners with a maximum capacity up to $Q = 80TPH$ as can be seen in appendix I, Tummers also produces bigger destoners with a maximum capacity of $Q = 125TPH$ or even $Q = 180TPH$ [106, 107].

Working principle
There are two types of destoners sold by Tummers, independent tank destoners and tank destoners integrated into the drum washer. Both work through the same principal. Figure 15 below shows a schematic drawing of the integrated destoner, the numbers in the text correspond to the numbers in the figure. The tubers are fed into a water filled tank by a feeding conveyor (2). A propeller (3) at the bottom on the tank forces the tubers back upward to the drum washer while the stones sink to the bottom. At the bottom of the tank a bar conveyor (1) takes out the stones and puts them on a conveyor belt for removal. Independent destoners contain a conveyor belt just below the water surface to retrieve the product where in integrated destoners the product is guided over a retaining wall (4). Destoners have the option to be built with the stone belt to the left, right or back in the same direction as where the feeding conveyor comes from. The destoner in figure 15 below has a right oriented stone belt [106].



(a) Front view.

(b) Side view.

Figure 15: Schematic drawing of an integrated destoner.

For industrial use of the integrated destoner, tweaking the rotational speed of the propeller is enough to adjust the machine for optimal performance. In some rare cases the integrated destoner is part of a machine line for cleaning heavily polluted product batches. In these cases the machine operator not only changes the propeller speed but also the height of the retaining wall. The height of the retaining wall can be adjusted by adding or removing wall segments. If the wall is too low, stones may pass over the wall before they get the time to sink to the bottom of the tank. If the wall is too high potatoes will hit the wall, sink to the bottom of the tank and end up on the stone conveyor. For most uses of the destoner it is enough to adjust the speed of the propeller and that way make sure the stones are separated from the product up to a sufficient level but being able to also adjust the height of the retaining wall gives the machine operator a second tool to further perfect the performance of the destoner [90].

Depending on the origin of the product, stones have varying weights. If the difference in density between the tubers and the stones is big enough, the propeller is easily set to a speed where the stones sink to the bottom and the tubers are forced upward, but when the difference in density becomes smaller, the separation gets harder. Potatoes for example weigh around $\rho_a = 1,080 kg/m^3$. The destoner is guaranteed to retrieve 100% of the stones when they are $\rho = 1,400 kg/m^3$ or heavier. Figure 16 below shows a rough estimation of the stone removal efficiency η for different weights [9].

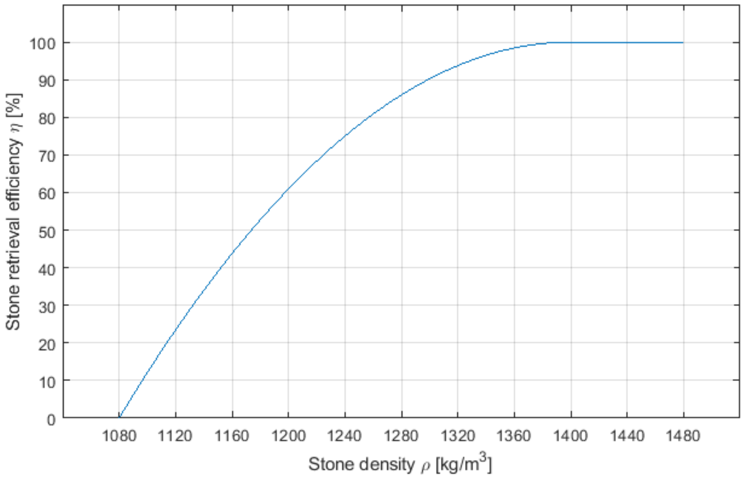


Figure 16: Estimation of the destoner efficiency for stones with different weights [9].

Machine dimensions

The destoner is engineered to exactly fit to the drum washer. There is no huge difference between the independent destoner and the integrated destoner. The width of both machines is the same, but only the independent destoner is equipped with a product belt to retrieve the product and is therefore equipped with a longer tank. To fit together in an optimal way, the destoner is available in five sizes just like the drum washer: the KS-320, KS-450, KS-600, KS-700 and KS-800. The dimensions of those five models are shown in table 2 below [106, 54].

Model	**Capacity** Q ***[TPH]***	**Output belt width** w_b ***[mm]***	**Output belt length** l_b ***[mm]***
KS-320	20	700	1,400
KS-450	40	1,000	1,800
KS-600	70	1,200	3,200
KS-700	125	1,400	3,200
KS-800	180	1,600	4,700

Table 2: List of destoner models and their most important parameters.

Options

The speed of the bar conveyor that removes the stones from the bottom of the tank can also be adjusted. If the speed is too low, stones will pile up at the bottom of the tank but if the speed is to high, stones are more prone to get stuck in the conveyor. The currents in the tank are also influenced by the stone belt. There are multiple configurations for the destoner. The older ones have a kink in the bar conveyor, as illustrated in figure 17a and the new ones have a straight bar conveyor as illustrated in figure 17b. In the old configuration flat stones where prone to get stuck between the roller in the kink and the chain belt. To solve this problem a system with a timer was designed. If the conveyor got stuck and did not move for a few seconds, the conveyor was reversed for a second and then put forward again. For the newer models without the kink in the belt, this system is not necessary anymore. With smart sensing a feedback loop can be integrated to optimize the speed of the bar conveyor based on the earlier mentioned principles. Because the speed of the stone belt influences the currents in the tank, it is important to keep this speed on a level as low as possible, where the belt is just able to remove all stones [90].

A disadvantage of the new destoner configuration is that the total height of the construction is bigger than that of the destoner with kinked belt. For the biggest washing lines, the KW-800, the new destoner configuration fits into the frame without the total washing line increasing in height. For the smaller washing lines the pipe system underneath the destoner becomes too small when designed to fit in the same frame as the destoner with the kinked belt. If the new destoner configuration is used in the smaller washing lines, the structure will gain in height. For some factories this is not possible due to limited available space. Because of this the straight stone belt design is only standardised into the design of the KW-800 [53].


(a) Old destoner configuration.
(b) New destoner configuration.

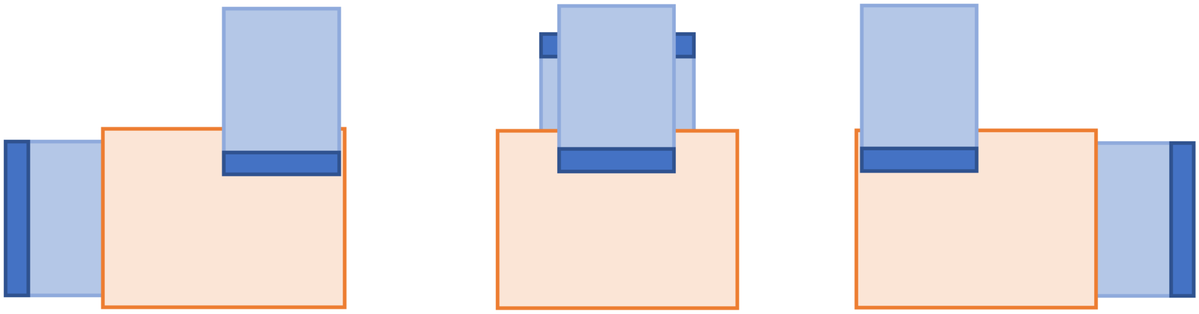
Figure 17: Old and new destoner configurations with two different bar conveyors.

The destoner can be built with the stone belt in different positions. For the KS-320, KS-450, KS-600 and KS-700 the entire machine can be mirrored and have the stone belt positioned at the left or right side. For the KS-800 the stone belt can only be directed backwards, it then removes the stones back in the direction of the product input belt. For the smaller machines the stone belt can not be positioned backwards because it will not fit underneath the product input belt. The KS-800 is originally designed with a backward positioned stone belt. Engineers are afraid that changing the stone belt direction to the left or right of the machine will change the fluid trajectories inside the tank and that way decrease the performance of the destoner. Because building a KS-800 with a different stone belt direction for testing is very expensive and customers have not been asking for these configurations yet, Tummers has decided to stay with just the KS-800-A. The input belt for the destoner is positioned opposite to the stone belt to give the product as long a trajectory as possible. This way all stones get the time to sink to the bottom of the tank. So if the stone belt is directed to the right, the input belt feeds the tubers into the left side of the destoner. If the stone belt is directed to the left ,the input belt feeds the tubers into the right side of the destoner and if the stone belt is directed backwards, the input belt feeds the tubers into the middle of the destoner. This configuration of stone belt and input belt positions is illustrated in figure 18 below [106] [54].

3.3.3 Drum washer

The drum washer is the most important part of the cleaning line for removing dirt from sticking to the product. There are many washing drums on the market, the key difference is the drum itself and the maximum capacity. Drum washers made by competitors regularly contain a round drum while Tummers produces an octagonal drum, this shape comes with a better washing result without damaging the product. Next to that Tummers is known for producing high-end machines for industrial purposes. Only parts of the highest quality are used and the machines are specifically designed to be maintenance free. Furthermore Tummers is the only party on the market that sells washing lines with capacities up to $Q = 180TPH$, as can be seen in appendix I competitors sell machines up to a maximum capacity of only $Q = 80TPH$. Tummers sells two types of drum washers, the separate drum washer (TW) and the washer with integrated destoner which will be referred to as washer/destoner (KW).

Working principe
Figure 19 below shows a schematic representation of the washer, the numbers in the text correspond to the



(a) Left oriented stone belt. (b) Backward oriented stone belt. (c) Right oriented stone belt.

Figure 18: Possible stone belt directions and corresponding input belt positions.

numbers in the picture. The product enters the drum washer from the left where it is submerged in the water and washed by rubbing it against itself and the walls of the rotating drum (1). This drum is powered by two electronic motors (2). The soil sticking to the product suspends into the water and sediments through the holes in the drum down into the cones underneath it. The sediment containing water is pumped from the cones (5) at the bottom of the machine to a water treatment system where the water gets separated from the soil and other particles to be recycled into the washing line again. The degree of filling ϕ is determined by a dosing disk at the end of the drum [107]. It is very important for the washer to contain big hatches in the cones at the bottom of the machine. When the valves underneath the cones get clogged, the hatches enable the machine operator to reach the valves and manually clean out the heaped up dirt and other waste.

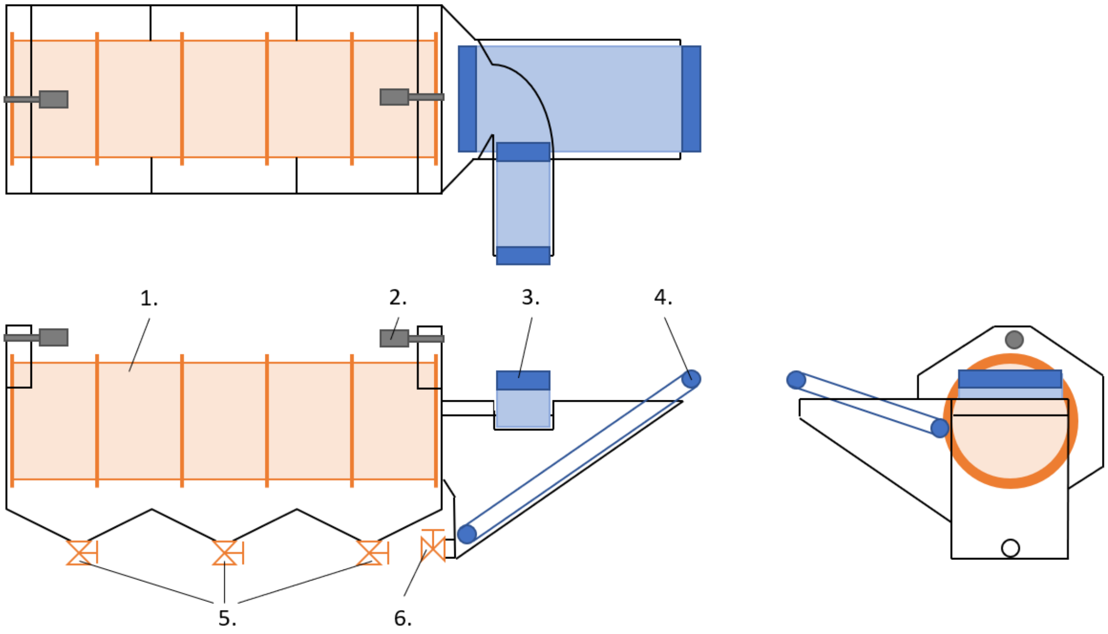


Figure 19: Schematic drawing of a drum washer with overflow channel.

Machine dimensions

The drum washer and washer/destoner have the same key parameters. The only difference is that the washer/destoner has an integrated destoner added before the washing drum. The washers are made in eight different sizes. They are made with five different options for drum diameters, from which the middle three are made with two different drum length options. The dimensions of those eight models are shown in table 3 below [107, 112].

Model	**Capacity** *Q [TPH]*	**Drum diameter** *d_d [mm]*	**Drum length** *l_d [mm]*	**Output belt width** *w_b [mm]*
TW/KW-320	15	1,000	2,500	700
TW/KW-450	30	1,300	3,650	1,000
	40	1,300	4,800	1,000
TW/KW-600	50	1,650	3,750	1,200
	70	1,650	5,000	1,200
TW/KW-700	100	2,000	5,000	1,400
	125	2,000	6,250	1,400
TW/KW-800	180	2,400	6,200	1,600

Table 3: List of drum washer models and their most important parameters.

Integrated floating parts remover
The drum washer can be equipped with one out of two built in options to retrieve floating debris. Either an overflow channel or a mechanical rake is used as a FPR. Figure 19 shows the washing drum with built in overflow channel, the numbers in the text correspond to the numbers in the figure. The floating debris are guided onto the waste belt (3) by strips in the water surface. The product will flow underneath the strips and end up on the product belt (4). Because dirt sinks to the bottom of the tank underneath the FPR, the polluted water is pumped from the bottom of this tank (6) to the earlier mentioned water treatment system too. The overflow FPR can be made with either a manually adjustable water level or with a water level that can be adjusted by an actuator, this system is called 'active overflow'. Two concentric pipes determine the water level in the entire washer. The inner pipe can be lowered when a lower water level is needed. The mechanical FPR has a rake chain installed above the tank. The rake scoops the floating debris from the water level onto a haulm removal belt.

The choice between implementing an overflow channel or a mechanical rake as a FPR in the drum washer can be made based on multiple factors.

Over all the mechanical FPR is way cheaper than the overflow FPR. This is caused by the fact that the mechanical FPR retrieves floating debris without water coming along with it. The floating debris can then be directly transported to a waste heap. In the overflow FPR, a lot of water comes along with the floating waste. This can not be prevented by using a permeable belt like for example a gauze belt because haulm and other small debris are prone to get stuck in the belt. This way the belt will get polluted internally. Because of the water coming along with the debris when using an overflow FPR, the debris have to pass through a dewatering drum before they can be transported to the waste heap. Installing a special dewatering drum to separate the haulm from the moisture makes the FPR way more expensive than the mechanical rake. More about this dewatering drum will be explained in section 3.3.4 [51].

Potatoes are regularly washed on high water levels in the drum. The mechanical FPR is placed above the tank behind the drum so that the rakes scoop the floating debris from the water surface. The mechanical FPR is not adjustable in height, therefore it can only be used for applications where the potatoes are only washed on a single water level. Factories that want to change the water level in the tank and still want to use the integrated FPR need to have an overflow system implemented in the drum washer because the overflow height can be adjusted [88].

Carrots are only washed on a single water level. This is because carrots are harder to clean. Due to the rough surface of the carrots that includes root hairs, dirt attached to the skin of the carrots is hard to remove. Because of this, carrots are washed on lower water levels than potatoes. Due to the low water level the carrots will rub against each other and that way scrub of the dirt. Because of this low water level, the mechanical FPR can not be used because the rakes are not able to touch the water surface. Thus designing a drum washer for carrots requires an overflow FPR [88].

Options The washing drums produced by Tummers have an octagonal shape instead of a round shape like that of the washers made by most competitors. Because of this shape the product is cleaned more thoroughly and the product output of the washing drum is more even. Tummers makes two types of washing drums, a perforation drum and a sleeve drum. The size and pattern of the holes and sleeves in the drum can be customised to meet customer requirements. For potatoes perforation drums are used. Some batches of potatoes, for example from the north of France, contain large amounts of very small stones. It is important to add a destoner in processing lines that handle these batches because otherwise the small stones will get stuck in the drum holes. The small stones need to be removed from the drum manually because they can not be sprayed loose. There are two perforation sizes. The standard perforation size is $d_p = 12mm$, this is big enough not to get clogged with dirt and haulm and small enough not to let small potatoes through. Next to the standard perforation size, drums with $d_p = 8mm$ perforation are sometimes sold as specials. Sleeve drums are commonly used for washing baby carrots that are destined for the fresh packs. When washed in perforation drums, the tips of the baby carrots can get stuck in the drum holes after which the carrots will break. For carrots that are cut afterwards this is not a problem but for fresh packs this needs to be prevented, therefore for this application sleeve drums are used. One of the difficulties of washing carrots are the root hairs that come from the carrots and get stuck in the holes in the drum. This way the drum can get clogged with root hairs and dirt after which the water can not leak through the drum and the machine looses washing quality and sometimes even overflows. Perforation drums are less prone to get clogged with root hairs than sleeve drums and therefore used for washing regular carrots. The amount of water used per ton of carrots with large amounts of root hairs needs to be enlarged to prevent clogging [80].

Two different types of output belts can be installed in the washer: a steel bar belt or a polyvinylchloride (PVC) mesh output belt. When processing potatoes the steel bar belt is recommended to be installed. This is caused by the fact that this type of belt is more robust and way less sensitive to wear. When a machine line is installed for washing carrots the PVC output belt is preferred. Carrots come with way more haulm than potatoes. This haulm, including root hairs, gets stuck in the bar belt easily and therefore a PVC mesh belt is preferred [88].

Instead of being filled with water, the drum washer can also be chosen for dry washing. In this case the product is not submerged into water but only rinsed by a spraying bar that is installed inside the drum. There are no cones and valves underneath the machine but a simple waste chute. A brush is installed inside the dry drum washer to clean the product. A second spraying bar is installed on the output side of the drum to rinse filth from the product. Sometimes a second brush is added on the outside of the drum when the drum washer is used to wash carrots. This brush cleans the root hairs and haulm from the drum. A third spray bar is then installed to clean this brush [52].

Nozzles can be installed above the output belt to spray the product, this way the last remaining parts of soil can be rinsed off. Jets can also be installed in the washer to spray product and floating debris from the dead corners. Product and floating debris often gets stuck in this corner because it does not lie in direction of the current. This dead corner is located at the exit side of the drum, opposite to the corner with the raising disk. Spraying nozzles are prone to get clogged because small amounts of dirt are still present in the water that comes from the water treatment system, therefore fresh water needs to be used in these nozzles or coarser nozzles need to be installed [59].

To recycle water in the drum and regulate the time tubers spend in it, circulation pumping can be installed. The water from the last cone underneath the drum is pumped into the entrance of the drum because the water in the end of the tank has the least dirt sedimented on the bottom. By increasing the amount of water being pumped, the product is flushed down the drum faster [80].

The integrated FPR can be installed with a waste stream directed to the left or the right of the machine. This applies to both the mechanical as the overflow FPR.

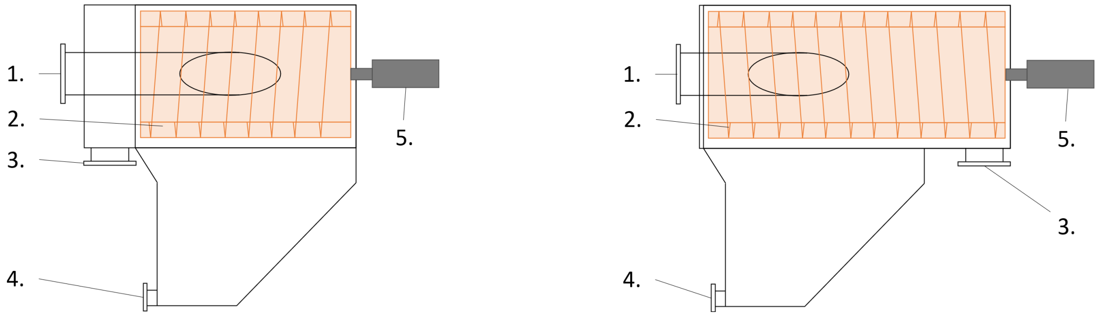
Water usage

Depending on the origin of the product, it is grown in different types of soil. In the Netherlands there are three main types of soil: sand, clay and peat. Potatoes or carrots that are grown in sand for example are easily cleaned. The sand washes off easily and sinks quite well because sand grains are way heavier than water. The specific gravity of silica sand, the ratio of the mass of the particles to the mass of the water they displace, is around $SG = 2.63$ [47, 17]. Potatoes or carrots that are grown in clay are less easily cleaned. The clay sticks to the product as so called clay caps. Furthermore peat is way lighter than sand, the most common organic peat in the Netherlands ranges from $SG = 1.45$ to $SG = 2.33$ but tropical soils can have specific gravities as low as $SG = 1.05$ [62, 39]. This leads to a phenomenon known as 'hovering' where the soil neither sinks to the bottom of the drum washer, nor it floats over the barrier in the FPR. This way the soil becomes very hard to remove from the washer. To also clean these lighter soil particles from the machine, once in a while the water in the system needs to be refreshed. For an average badge of potatoes with a medium pollution level, a relative drainage capacity of $Q_{dr} = 2m^3/ton$ is used. This means that $2m^3$ of water has to be ran through the machine per ton of potatoes to be cleaned [15]. For carrots this water consumption is $Q_{dr} = 3m^3/ton$. Batches of potatoes containing a lot of sand can be cleaned better by raising the water level in the tank, potatoes containing a lot of sticky clay are better cleaned by further opening the raising disk more so that the potatoes rub against each other more [88, 80].

3.3.4 Dewatering drum

There are two types of dewatering drums used in the processing lines made by Tummers, the reverse dewatering drum and the forward dewatering drum. The reverse dewatering drum is mostly used for dewatering slivers and peels that come from cutting and peeling lines. Waste streams that require a lot of haulm can not be dewatered while using the reverse dewatering drum because haulm gets stuck in the end of the drum where they can form a blockage after a while. This is caused by the fact that the incoming water stream washes the light haulm back down the drum. With heavier stones, clods, slivers and peels this problem does not occur. For this reason the more expensive forward dewatering drums are used for dewatering waste streams that are rich of haulm [51].

Working principle
Figure 20 below shows a schematic drawing of the two types of dewatering drums used in tuber washing lines, the numbers in the text correspond to the numbers in the figure. Figure 20a shows the reverse dewatering drum and figure 20b shows the forward dewatering drum. For the reverse watering drum the waste stream enters the dewatering drum through an intake pipe (1). The stream enters a rotating drum (2) powered by an electro motor (5). The water is forced through the holes in the drum by centrifugal force. The solid particles can not go through the holes in the drum and are transported back in the direction they came from by an auger. The solid particles leave the drum through a waste pipe (3) and the water leaks down from the drum housing and can be retrieved through the output pipe (4). The forward dewatering drum works almost the same way. The difference is that this dewatering drum is extended and the auger is rotating in opposite direction. Therefore the solid waste is transported out of the drum opposite the inlet side.



(a) Reverse dewatering drum.

(b) Forward dewatering drum.

Figure 20: Schematic drawing of the two types of dewatering drums.

Machine dimensions
Dewatering drums are available in three sizes: the OW-TZ-F/R-600x1000, OT-TZ-F/R-800x1150 and OW-T/Z-1000x1250 The dimensions of those three models are shown in table 4 below [108]. When two or more washing lines are installed in parallel or when multiple washers are installed in series, one big dewatering drum can be installed instead of multiple smaller ones according to customer preference.

Model	**Machine line capacity** *Q [TPH]*	**Drainage capacity** *Q_d [m^3/h]*
OW-TZ-F/R-0600x1000	40	180
OW-TZ-F/R-0800x1150	125	367
OW-TZ-F/R-1000x1250	180	650

Table 4: List of dewatering drum models and their most important parameters.

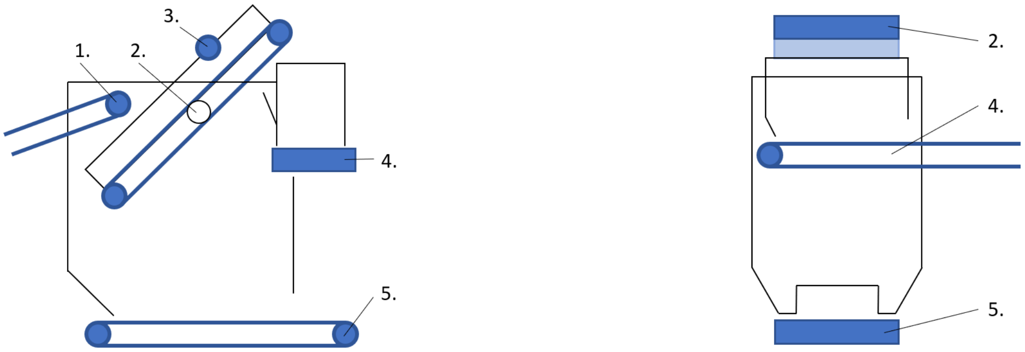
Options
The dewatering drum can be installed with the waste stream oriented to the left or to the right. Another available option is to install a buffer tank with pump. The waste streams from the machine line then first go into the buffer tank after which they can be pumped to the dewatering drum. For big machine lines it can

happen that all machines accidentally dispose of waste water at the same time, in this case too much water will be flushed into the dewatering drum, which can overload the machine. When a buffer tank is installed, the big amount of waste water can first flush into this tank and then be slowly processed by the dewatering drum afterwards.

3.3.5 Pintle belt

Pintle belts are a widely used way to retrieve haulm from agricultural product streams. They are for example integrated in potato and carrot harvesting machines but are also used in factory processing lines. Pintle belts can be used for processing both dry and wet product streams and are commonly used for potatoes and carrots.

Working principle
Figure 21 below shows a schematic drawing of the pintle belt that is used in tuber washing lines, the numbers in the text correspond to the numbers in the figure. The tubers are fed into the machine by the feeding conveyor belt (1). They drop onto a pintle belt (2), an inclined PVC conveyor belt that is covered by a mat of rubber cones. Due to the inclination, the round product will roll down the slope while haulm and dirt sticks between the rubber cones. The rubber cones are both rigid and wear-resistant while staying product friendly [117]. The haulm and dirt that sticks within the cones of the pintle belt is dropped onto the haulm belt (4) and the tubers that roll down end up on the product output belt (5). The pintle belt is equipped with a barrier roller (3) to prevent heaps of tubers from flowing over the top and ending up on the haulm belt. The angle of the pintle belt can be adjusted by means of a steel cable winch [103].



(a) Front view. (b) Side view.

Figure 21: Schematic drawing of a pintle belt.

Machine dimensions
Pintle belts are available in four standard sizes. The dimensions of those four models are shown in table 5 below. The capacities in this table only apply to pintle belts for processing potatoes, when for example processing carrots, the capacities are lower [103].

Model	**Capacity** Q ***[TPH]***	**Belt width** w_b ***[mm]***	**Belt length** l_b ***[mm]***
EB-1000x1500	15	1,000	1,500
EB-1200x1500	40	1,200	1,500
EB-1500x1500	70	1,500	1,500
EB-2000x1500	180	2,000	1,500

Table 5: List of pintle belt models and their most important parameters.

Options
The pintle belt can be installed with a haulm conveyor to the left or to the right of the machine. Because the direction of this conveyor does not change anything to the design of the pintle belt itself it is left out of

consideration throughout the rest of this report. An option to add to the pintle belt is the flap roller. This flap roller can be attached underneath the pintle belt on the return side to clean dirt and haulm sticking in between the rubber cones from the belt.

3.3.6 Drum polisher

The drum polisher is a newly developed machine by Tummers. The first model is sold and is now tested in practice. The drum polisher can be used to wash the product by removing remainders of dirt and polishing the product at the same time.

Working principle
Figure 22 below shows a schematic drawing of a drum polisher that is used in tuber washing lines, the numbers in the text correspond to the numbers in the figure. The product enters the drum polisher through the input chute (1). The machine consists of a slowly rotating drum (2) that is powered by two electronic motors (4). The drum is equipped with 18 rotating brushes (3). Inside the drum a spraying tube is placed to keep the product wet and to drain the dirt. A second shower is placed in the output side of the drum to rinse remainders of dirt from the product. A third spraying bar is placed on the outside of the drum to clean the brushes. The waste water leaks into a drainage chute (6) and the product leaves the drum through an output chute (5). Just like with the drum washer described in section 3.3.3, the degree of filling ϕ can be determined through the position of a dosing disk. [111, 52].

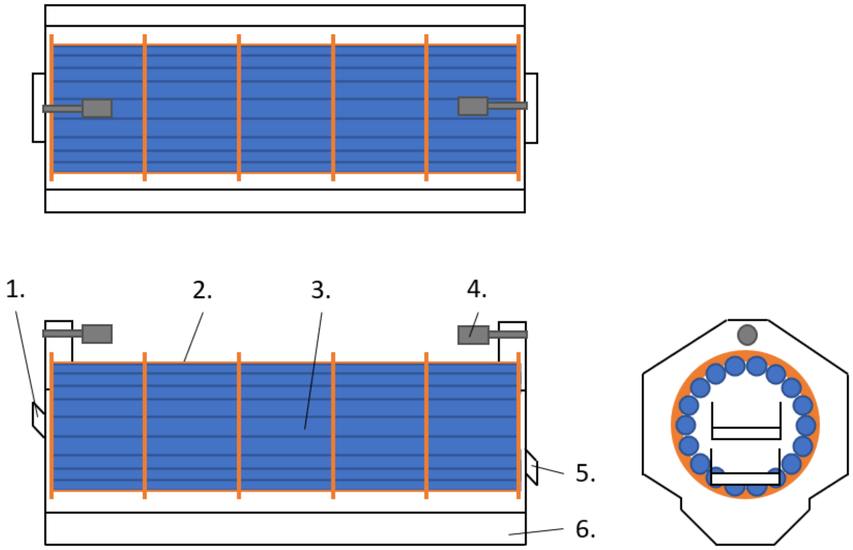


Figure 22: Schematic drawing of a drum polisher.

Machine dimensions
The first drum polisher model sold is the TP-1730x3200-18R. This model has a drum diameter of $d_d = 1,730mm$ and a drum length of $l_d = 3,200mm$ with $n = 18$ brushes and is used in a washing line with a maximum capacity of $Q = 25TPH$ [111].

3.3.7 Brine separator or clay bath

Glassed potatoes are potatoes with a lack of starch. Potato plants can contain two types of tubers: primary and secondary tubers. Primary tubers are directly connected to the roots of the plant, secondary tubers have no direct contact to the roots but are only connected to the primary tubers [35]. Glassed potatoes are primary potatoes that are drained of their starch by secondary potatoes they are connected to [85]. Because of the lack of starch, glassed potatoes are not suitable to be processed into most products. Glassed potatoes have a lower density than regular potatoes due to this lack of starch. To separate the glassed potatoes from the rest, a brine separator or clay bath can be used. Brine separators or salt baths are filled with a salt solution. Glassiness does not occur with carrots, therefore brine separators and clay baths are only used in potato washing lines. Next to this primary application, clay baths and brine separators can also be used to remove potatoes with a low solids content. This technique is used in some fries factories to remove potatoes that are not suitable to be processed into fries from the product stream. Glassiness only occurs roughly once in five years, depending on the weather during the growing season. The glassed ratio can lead up to 50% of the batch and therefore can form a huge seasonal problem for potato processing factories [23].

Because salt is very cheap and does not sediment on the bottom of a tank over time, brine separators have been a popular option to remove glassed potatoes. A big downside of brine separators is that the salt water accelerates corrosion, which lowers the service life of the machine. Secondly, waste water from brine separators could directly be disposed into the surface water in the past, today regulations have become more strict and waste water has to be treated before it can be disposed of. To be permitted for disposal after treatment the waste water is not allowed to contain high salt concentrations. A third downside of brine separators is that potatoes absorb the salt when they are kept in the tank for too long. Formerly potatoes sometimes stayed swerving in the tank for too long, which lead to some fries being too salty in fry factories. This issue was solved by installing the output belt over the whole width of the brine separator. A few years ago, in 2004, it has occurred that a batch of clay contaminated with carcinogenic dioxin was delivered to a factory that processes potatoes into fries. The peels of these potatoes were fed to dairy cows. When alarming dioxin rates were discovered in cow-milk, 148 Dutch dairy farms needed to be closed which lead to huge image damage of the fry factory [76]. Nowadays the regulations for clay used in food production are sharpened and contaminated batches of clay do not occur anymore. Because clay is more expensive than salt, the variable costs of clay baths are higher than that of the brine separator. Due to the previously stated disadvantages of brine separators, clay baths have become the standard and only some specific customers ask for a brine separator. Because of this, brine separators are left out of the scope of this research report after explaining the working principle, machine dimensions and options in the rest of this section [23].

Working principle
Clay baths and brine separators are the exact same machines but with a different substance added to the water. Figure 23 below shows a schematic drawing of a brine separator or clay bath that is used in tuber washing lines, the numbers in the text correspond to the numbers in the figure. The potatoes are fed into the machine by the input belt (1) so that the tubers fall into the tank. The tank is filled with a salt or clay mixture through the inlet valve (4). Due to the difference in density, healthy potatoes will sink to the bottom of the tank while glassed potatoes float to the surface where they are removed by the float belt (2). The healthy potatoes are transported out of the tank by the output conveyor (3). Both the float belt and the output belt are bar belts for water to be able to leak through. A discharge valve (5) is added to the bottom of the tank to remove waste water and sediment.

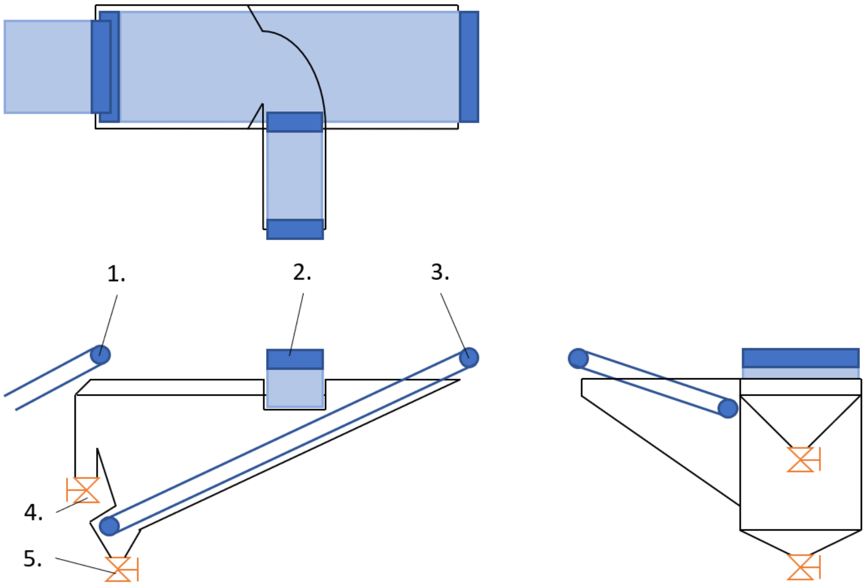


Figure 23: Schematic drawing of a brine separator or clay bath.

Machine dimensions
Just like most other machines, the clay bath and brine separator are designed to fit to the washer. This

machine is available in four different sizes: the FPR-K/Z-320, FPR-K/Z-450, FPR-K/Z-600 and FPR-K/Z-700. The dimensions of those four models are shown in table 6 below [105, 113].

Model	**Capacity** Q ***[TPH]***	**Output belt width** w_b ***[mm]***	**Output belt length** l_b ***[mm]***
FPR-K/Z-320	15	1000	3500
FPR-K/Z-450	40	1200	6000
FPR-K/Z-600	70	1400	8200
FPR-K/Z-700	125	1600	8500

Table 6: List of brine separator / clay bath models and their most important parameters.

Options
The output belt of the brine separator or clay bath can be equipped with a shower to rinse the product from residual salt or clay. Next to that, a mixing tank can be installed next to both the clay bath and brine separator. In this mixing tank the water and clay or salt mixture can be prepared prior to being added to the machine. This way the machine operator can make a big batch of it so that he does not have to look after the machine for that matter anymore. The mixing tank contains a mixer to ensure a homogeneous mixture. The mixture can be made by manually adding bags of salt or clay into the mixture tank but can also be automated by filling a hopper with salt or clay that is then added to the mixture tank automatically by an auger. Next to that, the brine separator and clay bath are available with the floating debris stream directed to the left or to the right of the machine [23].

Because the presence of glassed potatoes depends on weather related growing conditions, glassed potatoes are not always present in the product batch. Because of this the clay bath or brine separator does not always have to be used. To prevent unnecessary costs, the clay bath or brine separator can be filled with water without any supplements to act like a FPR, which will be discussed below. Another option is to install a bypass around the clay bath or brine separator to be able to temporarily remove it from the washing line when there are no glassed potatoes in the product stream.

3.3.8 Floating Parts Remover

Next to the FPR that can be integrated in the washer, Tummers also sells a separate FPR. This machine works exactly the same principle as the integrated overflow FPR, therefore the working principle is not further explained.

Machine dimensions
Just like most other machines, the FPR is designed to fit the capacity and product belt width of the washer. This machine is available in five different sizes: the FPR-V-320, FPR-V-450, FPR-V-600, FPR-V-700 and FPR-V-800. The dimensions of those five models are shown in table 7 below [104].

Model	**Capacity** Q ***[TPH]***	**Output belt width** w_b ***[mm]***	**Output belt length** l_b ***[mm]***
FPR-V-320	15	1,000	3,500
FPR-V-450	40	1,200	3,500
FPR-V-600	70	1,400	4,000
FPR-V-700	125	1,600	4,000
FPR-V-800	180	2,000	4,000

Table 7: List of FPR models and their most important parameters.

Options
The FPR is available with the floating debris stream directed to the left or to the right of the machine.

3.3.9 Roller spreader

Roller spreaders can be used for different purposes. First of all, as the name suggests, roller spreaders can be used to evenly spread the product stream over the width of the machine. This can for example be advisory when an unevenly spread product stream is directed to a roller dryer. To dry all tubers to the same extend, the product has to be equally spread over the roller dryer. Secondly the roller spreader can be used to remove excessive water from the product stream. When a product stream for example is guided from a flume to the roller dryer, the roller spreader can let the water leak through before the product enters the roller dryer. Thirdly the roller spreader can be used to remove small particles like broken product and remaining haulm from the product stream. This is not the leading function to implement a roller spreader into a washing line but more of a beneficial side effect [110].

There are two types of roller spreaders made by Tummers: the roller spreader and the delta-roller spreader. The roller spreader had been the standard over the years and has octagonal rollers. The delta-roller spreader is the newest technology designed by Tummers and has special triangle shaped rollers. Due to these special rollers the product is more evenly distributed over the width of the machine while bouncing of the product is reduced. The rollers are designed in such a way that the space between two rollers stays constant to prevent foreign objects from jamming the machine. Figure 24 below shows the two different rollers [110].

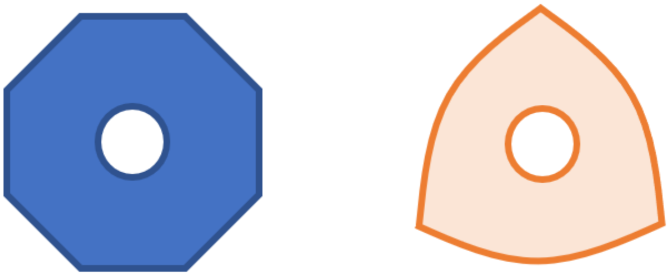


Figure 24: Schematic drawing of octagonal and delta rollers.

Working principle

Figure 25 below shows a schematic drawing of a roller spreader that is used in tuber washing lines, the numbers in the text correspond to the numbers in the figure. The tubers are fed into the machine by a feeder belt (1). The tubers are then guided by a chute onto a set of octagonal or delta rollers (2), depending on the type of roller spreader. After the water, haulm and other small debris have fallen in between the rollers, the product leaves the roller spreader through the output chute (4) while the waste stream leaves the roller spreader through the waste gutter (3).

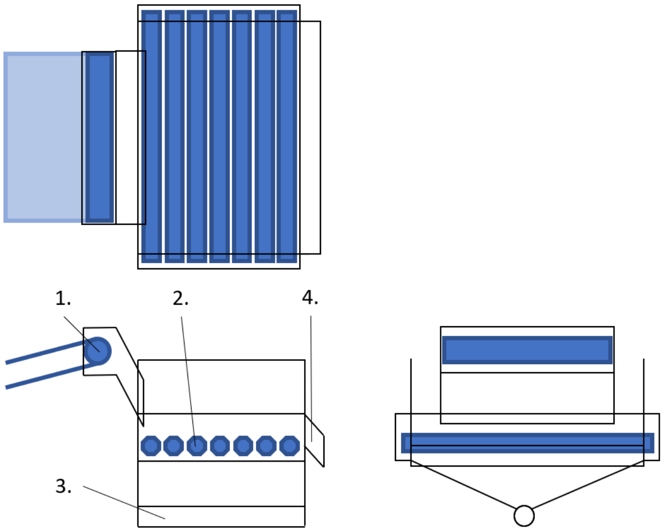


Figure 25: Schematic drawing of a roller spreader.

Machine dimensions

The roller spreaders are not specifically designed with capacities to fit the washers, this is because they are originally designed for the peeling line instead of the washing line. In the peeling line they are used to spread the product stream before it is graded by an optical sorter. Roller spreaders are available in seven sizes: the RS-0900-7R/DR, RS-1100-7R/DR, RS-1400-7R/DR, RS-1500-7R/DR, RS-1700-7R/DR, RS-1900-7R/DR and RS-2300-7R/DR. The machine codes ending on 'R' contain octagonal rollers and the machine codes ending on 'DR' contain delta rollers. The dimensions of those seven models are shown in table 8 below. In contrast to all other machines, the maximum capacities of the roller spreader models are unknown and irrelevant. Because the main goals of the spreader are spreading the product stream and dewatering, they are able to handle very high capacities. The limiting factor that makes a roller spreader suitable for a machine line is the width of it. The width of the roller spreader has to be slightly smaller than that of the roller dryer that follows up on it in the machine line. This way the product stream is evenly distributed over the width of the roller dryer [110].

Model	**Belt width** w_b ***[mm]***	**Amount of rollers** n_r ***[pc.]***
RS-0900-7R/DR	900	7
RS-1100-7R/DR	1,100	7
RS-1400-7R/DR	1,400	7
RS-1500-7R/DR	1,500	7
RS-1700-7R/DR	1,700	7
RS-1900-7R/DR	1,900	7
RS-2300-7R/DR	2,300	7

Table 8: List of roller spreader models and their most important parameters.

3.3.10 Roller dryer

There are multiple industrial machines on the market to dry tuberous products. Some examples are air dryers, that dry the tubers with cold or hot air and roller dryers that are either equipped with sponge or felt rollers to absorb the moisture from the product. The drying machine used in the machine lines of Tummers is the felt roller dryer. The felt is designed with a finger pattern to easily be replaced when worn out. The roller dryer is only used to dry potatoes. Carrots have much less adherent moisture and never have to be dried.

Working principle
Roller dryers are an efficient way for drying potatoes and work similarly to roller spreaders. Figure 26 below shows a schematic drawing of a roller dryer that is used in tuber washing lines, the numbers in the text correspond to the numbers in the figure. The product is fed in by a feeder belt (1) and falls through a chute onto a set of rollers (2). The first few rollers are made of rubber so the potatoes do not get damaged by the fall and get spread out evenly over the width of the machine. The other rollers are covered in felt to absorb the moisture from the potatoes. Pressure rollers (3) are placed underneath the felt rollers to squeeze out the moisture. The moisture ends up in a chute (4) at the bottom of the machine to get disposed of, while the potatoes leave the machine through the product chute (5). The roller dryer does not transport the product faster due to faster rotating rollers. The product that comes in pushes the product that is already present onto the next roller, this way the machine transports the product. In between batches or before maintenance these machines can be emptied manually of through an empty running system [109].

Machine dimensions
The roller dryers are designed with capacities to fit the washers. They are available in five sizes: the RD-450-1200-20R, RD-450-1500-20R, RD-450-2000-20R, RD-450-1500-28R and RD-600-2000-28R. The dimensions of those five models are shown in table 9 below [109].

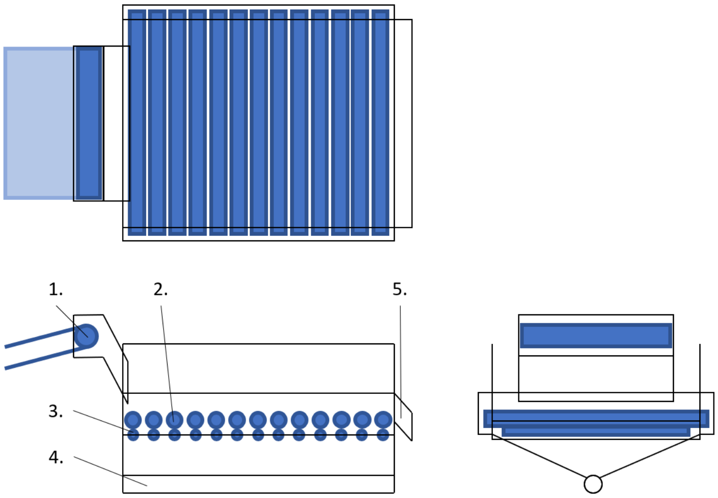


Figure 26: Schematic drawing of a roller dryer.

Model	**Capacity** Q ***[TPH]***	**Belt width** w_b ***[mm]***	**Amount of rollers** n_r ***[pc.]***
RD-450	25	1,200	20
	35	1,500	20
	45	2,000	20
	50	1,500	28
RD-600	70	2,000	28

Table 9: List of roller dryer models and their most important parameters.

Options

Roller dryers can be equipped with multiple extras. An empty running system can for example be added to mechanically remove all potatoes from the machine. This empty running system consists out of a bar, attached to a cloth that is wrapped around an axle. When the axle is rotated, the cloth unrolls from the axle and the bar is pushed from one roller onto the next. This way the product is emptied out of the roller dryer.

Next to the empty running system, the roller dryer can be equipped with Ultraviolet (UV) light bars for surface disinfection. UV light has a shorter wavelength and therefore falls outside of the visible light spectrum. UV waves break the molecular bonds that hold the bacterial or viral DNA together. When this DNA is broken, the viruses or bacteria are disabled to reproduce and therefore spread of those pathogens is prevented. Because some cross-contamination occurs between the product and the felt, UV light can be used to disinfect both the product and the felt [114].

Preventing spread of pathogens in the roller dryer is important for potatoes that are sold in fresh packs. In the time between packaging and consumption the pathogens can reproduce up to a level where the product is spoiled and not suitable for consumption anymore. Potatoes that are processed into flakes, fries or chips for example are processed at high temperatures that kill the pathogens. The washed product is stored in buffers between washing and processing but never longer than a couple of days so the pathogens are not able to spread up to dangerous levels. Because of this UV light has no added value in those washing lines.

UV light bars lose their function over time. To keep killing the pathogens, the light bars need to be replaced regularly. Because the light bars are quite expensive to replace, UV bars are not often installed above roller dryers.

4 Jigsaw puzzle model

Each machine that is part of the washing line portfolio has limited efficiency. It is the combination of machines following up on each other that makes the machine line highly efficient on removing all kinds of waste from the product stream. This is caused by the fact that the different machines are removing waste based on different separation principles. The FPR removes waste based on its ability to float on water for example and the pintle belt removes waste based on its ability to roll down a certain slope. As modular design of machine lines is intended, the different modules can be installed in different configurations based on the application of the machine line. In this section the recommended machine line configurations for different tuber processing applications are explained. Each machine is covered individually in the same order that the machines are recommended to appear in the machine line. Depending on the applications each machine will be chosen if to be implemented in the line, which model to implement and which options to apply.

Figure 27 below shows all different machine types from the washing line portfolio in the recommended basic order of machines. In special cases this order is changed due to the input variables. When the strategy explained in this section is applied into CPQ software, the machine lines that come out of this strategy are recommended to the customer. However, the CPQ software will allow the customer to manually change the order of the machines as well as the machine models and options to be installed. Important for the washing line design is that the rules for jigsaw puzzle modelling are followed as discussed previously in section 2.1.

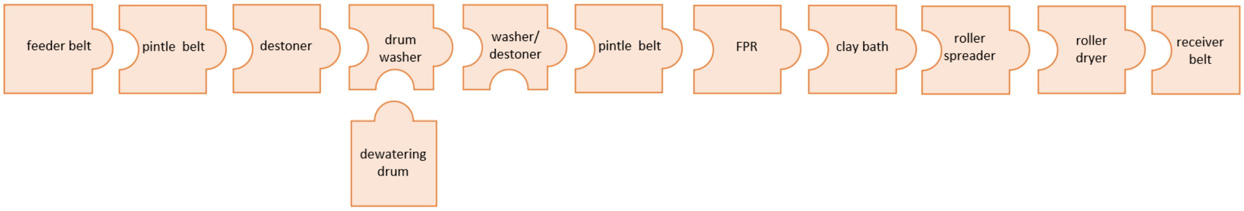


Figure 27: Example of a jigsaw puzzle model for a complete washing line.

As previously mentioned the configuration strategy for a specific washing line can be described through a blackbox model. In such a model only the inputs and outputs are known while the decision making process in the blackbox is still undefined. Figure 28 below shows a schematic overview of this blackbox model. In this model the inputs are details regarding the desired product, the input product, factory layout and customer preferences. These four types of inputs come from the customer side to determine which machines with which options to implement in the washing line. The filling of the blackbox in the current situation purely consists of the experience and personal knowledge of salesmen in the Tummers sales department. This research focuses on changing that to filling in this blackbox with a standardised model for modular design. The inputs structured in the four groups that are just mentioned, are listed in table 10 below more specifically. These inputs will form the parameters which the decision making process in the modular strategy, which is described in this section, will be based on.

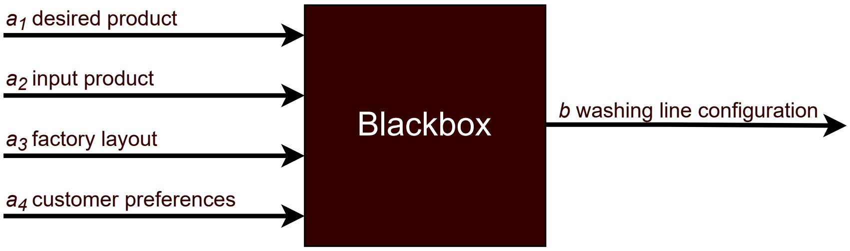


Figure 28: Blackbox model for the washing line configuration.

a_1 **Desired product**	a_2 **Input product**	a_3 **Factory layout**	a_4 **Customer preferences**
a_{11} Total capacity $[0-180TPH]$	a_{21} Dry haulm removal $[yes, no]$	a_{31} Direction of haulm stream $[left, right]$	a_{41} Washing on multiple levels $[yes, no]$
a_{12} Rinse clay residues $[yes, no]$	a_{22} Degree of pollution $[light, normal, heavy]$	a_{32} Location of platforms $[left, right]$	a_{42} Overflow type $[manual, active]$
a_{13} Product needs to be dry $[yes, no]$	a_{23} Soil type $[sand, mixed, clay, black]$	a_{33} Direction of stone stream $[left, right, backward]$	a_{43} Mixing tank $[yes, no]$
	a_{24} Amount of floating parts $[no, small, normal, large]$		a_{44} Spread product $[yes, no]$
	a_{25} Glassed potato removal $[yes, no]$		a_{45} Empty run system $[yes, no]$
	a_{26} Stones present $[yes, no]$		

Table 10: List of inputs for the blackbox model.

The product portfolio matrix that structures the different available outputs of the blackbox model consists out of six dimensions. The first dimension u sets out the different machines from set U, which is a list of the ten different machine types. The second dimension v sets out the machine sizes from set V, which is the set of available sizes per machine type as shown in figure 29 below. The feeder and receiver belt are only shown as the head and tail of a machine line in the figure to create a complete overview but are not part of the machine portfolio matrix. The third dimension w sets out the direction of the waste stream of the machine from set W, which is the set of available waste directions per machine type as can be seen in figure 30. The fourth dimension x sets out the motor location from set X, which is the set of available motor directions that can be chosen for two different machine types as visualised in figure 31a below. The fifth dimension y sets out the type of FPR of a machine from set Y, which is the set of FPR types that can be chosen for two different machine types as visualised in figure 31b below. The sixth and last dimension z sets out extra options that fall outside of the other dimensions from set Z, namely the addition of a mixing tank to the clay bath and emptying system to the roller dryer, as can be seen in figure 31c

$$U = [0, 1, ...9] \tag{2}$$

$$b(u, v, w, x, y, z) \in [0, 1, 2], \qquad u \in U, v \in V, w \in W, x \in X, y \in Y, z \in Z \tag{3}$$

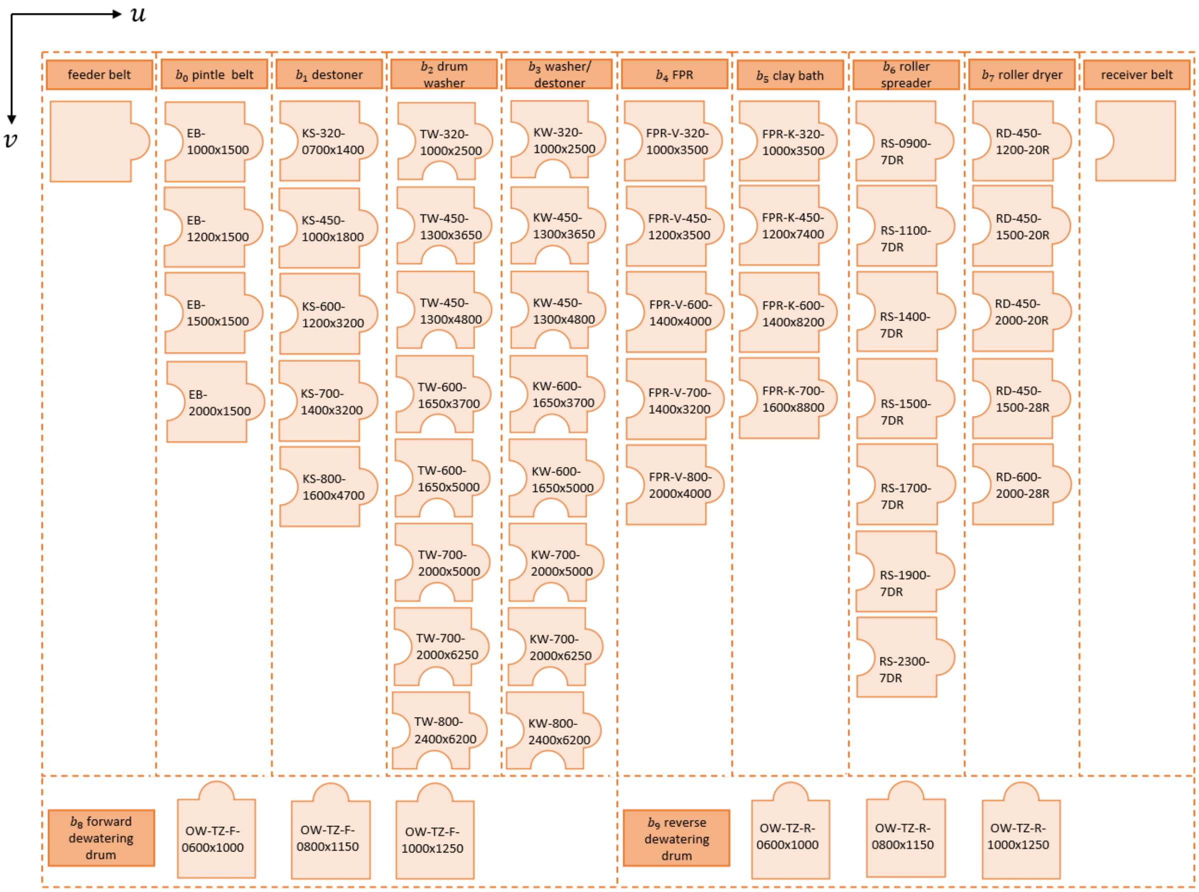


Figure 29: Overview of V, the set of available sizes per machine type.

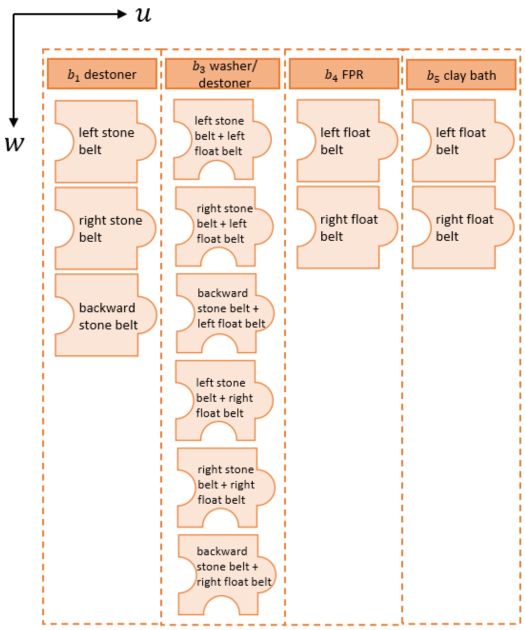
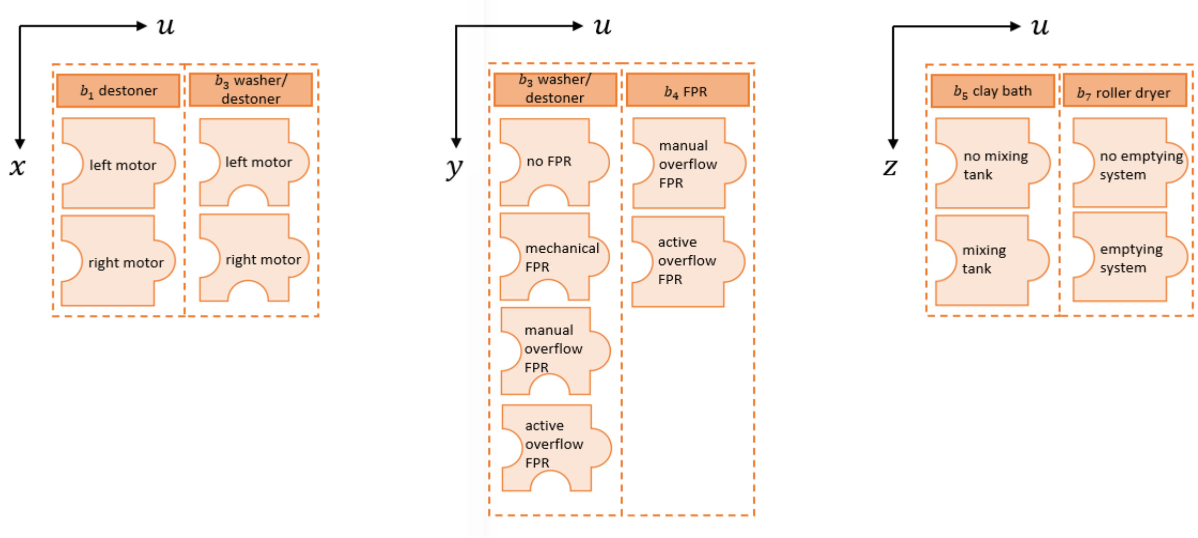


Figure 30: Overview of W, the set of available waste directions per machine type.



(a) Overview of X, the set of available extra options for two different machine types.

(b) Overview of Y, the set of available FPR types for two different machine types.

(c) Overview of Z, the set of available extra options for two different machine types.

Figure 31: The last tree dimensions of the machine portfolio matrix.

The output variables of the model that determine the configuration of the machine line directly depend on the input variables through a set of relations. The set of equations below shows all dependencies the model is based on. Equation 4 to 13 below show the parameter relations for determining the amount of copies to be installed in the washing line for each machine type. Equation 14 shows the parameter relations for choosing the right sizes for each machine type. Equation 15 to 17 are used to determine the direction of the waste belts of certain machines. The motor location for two machine types are selected while using equation 18. Equation 19 is used to find out what kind of FPR to choose for two different machine types. The optional placement of a mixing tank next to the clay bath can be chosen with equation 20 and the choice to install an emptying system in the roller dryer is based on equation 21.

$$b_0 = f(a_{21}, a_{24}), \qquad \forall v, w, x, y, z \tag{4}$$
$$b_1 = 0, \qquad \forall a, v, w, x, y, z \tag{5}$$
$$b_2 = f(a_{26}), \qquad \forall v, w, x, y, z \tag{6}$$
$$b_3 = f(a_{26}), \qquad \forall v, w, x, y, z \tag{7}$$
$$b_4 = f(a_{24}), \qquad \forall v, w, x, y, z \tag{8}$$
$$b_5 = f(a_{25}), \qquad \forall v, w, x, y, z \tag{9}$$
$$b_6 = f(a_{11}, a_{22}, a_{23}, a_{44}, b_0, b_4, b_5), \qquad \forall v, w, x, y, z \tag{10}$$
$$b_7 = f(a_{11}, a_{22}, a_{23}, a_{13}), \qquad \forall v, w, x, y, z \tag{11}$$
$$b_8 = f(a_{22}, a_{24}, a_{41}), \qquad \forall v, w, x, y, z \tag{12}$$
$$b_9 = f(a_{22}, a_{24}, a_{41}), \qquad \forall v, w, x, y, z \tag{13}$$
$$v = f(a_{11}, a_{22}, a_{23}), \qquad \forall u, w, x, y, z \tag{14}$$
$$w = f(a_{33}), \qquad \text{for } u = 1, \quad \forall v, x, y, z \tag{15}$$
$$w = f(a_{31}), \qquad \text{for } u = [4, 5], \quad \forall v, x, y, z \tag{16}$$
$$w = f(a_{31}, a_{33}), \qquad \text{for } u = 3, \quad \forall v, x, y, z \tag{17}$$
$$x = f(a_{32}), \qquad \text{for } u = [1, 3], \quad \forall v, w, y, z \tag{18}$$
$$y = f(a_{22}, a_{24}, a_{41}, a_{42}) \qquad \text{for } u = [3, 4], \quad \forall v, w, x, z \tag{19}$$
$$z = f(a_{43}), \qquad \text{for } u = 5, \quad \forall v, w, x, y \tag{20}$$
$$z = f(a_{45}), \qquad \text{for } u = 7, \quad \forall v, w, x, y \tag{21}$$

As can be seen there are many relations between the in- and outputs of the model, some of which are quite complex. To get a clear overview of the relations this section will explain them thoroughly structured by machine type and illustrated by choice schemes.

Customers do not always choose to install a single washing line to wash the maximum capacity of product they need. Sometimes customers choose to install multiple washing lines alongside each other and combine the product output to be packaged or processed further. The downside of installing multiple washing lines in parallel is that it is more expensive to install multiple small capacity lines than one big capacity line. The upside is that when one of the washing lines is down for maintenance, the other lines can stay operational. This way the factory experiences temporary decreases of the maximum capacity instead of downtime. This option can also be chosen by the customer in the online configurator, the customer then divides the maximum capacity he needs by the amount of washing lines he wishes to install alongside each other. The configurator will show a single machine line but when contacting Tummers for a price estimation or for for the first meeting the customer is able to state that he wants multiple of those washing lines installed in parallel [88].

4.1 Destoner

Stones are not only undesirable in the end product, they can also damage or obstruct machines in the line. As previously described in section 3.3.3, small stones are prone to get stuck in the holes of the washing drum. To prevent the drum from getting clogged with those small stones, a destoner can be added in front of the washing drum for lines that process product batches that regularly contain large quantities of those small stones. Stones can also damage machines in the processing line in a more harmful manner. If a stone for example is pumped into the tuber cutting system, it will critically damage the knife block and get stuck in the machine. The obstruction in the flow will be detected and the knife block will automatically be switched with a new one to prevent downtime, but the knifes in the block have to be replaced. Factories that process tuberous products regularly have an optical sorter placed behind the washing line to remove the last pieces of waste from the product stream. It is very important for the optical sorter to identify and remove stones to make sure the machines that follow up in the processing line do not get damaged. Optical sorters are very expensive, require a lot of computational power and slow down the production process. Furthermore stones are hard to remove from the product belt by the actuators in the optical sorter due to their weight and shape. Because of these factors it is important to retrieve as much waste from the product stream in the washing line as possible. The optical sorter is only intended to remove the last pieces of waste from the product stream [54].

Besides the machines, stones can also damage the product. When a batch of potatoes that contains a lot of stones enters the washing drum without being destoned first, the stones will fall on and rub against the potatoes. This way the potatoes can get damaged. It is very important for potatoes that are sold in fresh packs not to be bruised, because consumers will not buy a fresh pack that contains damaged potatoes. For potatoes that for example are turned into starch or flakes, bruises are less important. Because of this washing lines for potato fresh packs require a drum washer with integrated destoner. Tuberous products differ in fragility. The mechanical properties of tubers also differ slightly per variety and even per individual piece, therefore mean values are taken from a commonly used variety of both potatoes and carrots. Research from Antal et al. (2013) shows that carrots have a 38% higher hardness than potatoes [4]. Due to this difference in hardness potatoes are more prone to get damaged due to puncturing. Research from Abedi et al. (2019) and Pestka (2014) shows that the Youngs modulus of carrots is $Y = 12MPa$ while that of potatoes is only $Y = 2MPa$ [2, 83]. This difference in Young's modulus shows that potatoes deform more than carrots when subjected to a certain load, this leads to potatoes being more susceptible to bruises due to impact or compression. Because carrots are not prone to get damaged by stones in the washing drum, the destoner can theoretically be placed behind the washing drum or be left out of the line. Because placing a separate destoner behind the washer has no clear advantages and is more expensive for the customer, separate destoners are normally not recommended to be installed in washing lines. Sometimes when a washing line is made to process batches that include extreme amounts of stones and/or sand, a separate tank destoner is installed in front of the washer instead of installing an integrated destoner in the washer. Separate destoners are longer than integrated destoners and therefore have a bigger tank volume. Because of this bigger tank volume a separate destoner is able to remove bigger amounts of stones and sand than an integrated destoner. Figure 65 in appendix K shows a selection chart for choosing the right destoner model [54].

4.2 Drum washer

Depending on the previously described choice regarding the destoner, a drum washer with or without an integrated destoner is chosen with the preferred stone belt direction. Then the size of the washer is chosen, depending on the required output capacity and the pollution of the input product. To take this level of pollution into account in the selection of the washer, a parameter is defined for the calculation capacity Q_{calc}. In this calculation capacity, certain factors are taken into account due to the degree of pollution. The calculation capacity is set equal to the required maximal output capacity $Q_{calc} = Q$. Then firstly the degree of pollution is determined. When a batch contains a lot of dirt and is therefore heavily polluted, a bigger washer is needed to clean the product and the calculation capacity is raised by 20%, $Q_{calc} = 1.2 \cdot Q$. When a batch contains a normal amount of dirt, the calculation capacity is kept the same, $Q_{calc} = Q$. If a batch is only slightly polluted, the calculation capacity is lowered by 20%, $Q_{calc} = 0.8 \cdot Q$. Secondly the soil type is determined. According to Bergthaller et al. (1999, p. 237) each factory installs different units to wash potatoes according to local needs, depending on soil quality of the production area. While sandy soils require little treatment, heavy loamy soils need much more sophisticated washing systems [11]. Some soils like sand do no stick to the tubers much and are therefore easily removed with water. For sand-like soils the calculation capacity is reduced with 20%. Other soils like clay or soils of both sand and clay mixed together stick to the tubers more, for them the calculation capacity does not change. Black soil or chernozems is a special type of greasy soil that is hard to remove from the product. This type of soil is rich in organic matters and can be found on the grass steppes in continental Russia, Canada, India, the United States and some parts of South America [32, 16]. Washing lines that encounter product batches that are contaminated with black soil often require more thorough washing and therefore for this application the calculation capacity is raised by 20%. When the calculation capacity is determined, the washer size can be chosen. In section 3.2 the maximum capacities of each washer are determined. The washer model where the calculation capacity fits the capacity range is chosen to be implemented in the washing line. Figure 66 in appendix K shows a flowchart to illustrate the determination of the calculation capacity. This flowchart can directly be connected on top of the choice scheme in figure 67 of appendix K.

When the right washer model is chosen, the options for integrating an FPR are considered. If floating debris are present in the product stream, the first part of them need to be removed through an integrated FPR. As described in section 3.3.3 above, there are two types of integrated FPRs: the mechanical and the overflow FPR. In case of light pollution and with no need to wash on multiple water levels, the cheaper mechanical FPR can be installed in the washer. The mechanical FPR is equipped with an output belt for the floating debris to either the left or the right side of the machine. At higher degrees of pollution the overflow FPR has to be installed. There are two choices for the overflow FPR: active of manual overflow. The water level in the active overflow FPR is controlled automatically. For the manual overflow FPR this has to be done manually, which is cheaper but less efficient. The overflow FPR has a chute system to remove the floating debris and the water that comes with it. Figure 67 in appendix K shows a selection chart for choosing the right washer configuration according to this strategy.

4.3 Dewatering drum

The discharge water from the machines in the washing line needs to be cleaned from small stones and clods. This is caused by the fact that stones and clods increase wear in pumps and require extremely fast water flows not to sediment in the pipes. There are two types of dewatering drums sold by Tummers: the reverse and the forward dewatering drum. The reverse dewatering drum is cheaper and used to dewater waste streams rich of slivers, peals, stones and/or dirt. Because haulm is prone to get stuck in the end of the drum and this way jam the machine, it can not be used for dewatering waste streams that are rich of haulm. This problem does not occur to the forward dewatering drum, which is more expensive and used to dewater the haulm rich waste stream that comes from the overflow FPR. Reverse dewatering drums are installed in machine lines with a washer that is not equipped with an overflow FPR. Depending on the required maximum capacity of the washing line, one out of three dewatering drum models can be chosen. Each of them can be equipped with a waste removal directed to the left or to the right of the machine. Figure 68 in appendix K shows a selection chart for choosing the right dewatering drum model [51].

4.4 Pintle belt

Pintle belts can be added in two places in the washing line. As described previously in section 3.3.1 they can be added in front of the washing line for dry removal of haulm, loose dirt and small clods. It is important to remove haulm from the product as early as possible. Haulm forms one of the biggest problems in washing lines. It entangles into clusters and heaps up in machines, blocking the flow of both product and water. It gets stuck in belts which can break due to haulm between the rollers. Haulm also clogs the perforation in the drum washer, this prevents water and dirt from going through the holes in the drum. Valves in the machine line to dispose waste water can also get clogged by haulm. Another reason to remove haulm as early as possible in the washing line is because wet removal of haulm is way more expensive than dry haulm removal. This is caused by multiple factors. Dry haulm removal machines only need a conveyor belt for haulm disposal. Wet haulm removal machines need a dewatering drum to separate the haulm from the waste water too, which then also has to be processed by the water treatment system. Because pintle belts are very sensitive to wear, a pintle belt is only added before the washer when big amounts of haulm occur in the input product, otherwise it is placed after the destoner for stones not to damage the belt [54].

The second spot in the washing line to add a pintle belt is after the washer. Most of the non-floating haulm that is not retrieved by the integrated FPR can be removed from the product stream here. While most of the haulm floats, some doesn't. When potatoes for example are brought in for processing straight after being harvested, some of the haulm is still green and has not dried out yet. This haulm does not float and is therefore not removed by the integrated FPR. Other particles that do not float and therefore are hard to remove from the product stream are pieces of wood, remainders of other agricultural products and golf balls. The plants that Brussels sprouts or broccoli's grow on for example stay in the soil after being harvested as well as corn cobs. These plants form hard stumps that, just like the corn cobs, are harvested together with the potatoes and are hard to remove from the product stream because they do not float [59]. Although the inclined pintle belt designed by Tummers is able to remove part of these waste sources, they are not able to remove everything. Remainders of waste that still pass the washing line can be removed by the optical sorters further down the processing line. Depending on the desired maximum capacity, the right pintle belt can be chosen with the help of the choice scheme in figure 69 in appendix K. The pintle belts are not chosen due to the capacity but due to the width of the belt that feeds the product to the pintle belt. To be consistent and clear with the choice schemes, the widths of the output belts are represented by the respective maximum capacities of the machines they belong to.

A good way for dry removal of these stumps, loose soil and small clods that has proven its effect in agriculture, is through a special pintle belt, which is illustrated in figure 32 below. The numbers in the figure correspond to the numbers in the text. The pintle belt (2) is positioned horizontally and fed by a feeder belt (1). A set of two rollers (3) is placed above the pintle belt to pull the haulm through, which is disposed of at the end of the pintle belt. The tubers are not pulled through the rollers and leave the pintle belt on the right side. Small clods and loose soil settle in between the spikes of the pintle belt, pass underneath the rollers and are also disposed of at the end of the pintle belt. Because this machine is proven to be very good at removing remainders of agricultural products like stumps and corn cobs from the product stream in dry state but is not part of the Tummers product line yet, it could be a great project for research and development [65].

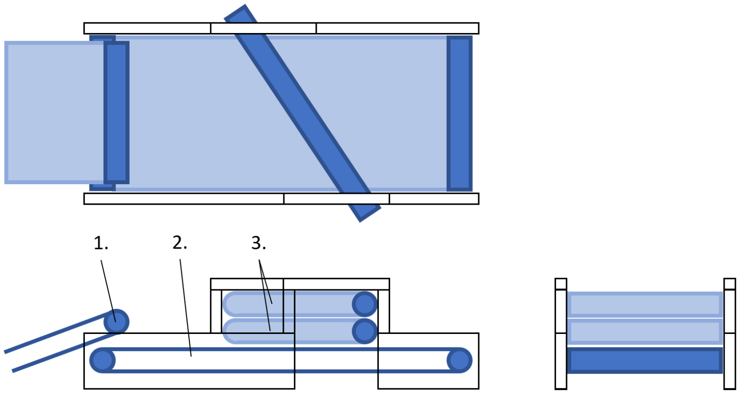


Figure 32: Schematic drawing of a special pintle belt.

4.5 Clay bath

As previously discussed in section 3.3.7, clay baths are used to remove glassed potatoes from the product stream. Depending on the desired maximum capacity of the washing line, the right clay bath can be chosen with the help of the selection chart in figure 71 in appendix K. All clay bath models can be equipped with a belt for removing the floating waste either positioned to the left or to the right of the machine. A mixing tank can be added for a constant supply of clay mixture and a shower can be added above the product output belt to rinse reminders of clay from the tubers. Because the shower leaks too much fresh water into the clay bath and deludes the mixture, a separate shower conveyor is preferred to be placed after the clay bath to rinse remainders of clay from the product. When a clay bath is followed up by a roller dryer, the product always has to be rinsed to prevent the clay from sticking to the felt rollers.

Clay baths are designed a bit wider than the output belt of the machines that feed them. This is done to give the potatoes more space in the tank to be able to sink to the bottom. When the clay bath is used for removing potatoes with too low of a solids content from the product this extra wide tank is needed because these undesired potatoes can form up to 15 to 20% of the product stream. When the clay bath is used for removing glassed potatoes this extra wide tank is not needed. Because glassed potatoes regularly only form up to 5% of the product stream, the clay bath can be chosen one level smaller. A line with for example a washer model KW-600 can then be equipped with a clay bath model FPR-K-450 because both have a product belt width of $w = 1200mm$.

4.6 Floating Parts Remover

If the batches of product processed by a washing line contain a huge amount of floating parts, a separate FPR can be placed in the line. This FPR is placed after the washer and, if present in the washing line, after the clay bath. This way potential clay residues are washed from the tubers in the FPR. Depending on the desired maximum capacity of the washing line, the right FPR can be chosen with the help of the selection chart in figure 70 in appendix K. All FPR models can be equipped with a belt for removing the floating waste either positioned to the left or to the right of the machine.

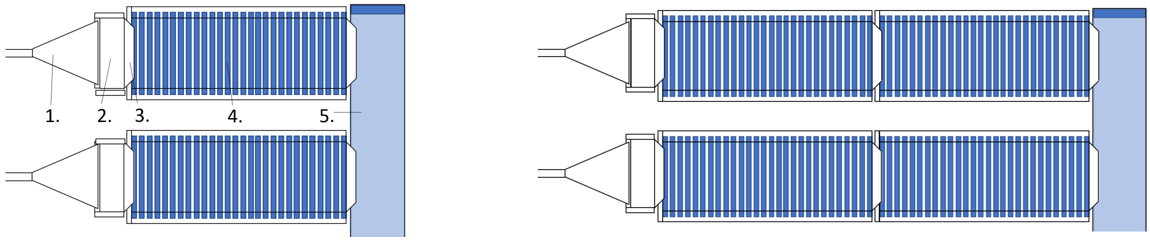
4.7 Roller spreader

If a roller dryer is fed by a flume system, the product has to be dewatered first. In this case a roller spreader is added in between the flume and the roller dryer. If a roller dryer is directly following up on a washer, the product is not evenly spread over the width of the machine. This is caused by the fact that the product leaves the washing drum on either the left or the right side of the machine. To evenly spread the product over the width of the roller dryer a roller spreader is added in between the two machines. The selection chart in figure 72 of appendix K can be used to choose a roller spreader that fits the machine line [23].

4.8 Roller dryer

Roller dryers are only used in case a product has to be dried after being washed. This applies to potatoes used in fresh packs. The roller conveyor is always the last machine in the washing line. Tubers that are processed after being washed like for example into flakes, starch or fries, do not need to be dried.

To be able to dry product streams with higher capacities, multiple roller dryers can be positioned in parallel. Figure 33 below shows a schematic drawing of multiple connected roller dryers, the numbers in the text correspond to the numbers in the figure. To evenly divide the product stream over the two roller dryers, chutes or a flume system need to be installed. The product stream is divided into two by the flume system. The tubers are fed by the flume (1) onto the roller spreader (2) where they are dewatered and spread out. Through a chute (3) they are guided onto the roller dryer (4) after which the two product streams come together again on a belt conveyor (5). The highest capacity that Tummers has built roller dryer systems for is $Q = 100TPH$. For this configuration two RD-600-28x2 dryers have been installed in parallel, as visualised in figure 33a. If an order will come in for a washing line with the biggest washer/destoner, the KW-800 from which the product needs to be dried, a system of two parallel sets of two serial RD-600-28x2 roller dryers can be installed. This setup is illustrated in figure 33b. Together this set of roller dryers is able to dry a product stream with a maximum capacity of $Q = 200TPH$. Up to today the big KW-800 washers are only sold for potatoes that are turned into flakes. For this application the potatoes do not need to be dried after being washed. The selection chart in figure 72 of appendix K can be used to choose a roller dryer that fits the machine line [23].



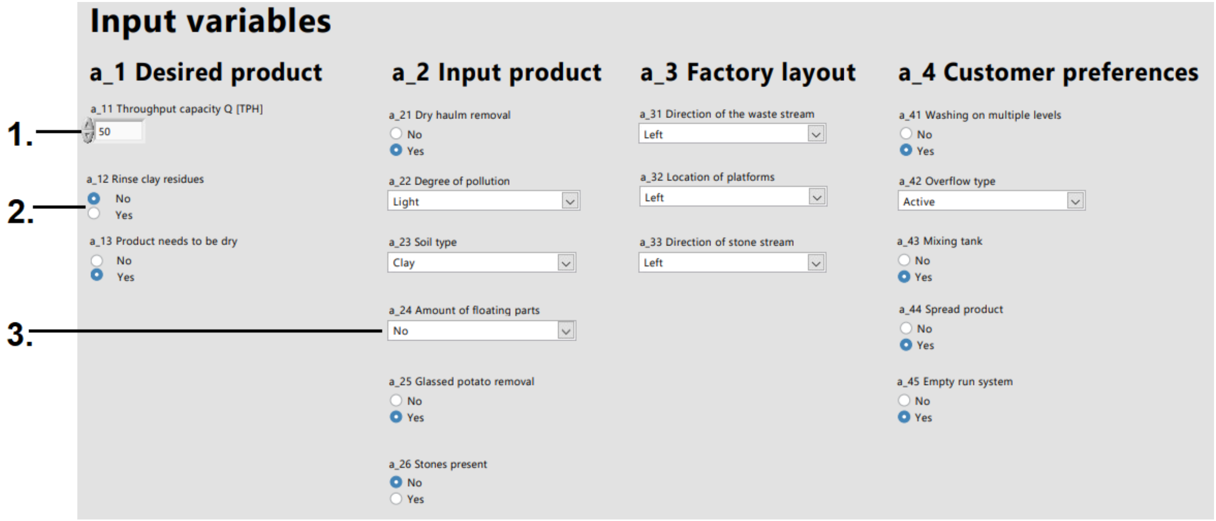
(a) $Q = 100TPH$ setup with 2x RD-600-28x2. (b) $Q = 200TPH$ setup with 4x RD-600-28x2.

Figure 33: Configuration with multiple roller dryers.

4.9 Constructing the model

There are multiple software tools that can be used to construct a basic version of the model for modular design of the washing lines. High-level, general-purpose programming languages like Matlab or Python can be used to make a simple text based model. The input parameters then have to be defined and loaded into the script which results in a set of output parameters which are also defined in lists. A way more interactive, visually attractive and easy to use software to construct this model is LabView. LabView works with two windows, one is a panel where all the input parameters can be filled in and the output parameters are shown and the other is a visual programming window. This visual programming window shows the structure of a graphical block diagram, the LabView-source code, on which different function-nodes can be connected by drawing wires. This way the data flow is used as a programming language. Using a visual instead of a text based modelling software for this first basic model, enables the programmer to do test runs while programming to check if the model gives the right outputs with respect to the filled in parameters. The visual panel for the LabView-source code shows the different inputs needed for each function node and highlights modelling errors in real time, this eases working with the software for inexperienced programmers. The model as described in this section constructed in LabView can be found in appendix L where figure 73 shows the panel with the in- and outputs and figure 74 shows the LabView-source code. This model can be seen as a configurator that as previously discussed can be used to configure washing lines according to customer and application specifics. Because this LabView model only shows the amount and type of machines recommended according to the filled in input parameters, a more advanced model is still recommended to be created in CPQ software to get all functionality described in section 4.11.

To construct the model, first all the parameters are defined in the parameter panel which is shown in figure 34 below, the numbers in the text correspond to the numbers in the figure. Figure 34a below shows the input variables. The input variables are created out of different tiles: numeric control tiles (1), boolean tiles (2) and system ring tiles (3). Figure 34b below shows the output variables. The output variables are created out of a gauge tile (4) for the calculation capacity Q_C and multiple string indicator tiles for the machine line configuration b. In the output section of the panel, the number of machines, specifications and potential options that are recommended by the model are shown.



Input variables

a_1 Desired product

a_11 Throughput capacity Q [TPH]: 50

a_12 Rinse clay residues
● No
○ Yes

a_13 Product needs to be dry
○ No
● Yes

a_2 Input product

a_21 Dry haulm removal
○ No
● Yes

a_22 Degree of pollution: Light

a_23 Soil type: Clay

a_24 Amount of floating parts: No

a_25 Glassed potato removal
○ No
● Yes

a_26 Stones present
● No
○ Yes

a_3 Factory layout

a_31 Direction of the waste stream: Left

a_32 Location of platforms: Left

a_33 Direction of stone stream: Left

a_4 Customer preferences

a_41 Washing on multiple levels
○ No
● Yes

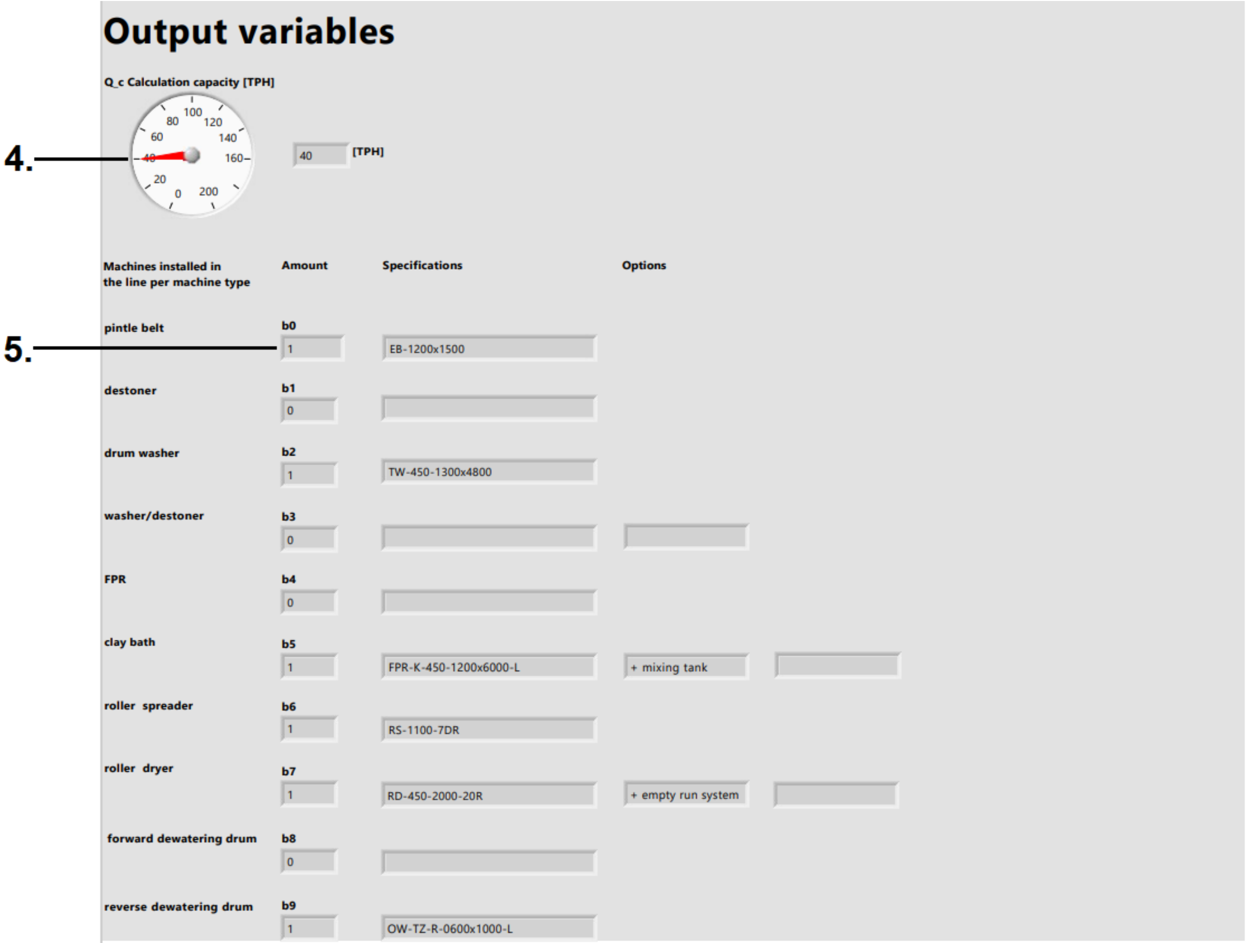
a_42 Overflow type: Active

a_43 Mixing tank
○ No
● Yes

a_44 Spread product
○ No
● Yes

a_45 Empty run system
○ No
● Yes

(a) Input variables.



Output variables

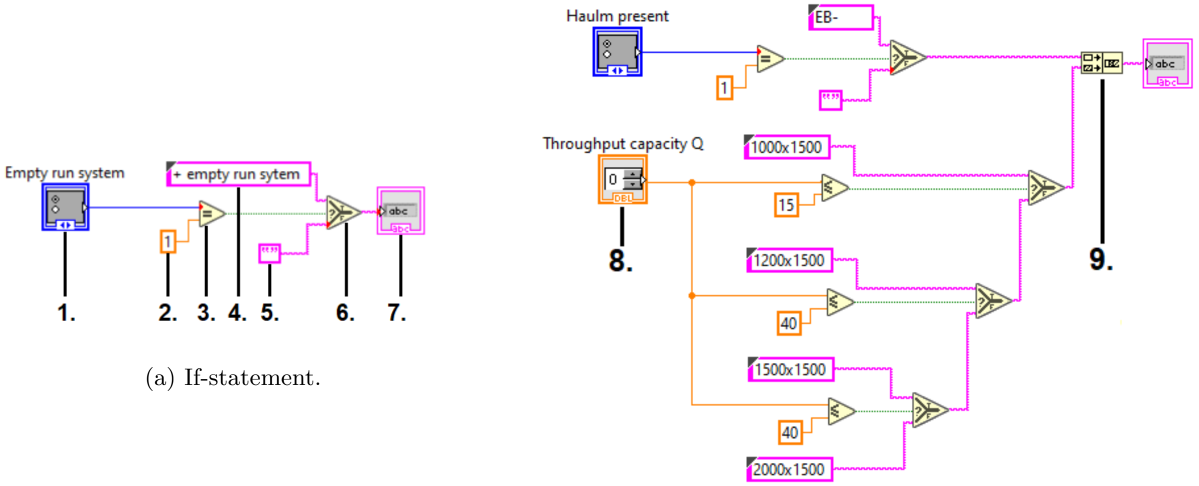
Q_c Calculation capacity [TPH]: 40 [TPH]

Machines installed in the line per machine type	Amount	Specifications	Options	
pintle belt	b0: 1	EB-1200x1500		
destoner	b1: 0			
drum washer	b2: 1	TW-450-1300x4800		
washer/destoner	b3: 0			
FPR	b4: 0			
clay bath	b5: 1	FPR-K-450-1200x6000-L	+ mixing tank	
roller spreader	b6: 1	RS-1100-7DR		
roller dryer	b7: 1	RD-450-2000-20R	+ empty run system	
forward dewatering drum	b8: 0			
reverse dewatering drum	b9: 1	OW-TZ-R-0600x1000-L		

(b) Output variables.

Figure 34: LabView panel where the parameters are defined.

After all parameters are defined, the relations between them are defined in the LabView-source code, of which a full version can be found in figure 74 in appendix L. This source code is a very complex diagram that connects all the input and output parameters and defines the logic between them. This complex model is well structured and build up out of many different if-statements to define the corresponding output for every possible combination of input parameters. An overview with the basic programming structures used in the LabView model is shown below in figure 35. Figure 35a shows an example of how such an if-statement is programmed, the numbers in the text correspond to the numbers in the figure. The input parameter (1) is connected to an 'equal' tile (3). This tile compares the value of the input parameter with the value of the numeric constant (2) and gives a boolean value for the corresponding conclusion. The 'select' tile (6) then checks if this boolean value is true or false. If true, the output of the 'select' tile will be the text defined in the string constant (4), if false the output will be an empty string constant (5). According to this example, if the customer wishes an empty run system to be installed in the roller dryer, the empty run system is added as an option in the output parameters and otherwise the option is left blank. A set of if-statements can be formed by connecting the output of a second if-statement to the 'false' node of the 'select' tile of the first if-statement. An example of such a set is shown in figure 35b below. An if-statement is connected to a 'string combiner' tile (9), this way the machine code that describes the machine specifics can be generated. If haulm is indicated to be present in the input parameters, the machine code is started with 'EB-'. According to the value filled in for the throughput capacity Q in the numbers list tile (8), the right machine size is then selected and added to the machine code. Boundary conditions can be specified for the input parameter tiles. This way for example the throughput capacity can be set to be an integer value between 0 and 180 TPH.



(a) If-statement.

(b) Set of if-statements.

Figure 35: LabView source code examples.

When the model is set up as a complex combination of these if-statements and describes all possible input combinations, it can be iteratively checked and improved. To do this, multiple different situation examples are used. For each example a list of input parameters is determined after which the complete selection chart in figure 77 in appendix K is followed to construct a machine line. Then the same input parameters are filled into the LabView model, after which the model is ran. If the machine lines coming out of the model differ from that coming out of the choice scheme, the model is improved until it gives the correct machine line recommendations for all examples. The basic machine line configuration model is then finished.

4.10 Model application examples

In this section the modular design strategies for machine lines and individual machines, which are set out in the previous sections and incorporated in the LabView model, are applied into real world examples. The examples are based on machine lines that are actually sold by Tummers in the past. Most of the machine lines are visited to see the line in practice and speak to the operator about its functioning, information about the other lines is retrieved from the engineers that designed the line and sales representatives that sold it to the customer. To check the model, the examples will be considered as future sales and the machine line configuration that results from following the model is compared to the machine line that was sold in practice. Both the decision scheme describing the jigsaw puzzle model and the LabView model are used to determine the machine line configuration according to the model for each different application example.

4.10.1 Belgian fries and rösti factory

In Belgium a potato washing line will be sold to a big potato processing company. The washing line has to be build alongside an existing washing line in a special potato washing location. From this location the clean potatoes are supplied to a french fries factory on the other side of a road. After a few years of operation a second factory needs to be supplied from the washing location, this factory produces rösti rounds. Just like the existing washing line, the new line needs to be able to process a maximum of $Q = 90TPH$. Depending on the season, the input product may contain glassed potatoes and large amounts of dirt, clods and haulm. The input product also contains medium amounts of stones and floating debris other than haulm. The potatoes are grown in soils consisting out of clay and/or sand. The platforms are to be placed on the right and the waste streams need to be directed to the left side of the machine line. The washing line will be fed from a set of potato bunkers containing potatoes in different sizes and qualities. These bunkers on their turn are filled by a storage line that contains a dry desoiler and large parts remover among others. The potatoes are washed on a single water level [9].

Figure 77, 82 and 87 in appendix O show a filled in choice scheme for configuration of the machine line in this example, a floor plan for the line as it is sold to the customer and the in- and outputs of the LabView model. The white machine line in the right part of the figure is the existing line and the coloured one represents the new line. The product enters the line via the belt conveyors in the top right corner of the figure and leave the line through the roller dryers at the bottom. The filled in choice scheme will now be explained. Simple choices that are directly based on the conditions given in the introduction above will not be explained in further detail.

Because of the heavy pollution and mixed soil, the calculation capacity equals $Q = 90 \cdot 1.2 = 108TPH$. The first choice in the scheme is for placement of a dry pintle belt. Because the existing washing line does not contain a pintle belt for dry haulm removal before the washer, this is also not added in the new line. If a pintle belt for dry haulm removal needs to be added to the line, this can be added in the storage line that is prior to the washing lines.

The belt that feeds the washing line comes into the building through the top of the left wall, this leads to the destoner being fed from the left side. This floor plan leaves enough room for the stone belt to be backward oriented. From the back the stones are transported out of the building by a transport belt that is oriented to the left. Because the platforms are located to the right of the machine line, the motor of the destoner is preferred to be installed on the right side. This way mechanics are able to reach the motor in an easy way to conduct inspections and maintenance. Because of the rösti factory that has to be supplied in the future, the calculation capacity is enlarged by 20%, which leads to the choice for a KW-700 washer with an elongated drum. The washer is equipped with a manual overflow system because the potatoes are washed on a single water level.

A mixing tank to feed the clay bath is unnecessary because it can be fed out of the same tank the clay bath in the existing line is fed out of. To rinse the clay from the tubers, a shower conveyor is added after the clay bath.

The potatoes need to be dried before transporting them to the factory because they are stored in a set of bunkers before being processed into fries. When the potatoes would be stored in the bunkers in wet state, they would begin to rot. Because of this, a roller spreader and roller dryer need to be implemented in the line. The roller spreader first dewaters the potatoes when they come out of the clay bath after which the remaining moist is removed by the roller dryers. An empty run system has to be installed to remove the potatoes from the roller dryer when a batch of a different quality or with a different tuber size is processed [15].

Table 11 below shows one list of the machines that are recommended by the model and one of the machines that are installed in the exemplary washing line. The machines are listed according to their appearance in the washing line. Table 12 shows the CTO changes that are made to the recommended model and the ETO needed to complete the washing line.

Machine	Recommended model	Ordered model
Destoner/washer	KW-700-2000x6250-A-DDSL-OH	KW-700-2000x6250-A-DDSL-OH
Dewatering drum	OW-TZ-F-0800x1150-L	OW-TZ-F-0800x1150-L
Pintle belt	EB-2000x1500	EB-2000x1500
Clay bath	FPR-K-600-1400x8200-L	FPR-K-600-1400x8200-L
	Mixing tank	Mixing tank
	Shower conveyor	No shower conveyor
Product stream divider	Dividing chute	Flume system
Roller spreader	2x RS-1900-7DR	2x RS-2000-7R
Roller drier	2x RD-600-2000-28R-LD	2x RD-600-2000-28R-LD

Table 11: List of machines to be installed in the first exemplary washing line with a capacity of $90TPH$.

Machine	Recommended model	CTO changes	ETO changes
Destoner/washer	KW-700-2000x6250-A-DDSL-OH		
Dewatering drum	OW-TZ-F-0800x1150-L		
Pintle belt	EB-2000x1500		
Clay bath	FPR-K-600-1400x8200-L		
	Shower conveyor	No shower conveyor	
Product stream divider	Dividing chute		Flume system
Roller spreader	2x RS-1900-7DR	2x RS-2000-7R	
Roller drier	2x RD-600-2000-28R-LD		

Table 12: List of changes to the recommended model for the first exemplary washing line.

As can be seen in the table above, most of the machine line ordered by the customer equals the recommended machine line. Because the modular configuration software enables the customer to replace recommended modules with other standardised modules, only a small part of the line has to be ETO. Below the parts of the machine line ordered by the customer that differ from the recommended models are explained.

The washing line is built along the right wall of the building with the waste streams directed to the left. Because of this, the two roller spreaders and roller dryers do not fit in the standard setup. To be able to place the two roller spreaders and roller dryers more to the left while dividing the product stream equally into two, a flume system is installed in the line. A benefit of the flume system is that residual clay from the clay bath is rinsed from the potatoes. This makes placement of a shower conveyor redundant. Because the flume system has to be designed customer specifically, this part of the structure is considered as ETO and comes with extra costs [9].

Because this machine line is ordered before the new delta-roller spreader was developed, a roller spreader with octagonal rollers in installed. This roller spreader is wider than the recommended standard delta roller spreader.

4.10.2 Belgian fresh packer for organic potatoes

In Belgium a potato washing line will be sold to a company that produces fresh packs that are sold in supermarkets. The line is placed next to an existing potato processing line produced by a competitor called Grisnich. The new washing line will for 40% of the time be used to process organic potatoes. The maximum capacity the line needs to be able to process is $Q = 20TPH$. For the washing of the potatoes rainwater is used. The water in the machines is to be refreshed on a daily basis. The washer only has to be able to wash the potatoes on a single water level. Glassed potatoes are not required to be removed from the product stream. Product batches contain medium amounts of stones, dirt and clods and small amounts of haulm and other floating debris. The potatoes are grown in soils consisting out of clay and/or sand. The platforms are to be placed on the left and the waste streams need to be directed to the right side of the machine line. The washing line will be fed from a set of potato bunkers containing potatoes in different sizes and qualities. After being washed, the potatoes are stored for a maximum of three days before being packaged [115].

Figure 78, 83 and 88 in appendix O show a filled in choice scheme for configuration of the machine line in this example, a floor plan for the line as it is sold to the customer and the in- and outputs of the LabView model. The machine line in the left of the figure is the washing line made by Tummers. The product enters the machine line in the destoner at the bottom of the figure and leaves through the roller dryer at the top. The machine line right of the Tummers line is the water treatment system. The green part of the figure represents the platform next to the machine line. The filled in choice scheme will now be explained. Simple choices that are directly based on the conditions given in the introduction above will not be explained in further detail.

Because of the normal pollution and the mixed soil, the calculation capacity equals $Q = 20TPH$. The first machine choice in the scheme is if a pintle belt has to be installed for dry haulm removal. Just like in the previous example, there are no extensive amounts of haulm present in the washing line and the other washing line has no pintle belt installed in front of the washer. If a machine would be installed for dry haulm removal it would be in the storage line, but due to the small amount of haulm this is unnecessary.

The machine line is built on the left of the Grisnich line. This line has waste streams oriented to the left and the waste of the new line is directed to the right. The platforms are build on the left side of the line. The washer/destoner is build accordingly with a destoner motor located on the right side and stone and floating debris belts oriented to the left. To be able to remove debris from the waste water stream of both the Tummers and the Grisnich line, a bigger dewatering drum is chosen to be installed [115].

The potatoes need to be stored in a bunker for three days before being packaged. Afterwards the potatoes are packaged in fresh packs to be sold in the supermarket. Because of those two reasons, the product needs to be dried from all remaining moisture. This is done by a roller dryer. The potatoes go through the integrated FPR after being washed, a roller spreader is not needed because the product is already spread out over the width of the output belt quite evenly. The roller dryer is equipped with an empty run system to clean the machine between the washing of batches with different tuber sizes and qualities [115].

Table 13 below shows one list of the machines that are recommended by the model and one of the machines that are installed in the exemplary washing line. The machines are listed according to their appearance in the washing line. Table 14 shows the CTO changes that are made to the recommended model and the ETO needed to complete the washing line.

Machine	**Recommended model**	**Ordered model**
Destoner/washer	KW-450-1300x3650-L-DDSL	KW-450-1300x3650-L-DDSL
Second washer	-	TW-N-450-1300x3650-DDSL
Roller spreader	RS-0900-7DR	-
Roller drier	RD-450-1500-20R-LD	RD-450-1500-20R-LD-UV
Dewatering drum	OTZ-R-0600x1000-L	OTZ-R-0800x1150-L

Table 13: List of machines to be installed in the second exemplary washing line with a capacity of $20TPH$.

Machine	**Recommended model**	**CTO changes**	**ETO changes**
Destoner/washer	KW-450-1300x3650-L-DDSL		
Second washer		TW-N-450-1300x3650-DDSL	
Roller spreader	RS-0900-7DR	No spreader	
Roller drier	RD-450-1500-20R-LD		+UV
Dewatering drum	OTZ-R-0600x1000-L	OTZ-R-0800x1150-L	

Table 14: List of changes to the recommended model for the second exemplary washing line.

As can be seen in the table above, the machine line sold to the customer differs from the recommended washing line because it consists out of two more machines. The addition of the extra washer is caused by the fact that the potatoes are sold as high quality organic potatoes. Because of this the customer wants to clean them very thoroughly by adding a second washer in the machine line. This washers is a CTO model which can be chosen by the customer from the standard modules in the modular design software. The dewatering drum sold to the customer is not for dewatering the floating parts coming from the integrated FPR as discussed in section 3.3.3. To make sure the product is evenly spread over the roller dryer when coming directly from the washer, a roller speader is recommended to be installed. Because this roller spreader was not developed yet when the line was sold to the customer, it is not implemented in the line [115].

The only part of this line that is sold as ETO are the UV lamps above the roller dryer. As previously described in section 3.3.10, UV lamps loose their ability to kill bacteria and viruses over time. Because bacteria and viruses in the product were less of a problem than the customer initially thought and new UV lamps are quite expensive, the customer stopped installing new UV lamps. This project is the only project in which Tummers has ever installed UV lamps [115].

4.10.3 Russian fries factory

In Russia a new factory will be build for producing french fries for the Russian market. With the build of this factory the Russians want to replace the import of foreign fries with their own. The washing line in this factory needs to be able to process up to $Q = 70TPH$ of potatoes. The factory will be build in the Tula region, that is known for its black soil, which is explained in section 4.2. Depending on the season, glassed potatoes and/or large amounts of haulm and other floating debris occur in the input product. The potatoes have a normal degree of pollution regarding stones, dirt and clods. The machine line is positioned with the stone belt to the left, floating waste streams to the right and the platforms located at the left side. This factory is ordered to be build from scratch in 2022. The customer wants to build a modern automated washing line that is able to wash at multiple levels. After the washing line the product will be rinsed and processed into fries directly without being temporarily stored in a bunker [42].

Figure 79, 84 and 89 in appendix H show a filled in choice scheme for configuration of the machine line in this example, a floor plan for the line as it is sold to the customer and the in- and outputs of the LabView model. The product enters the machine line at the destoner in the top of the figure and leaves from the output belt of the clay bath at the bottom. The green part of the figure represents the platforms installed next to the machine line. The filled in choice scheme will now be explained. Simple choices that are directly based on the conditions given in the introduction above will not be explained in further detail.

Because of the normal pollution and the presence of black soil, the calculation capacity equals $Q = 70 \cdot 1.2 = 84TPH$.

To automate the washing line as much as possible, an active overflow system is placed that enables washing on different levels by the push of a button. The clay bath is equipped with a mixing tank. The clay level in the clay bath is measured and if this clay level is too low, fresh clay mixture is pumped into the clay bath from the mixing tank. The mixing tank is also equipped with a sensor to measure the clay level. This clay level can be raised by an auger that feeds clay from a hopper with a big-bag above it. This way only the big-bags of clay need to be replaced when empty, the rest of the clay system works autonomously via the computer system.

The tubers are rinsed from residual clay by spraying bars above the roller sorters that come after the washing line. These roller sorters with spraying bars are bought from a different company than Tummers because this customer wanted spraying bars that combine water and air flow to rinse the tubers more thoroughly. Because the tubers are processed immediately after leaving the washing and sorting line, they do not need to be dried.

Table 15 below shows one list of the machines that are recommended by the model and one of the machines that are installed in the exemplary washing line. The recommended machines are listed according to their suggested appearance in the washing line, this does not apply to the ordered machines. Table 16 shows the CTO changes that are made to the recommended model and the ETO needed to complete the washing line.

Machine	Recommended model	Ordered model
Destoner/washer	KW-700-2000x5000-L-DDSR-OA	KW-700-2000x5000-L-DDSR-OA
Dewatering drum	OW-TZ-F-0800x1150-R	OW-TZ-F-0800x1150-R
Pintle belt	EB-2000x1500	EB-1500x1500
Clay bath	FPR-K-600-1400x8200-R	FPR-K-600-1400x8200-R
	Mixing tank	Mixing tank
FPR	FPR-V-700-1600x4000-R	FPR-V-700-1600x4000-R

Table 15: List of machines to be installed in the third exemplary washing line with a capacity of $70TPH$.

Machine	Recommended model	CTO changes	ETO changes
Destoner/washer	KW-700-2000x5000-L-DDSR-OA		
Dewatering drum	OW-TZ-F-0800x1150-R		
Pintle belt	EB-2000x1500	EB-1500x1500	
Clay bath	FPR-K-600-1400x8200-R		
	Mixing tank		
FPR	FPR-V-700-1600x4000-R		

Table 16: List of changes to the recommended model for the third exemplary washing line.

The customer of this washing line is a multinational company that already has multiple operational factories in other countries. This new Russian fries factory is built as a replica of an existing fries factory in Belgium. The factory in Belgium is built in the time that Tummers only supplied pintle belts with widths of $w_b = 1000mm$, $w_b = 1200mm$ and $w_b = 1500mm$, therefore the EB-2000x1500 is not installed in this line. Because the smaller pintle belt did a good job in the Belgian factory, it is also chosen by the customer to be installed in the new Russian factory.

The most common order of placing the machines in a washing line is to place the clay bath before the FPR. This way the last remainders of clay are washed from the product before being dried. Some customers, like the one in this example regularly experience a lot of floating debris in their product and therefore want to place the FPR before the clay bath. This way the haulm and other floating debris are first retrieved ($\rho < 997kg/m^3$), this waste goes onto the biodegradable waste pile. Afterwards the waste that floats on the clay mixture is removed from the product stream ($997kg/m^3 < \rho < 1300kg/m^3$), these are the glassed potatoes which are used as animal feed. If lots of inedible floating debris end up in this waste stream, when the clay bath is placed in front of the FPR, this waste pile becomes unsuitable to be used as animal feed. For this customer all machines can be chosen from the modules that are available, no ETO is needed to design this washing line [15].

4.10.4 Brazilian fries factory

In Brazil a washing line is needed to feed a french fries factory. The machine line has to be able to process up to $Q = 80TPH$. The input product contains large amounts of dirt and large clods and stones but also corn cobs and stumps which are hard to remove as discussed in section 4. The amount of haulm is normal and glassed potatoes do not occur in the input product. Most potatoes are grown in the south of Brazil, because of the moderate climate [74]. About 6.5% of the soil in the south of Brazil is black soil, therefore the washing line has to be able to clean product grown in that [31, 18]. There is limited space in the length direction but more space in the width. The stones need to be removed in backward direction through a wall and the floating waste can be directed to the left of the machine line. Platforms are not needed in this project. After being washed the product is stored in bunkers for a few days before being processed into fries.

Figure 80, 85 and 90 in appendix O show a filled in choice scheme for configuration of the machine line in this example, a floor plan for the line as it is sold to the customer and the in- and outputs of the LabView model. The product is fed into the dry desoiler at the top right angle of the picture and leaves through the roller dryer at the bottom. The filled in choice scheme will now be explained. Simple choices that are directly based on the conditions given in the introduction above will not be explained in further detail.

Because of the heavy pollution and the presence of black soil, the calculation capacity equals $Q = 80 \cdot 1.2 \cdot 1.2 = 115.2TPH$. Because the corn cobs and stumps need to be removed from the product stream, a pintle belt for dry haulm removal is placed before the washer. There is limited space in the length direction of the factory floor, therefore the dry pintle belt is placed to the left of the washing line. The destoner is therefore fed from the left. To dispose of the stones through the wall, the destoner is equipped with a backward oriented stone belt. The floating waste leaves the machine line at the right side and the motor is installed at the left side. Because the corn cobs and stumps are not floating, the pollution degree is high but the amount of floating waste is normal. Because the customer does not regularly want to change the water level in the washer, a manual overflow FPR is installed to remove the floating debris to the left which is then separated from moisture by a dewatering drum. After the washer, the product goes over a second pintle belt to remove the remaining haulm, corn cobs and stumps. Glassed potatoes do not occur in the product stream, therefore the product is divided by a chute directly after the pintle belt. The two product streams each go over a roller dryer to remove moisture from the product because it has to stay in storage bunkers for a few days before being processed into fries. The product is already dewatered by the pintle belt but needs to be spread after the dividing chute, therefore a spreader is advised to be installed. The roller dryer is not equipped with an empty run system because the product batches are relatively big. When the product needs to be removed from the roller dryer this is done manually by the machine operator.

Table 17 below shows one list of the machines that are recommended by the model and one of the machines that are installed in the exemplary washing line. The machines are listed according to their appearance in the washing line.

Machine	**Recommended model**	**Ordered model**
Dry desoiler	-	DS-16x1200
Pintle belt	EB-2000x1500	EB-2000x1500
Destoner/washer	KW-700-2000x6250-A-DDSL-OH	KW-700-2000x6250-A-DDSL-OH
Dewatering drum	OW-TZ-F-0800x1150-L	OW-TZ-F-0800x1150-R
Pintle belt	EB-2000x1500	EB-2000x1500
Product stream divider	Dividing chute	-
Roller spreader	2x RS-1900-7DR	-
Roller drier	2x RD-600-2000-28R	RD-600-2000-28R

Table 17: List of machines to be installed in the fourth exemplary washing line with a capacity of $80TPH$.

Machine	**Recommended model**	**CTO changes**	**ETO changes**
Dry desoiler		DS-16x1200	
Pintle belt	EB-2000x1500		
Destoner/washer	KW-700-2000x6250-A-DDSL-OH		
Dewatering drum	OW-TZ-F-0800x1150-L	OW-TZ-F-0800x1150-R	
Pintle belt	EB-2000x1500		
Product stream divider	Dividing chute	No divider	
Roller spreader	2x RS-1900-7DR	No roller spreader	
Roller drier	2x RD-600-2000-28R	RD-600-2000-28R	

Table 18: List of machines to be installed in the fourth exemplary washing line.

To remove excessive loose dirt from the product stream before entering the washer, the customer wants to install a dry desoiler before the first pintle belt. This dry desoiler is not taken into the choice schemes but is part of the standard Tummers equipment. Therefore it can be added to the line as CTO. For logistical reasons, the haulm needs to be removed from the building at the left top angle of figure 85. Because of this, a right oriented dewatering drum is chosen instead of a left oriented one. The moisture extracted by the roller dryer flows down the haulm chute, it flushes away the waste that comes from the second pintle belt and the integrated FPR. Then it passes underneath the washer to feed the dewatering drum.

The potatoes are not packaged after being washed but only temporarily stored in a stainless steel bunker before being processed into fries. For this reason the product does not need to be perfectly dry. A single roller dryer can be installed instead of the recommended set of two roller dryers and a dividing chute. Because only a single roller dryer is installed without a dividing chute and the product is already dewatered, a roller spreader is not needed anymore. These changes in configuration can also be performed manually in the configuration software. For this specific project no ETO components are needed, except for the haulm chute.

4.10.5 Indian potato flake factory

In India a washing line will be sold to a company that produces potato flakes. The maximum capacity the line needs to be able to process is $Q = 9TPH$. The waste streams have to be oriented to the right and the motors can be installed on the left side of the machines. The input product contains medium amounts of stones and floating parts like haulm and small amounts of loose soil and clods. Dry removal of haulm is not needed and glassed potatoes do not occur. The vast majority of potatoes are grown in the northern half of India [68]. The soil in this part of the country consists mainly out of alluvial, red and black soil. Alluvial soil is formed as sediment from rivers and consists of a mixture of clay and sand [99]. To guarantee optimal washing quality, the washing line has to be able to wash the black soil from the product.

Figure 81, 86 and 91 in appendix O show a filled in choice scheme for configuration of the machine line in this example, a floor plan for the line as it is sold to the customer and the in- and outputs of the LabView model. The product is fed into the destoner at the top of the figure and leaves the washing line through the output belt at the bottom. The filled in choice scheme will now be explained. Simple choices that are directly based on the conditions given in the introduction above will not be explained in further detail.

Because of the light pollution and the presence of black soil, the calculation capacity equals $Q = 0.8 \cdot 1.2 \cdot 9 = 8.64TPH$. The input product contains only small amounts of floating debris, dirt and clods and washing on multiple levels is not needed. Therefore the customer only needs an integrated FPR and a pintle belt to remove the non floating haulm. Because the potatoes are processed into flakes directly after being washed without intermediate storage, they do not need to be dried.

Table 19 below shows one list of the machines that are recommended by the model and one of the machines that are installed in the exemplary washing line. The machines are listed according to their appearance in the washing line. Table 20 shows the CTO changes that are made to the recommended model and the ETO needed to complete the washing line.

Machine	**Recommended model**	**Ordered model**
Destoner/washer	KW-320-1000x2500-R-DDSR	KW-320-1000x2500-R-DDSR
Dewatering drum	OW-TZ-R-0600x1000-R	OW-TZ-R-0600x1000-R
Pintle belt	EB-1000x1500	EB-1000x1500

Table 19: List of machines to be installed in the fifth exemplary washing line with a capacity of $9TPH$.

Machine	**Recommended model**	**CTO changes**	**ETO changes**
Destoner/washer	KW-320-1000x2500-R-DDSR		
Dewatering drum	OW-TZ-R-0600x1000-R		
Pintle belt	EB-1000x1500		

Table 20: List of changes to the recommended model for the fifth exemplary washing line.

As can be seen in the table above, the recommended washing line perfectly equals the ordered washing line. CTO and ETO changes to the recommended line are not needed to design this washing line.

4.11 CPQ software implementation strategy

As previously described in section 2.1, CPQ software can be used to digitise modular design. All modules from the machine portfolio are defined in the CPQ software. For each module the corresponding parameters, KPIs, CAD model, parts list and price information is described. This information can automatically be retrieved from other software packages that are already used by the company. The most common software packages are compatible with the CPQ software through standard integrations. CAD models can for example be automatically loaded from SolidWorks or HiCAD and price information can be retrieved from ERP software like Ridder IQ or Dynamics 365. The CPQ software is programmed so that the user is able to answer a list of simple questions about the project. These questions follow the model that is previously described in section 4. To answer them, the user does not necessarily need to have a lot of technical knowledge. The questions regard the wants and needs of the customer and the constrains that apply to the project. The answers to these questions are then compared with the predefined parameters of the modules to define a recommended machine line. The user is presented with a three dimensional CAD representation of this machine line, the machine line characteristics, a list of the applied machine models and options and a rough quotation. The user is then able to tweak the answers to the questions asked by the software to generate different machine lines. When the answers are made definitive, the user is enabled to manually change the machine line configuration out of the available modules and add or remove options to the machines. When this is done, the user is shown the final design and quotation. The user can state if there are any customer specific wishes that are not included in the modular design and therefore are ETO. ETO will always stay available for customer specific wishes but comes with higher costs to keep the project profitable for Tummers and to discourage the customer to deviate from the standard modules. Key is for the company to ensure a comprehensive portfolio of machines and options so that ETO is kept to a minimum. Figure 36 below shows an illustration of how CPQ software works [92, 96].

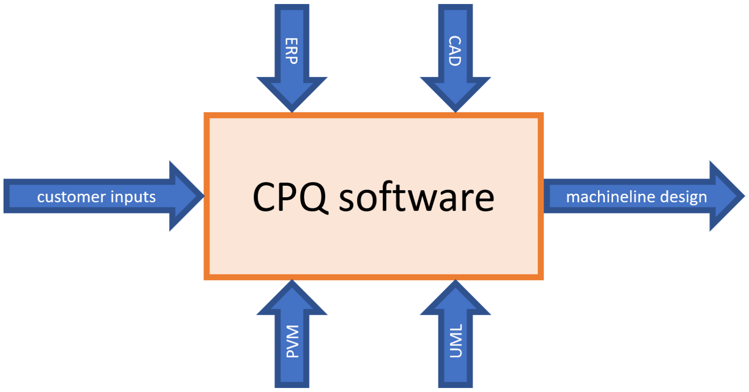


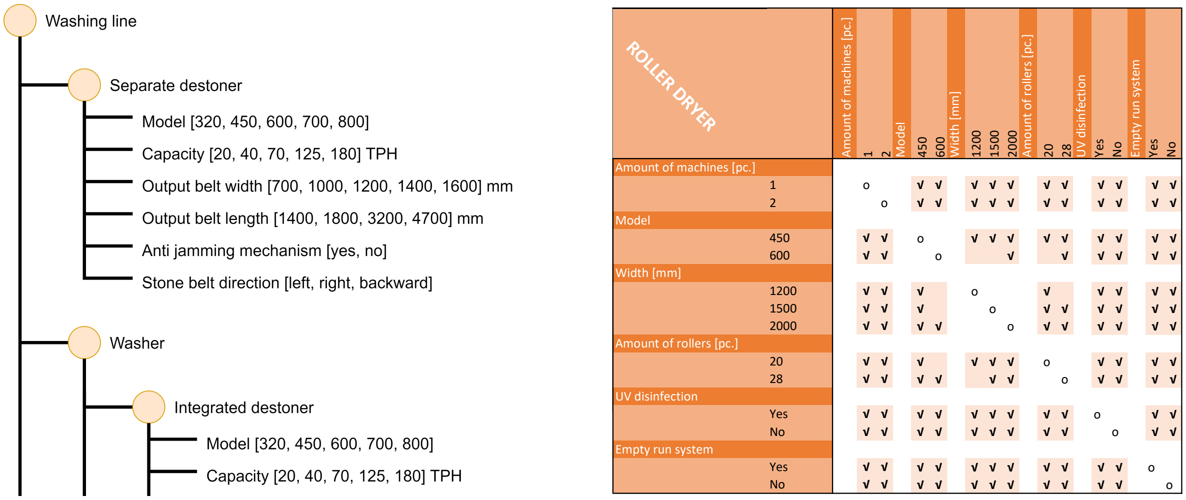
Figure 36: Illustration of how CPQ software works.

CPQ software is based on the method of parametric design. According to the method of parametric design, objects are shaped according to logarithmic processes. Parameters and rules between them determine which design follows up from which input parameters [116]. When modular design and parametric design are combined and automated, this leads to automated generation of design. In this method a parametric model can be used to determine which modules to combine into a final design. The creator of the model defines all the parameters, the available modules and the logic between them. The user is then enabled to generate a specific design by filling in the initial parameters. Although parametric modelling can be done through physical models or flow charts, parametric models nowadays are most commonly constructed in software packages. This can be either through a graphical or a text-based algorithm editor. An example of a text-based algorithm editor is Python. In a text-based algorithm editor a script is written. The script first describes the parameters, then the rules that form the logic on how the parameters relate to each other and ends in a set of lines that describe how to visualise the result. Text-based algorithm editors require knowledge of programming and enable the user to make a very specific model. Graphical algorithm editors require no programming knowledge and therefore are easier to get into. The most popular graphical algorithm editors are parametric CAD models. The CAD models are automatically generated based on the input parameters and the predetermined logic of the model. Engineering companies use parametric models to be able to quickly design a tailor made solution for a customer but parametric design is also used in architecture for example to design urban structures [100].

CPQ software works with a hierarchical approach within the company. Checks are build within the software to ensure standardisation and prevent miscommunications between different departments. When the sales department wants to configure a washing line that deviates from the standards for example, this order first has to be approved by a project engineer to ensure the design is technically feasible. Some users have more rights within the software than others, this way inexperienced users are prevented to make mistakes because they are checked by their superiors [29].

In an advanced level of implementation, the CPQ software is able to check the planning automatically through the ERP software. When an order is generated, the CPQ software checks the parts list against the inventory that is kept in the ERP software. When parts that are ordered are not in the inventory or reserved for other customers and their delivery time exceeds the time before they are needed in manufacturing, the delivery time for the washing line will be extended. Furthermore the hours that are needed to manufacture the different modules in the washing line are checked with the available personnel and the currently scheduled orders to further calculate the delivery time of the washing line [29].

Before implementing the CPQ software into the company, a proper understanding of the portfolio and selection methodology is needed. Therefore fist a Product Variant Master (PVM) has to be made. The PVM is a schematic hierarchical overview of all products and is used to visualise the product range. The PVM consists out of two parts. The left side of the PVM shows the different modules that occur in the portfolio in a hierarchical structure. The right side of the PVM shows the variable parameters of these modules and their different available options. An example to illustrate the PVM is shown in figure 37a below. This illustration only shows a small part of the complete PVM for the Tummers washing line portfolio. The complete PVM can be found in figure 47 in appendix D [40].



ROLLER DRYER	Amount of machines [pc.] 1	2	Model 450	600	Width [mm] 1200	1500	2000	Amount of rollers [pc.] 20	28	UV disinfection Yes	No	Empty run system Yes	No
Amount of machines [pc.]													
1	o		√	√	√	√	√	√	√	√	√	√	√
2		o	√	√	√	√	√	√	√	√	√	√	√
Model													
450	√	√	o		√	√	√	√	√	√	√	√	√
600	√	√		o			√		√	√	√	√	√
Width [mm]													
1200	√	√	√		o			√		√	√	√	√
1500	√	√	√			o		√	√	√	√	√	√
2000	√	√	√	√			o	√	√	√	√	√	√
Amount of rollers [pc.]													
20	√	√	√		√	√	√	o		√	√	√	√
28	√	√	√	√		√	√		o	√	√	√	√
UV disinfection													
Yes	√	√	√	√	√	√	√	√	√	o		√	√
No	√	√	√	√	√	√	√	√	√		o	√	√
Empty run system													
Yes	√	√	√	√	√	√	√	√	√	√	√	o	
No	√	√	√	√	√	√	√	√	√	√	√		o

(a) Part of the PVM of the Tummers washing line portfolio. (b) Product variant matrix for configuring a roller dryer.

Figure 37: Preparation before implementing the model in CPQ software.

After the PVM is constructed, the Product Variant Matrices have to be made. These matrices show which combinations of machine options can be combined and which can't. For this project a Product Variant Matrix is made for every individual machine and one for the washing lines that contains the machines with less detailed options to keep the overview clear. Figure 37b above shows an example of such a Product Variant Matrix. The combination of options that are available for the machines are indicated with a checkmark and the options that are unavailable are left blank. The set of Product Variant Matrices is added in appendix E.

To implement the model into the company and build the configurator, a dedicated employee is needed. When the implementation is laid on existing employees as a secondary task it has no priority and will be performed very slowly and sloppy. Therefore a dedicated employee needs to be hired part or full time to ensure a successful implementation of the modular approach.

There are multiple suitable strategies to use CPQ software for modular design of tuber washing lines. The most suitable strategy will be discussed in a three phase system. A logical path is for the company to first implement phase I, solve the teething problems that often come with implementing new technologies and then when the technology has proven itself after some time, move onto phase II and III consecutively.

4.11.1 Phase I

In the first phase the CPQ software is only implemented in house in the company. For the modular approach to work, it has to be implemented throughout all different departments of the organisation as described in section 2.1. In this phase, the sales department only uses the CPQ software in house to design the washing line. All previously described benefits of modular engineering apply. In addition to that, the differences in machine line configurations between different salesmen are reduced because every salesman uses the same configuration model. A necessary task that has to be performed before this implementation phase, is to re-do most of the CAD drawings. For the CPQ software to be able to generate 3D models, all CAD models need to be structured in the same way. If the CAD models are not structured similarly, the CPQ software is unable to exchange modules and automatically build up an assembly. Because Tummers has changed from using Hicad as CAD software to using SolidWorks, all models need to be re-done already so this will not lead to a lot of extra work. From the existing detailed CAD models, simplified shell structures can be made. The CPQ software only needs models up to module level because parts lists can be retrieved from the ERP software. This reduces the computing time that is needed to generate a tailor made 3D model by the CPQ software significantly without losing any functionalities. For applications that require more detail, up to part level, the detailed CAD models can be used. For this implementation phase a CPQ license for five people of the sales office staff is needed.

4.11.2 Phase II

In the second phase, the CPQ software is introduced to the customers. The salesman takes a tablet or laptop with him when visiting the customer for the first time. During the first consult the wants and needs of the customer and the relevant boundary conditions for the washing line design are discussed and defined in the CPQ software on the tablet. The customer is then included in the process. After the questions are answered and a first recommended model for the washing line is presented, the model can be tweeked by changing the answers to the questions or adjusted manually by changing the machine line configuration out of the set of predefined modules and options. Because the customer is included in the process, miscommunication between salesman and customer is prevented. Also the salesman is equipped with powerful information and visuals which help selling the machine line to the customer. Tummers works with a lot of regular customers that come back every few years for new projects. When everyone in the company is accustomed to the software after phase I, the customers are familiarised with the software in phase II. For this implementation phase an additional CPQ license for five people of the field staff of the sales office is needed.

4.11.3 Phase III

In the third and final phase, the CPQ software is made available in an online tool on the company website. The customer is then able to independently use the tool to configure a specialised washing line. The software tool is very easy to use and comes with clear instructions, still it is beneficial for the regular customers that they are already accustomed to the software with the help of a salesman in phase II. Through the software tool, the customer is supplied with specific and clear information, images and three dimensional models of the washing line they would like to order. When a customer wants to use the software tool, he first needs to fill in his contact information. If the customer has only used the tool without asking for a quotation and/or meeting with a salesman afterwards, the customer is automatically supplied with emails about the offer and can be called by the sales department after a few days. Because the customer sells himself the washing line by using the software, less work is needed from the sales department. When a meeting is held between the customer and a salesman after using the software, the customer knows better what he wants, which reduces miscommunications and other sales mistakes. The company gathers competitive advantage by implementing the software in an online tool and improving its professional image. Despite of that, customers can easily figure out what specific washing line they want and then buy it from a competitor. This can only be prevented by staying ahead of competition while offering top quality machines for a good price and developing unique machines. For this implementation phase an additional CPQ license for an online showroom is needed.

An analysis of the different relevant CPQ softwares and recommendation of which software to use for implementing modular design throughout the organisation of Tummers can be found in appendix C.

5 Smart washing line control

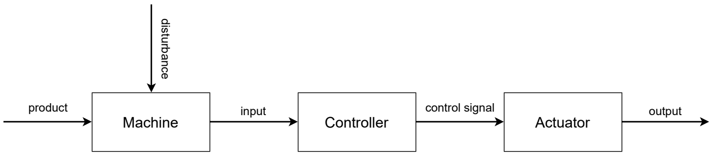
As previously discussed, different product batches come with different kinds and levels of pollution. Next to that different washing applications come with different requirements regarding the washing quality. Something important for every application is that the quality of the output product has to be constant and compliant with the standards. To make sure a constant washing quality is realised while processing different batches consecutively, machine operators are hired to keep an eye on the performance of the washing line, tweak settings of the machines and perform small maintenance jobs. Because of growing machine complexity, decreasing quality of machine operators and increasing possibilities for smart control, it would be advisory to install a network of sensors actuators and controllers to control the washing line in a smart way, realising an adaptive washing line. In this section control strategies will be discussed for the different machines in the washing line accompanied by control schemes for clarification. This section will form the basis for setting up a DT for smart control of the washing lines. A thorough analysis of which sensors to install for smart control of the washing line can be found in appendix Q. The total costs of installing the smart control system as described in this section lay around €122, 000. Appendix Q.11 shows a schematic overview of where each specific sensor is placed in the washing line.

As described in section 2.2, smart control has lots of benefits over manual control of the washing line. Sensors are installed in the different machines in the washing line to measure certain parameters that give important information about the functioning of the washing line, called KPIs. For each of the KPIs specific thresholds are determined. If the thresholds are breached, the system will know that action has to be taken to optimise the functioning of the machine. Algorithms in the CPS will calculate what needs to be done and the CPS sends the right output signals to the right actuators in the specific machine.

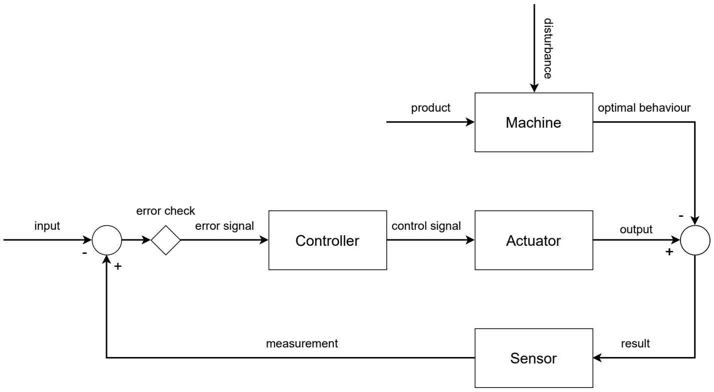
There are two types of control that can be applied to the machines. With open loop control the controller receives an input signal and then sends its output to actuators that make changes in the system. An example can be a transport conveyor that is fed with a certain product capacity Q. The controller then determines what belt speed v_b is needed for this capacity and sends a signal to the electric motor to power the conveyor. In a closed loop a sensor is built into the system. This sensor checks if the behaviour of the system fits the input signal. If the system behaviour deviates from the desired behaviour and therefore from the input signal, the controller is corrected. In the same example a proximity sensor for example can be placed above the conveyor belt to measure the height of the transported product. If the pile on the belt is too high the controller gets a signal to increase the belt speed. This process is repeated either continuous or discrete. In continuous control the control loop is repeated continuously and in discrete control it is repeated on an interval basis. The structure for both kinds of loops are shown in figure 38 below [6].

Important KPIs that are often used in feedback loops for processing lines are good-to-bad and bad-to-good ratios. The good-to-bad ratio defines the amount of suitable product that ends up in the waste stream. In case of the destoner this can be the amount of potatoes that end up on the stone belt. The bad-to-good ratio defines the amount of unsuitable product or waste that ends up in the product stream. In the same example this can be the amount of stones that remain in the product stream after the destoner. In smart systems these KPIs can be measured to analyse the functioning and efficiency of the machine line. Through feedback loops these KPIs are commonly used to detect malfunctioning of the line and correct the machine settings after sending the error signal to the controller.

In this section the smart control options for the machines in the Tummers washing line are discussed. The machines in washing lines can be equipped with multiple sensors to acquire data. The information obtained by these sensors is send to the central computer through a DAC device [124]. Sensors can for example be used to monitor performance, wear, production errors, safety issues and other deviations from the optimal functioning of the processing line. The sensors can be connected in different network topologies. The network topology is the way the network of sensors and routers is structured. For the washing line the tree-network is the best fitting topology, figure 39 below shows a schematic picture of this topology. Every machine contains multiple drive-system monitoring sets and all product belts contain a belt monitoring sensor. To keep the figure clear, these sensors are left out of the overview. For that same reason the valve blockage sensors are presented as one single sensor instead of one for every cone underneath the washer, the same applies for the flow meters. In this network structure, every sensor is connected to a sensor node and for each machine the sensor nodes are connected to a router. The machine routers on their turn are connected to the main router. The main router communicates with the server to store all data, which is connected with the computers in the control room and with the mobile devices of the machine operators and mechanics. Professionals from Tummers and Eltra, which make the software to control the washing lines, are able to log into this system via a secured Virtual Private Network (VPN) connection. One of the benefits of this network topology are that



(a) Open loop.



(b) Closed loop.

Figure 38: Two kinds of control schemes.

the network is very flexible and sizable, which is ideal for a modular washing line. The fact that the network is structured with a router per machine makes it possible to analyse the performance of individual machines. Downsides of this topology can be that it takes more cabling than other methods and that branches can be detached from the system when a router fails or when a connection is broken [118]. These problems however, can easily be solved. When the sensors and routers are connected through WLAN or internet connections, cabling can be reduced. When a router breaks down, the power is lost or the signal is blocked or interfered, the sensor can re-route to another router. This way a self-healing network is realised [81].

While researching smart design of the washing lines, the drum polisher, FPR, roller dryer and roller spreader are left out of the scope because they are simple machines that do not need to be controlled in a smart way and do not include wear sensitive parts that need to be checked for predictive maintenance. Both the roller spreader and roller dryer are left out of the scope for smart control because they have no settings that can be changed. The drum polisher is also left out of the scope for this section because it is just designed and needs to be tested further before it can be optimised with smart control.

5.1 Throughput

For a multi machine processing system to work, the input and output of all machines in the line need to be equal. This applies to the throughput of product but also to the throughput of dirt and water. If the input of a machine is bigger than the output, it will overflow after a while and if a machine has a bigger output, it will run empty over time. To prevent these events from happening the mass and/or volume flows between different parts of the machine line need to be monitored and controlled. The relations that set the basis for controlling the machines are described here and the sensors will be described later in appendix Q. It is also important to reduce the belt speed of the output belts in the different machines to a minimum. On the one hand to handle the product gently and on the other hand to reduce wear in the belts. The wear in the belt depends on a wide variety of factors and therefore a dynamical model is needed to predict it. The tension in the belt is constant because no variable tensioning system is installed. Because of this the belt wears out on the return side due to contact with the pulleys and rollers. Also the weight on the belt mainly influences wear of the rollers and not wear of the belt itself. Because of these points, the wear in the belt can be assumed to be linear with the amount of rotations. While reducing belt speeds to minimise wear of the

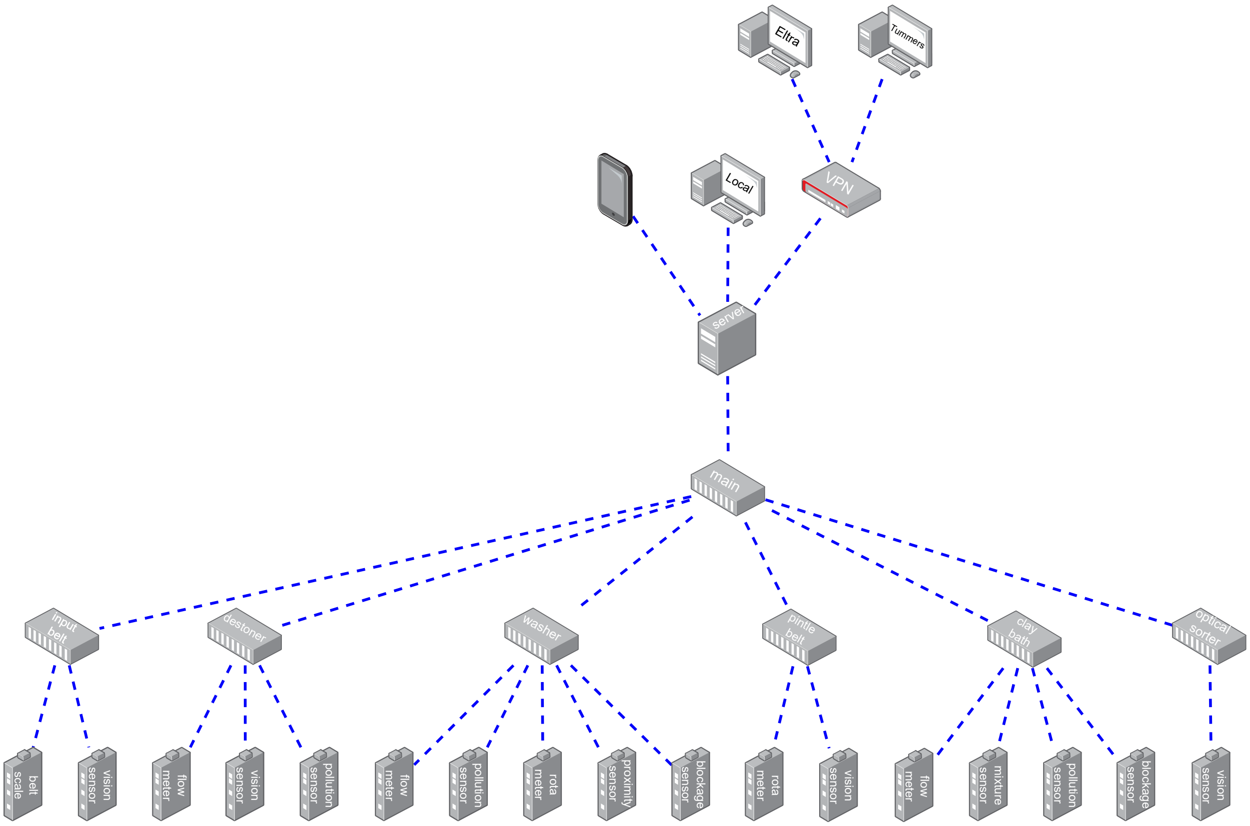


Figure 39: Topology for the washing line sensor network.

belts, the maximum load the belts are designed for has to be taken into account as well as spreading the product over the belt evenly for optimal performance of the machines in the washing line [125].

As previously described in section 2.2.2, flow charts can be used to visualise the different flows in the washing line. These flow charts can be combined with real time data to monitor the system. Figure **??** in appendix P shows a flow chart that represents an extensive washing line with all machines in the order which is recommended earlier. The data are an estimation based on customer tare calculations. The ovals represent material heaps of different kinds and the squares represent different machines in the washing line. The arrows in between are the material flows. The orange arrows represent product flows, the blue ones represent water flows, the yellow ones bio-waste and the brown ones represent dirt and stones. The steams between different machines never consist out of a single material because the efficiency of machines is never 100%. Waste particles that are hard remove stay in the product stream, water sticks to the product and dirt comes into the water flows. For this scheme the assumption is made that the machines have a 100% combined efficiency. While the amount of water ending up in the product, organic waste or inorganic waste heaps are very small, they are left out of consideration. As an approximation, the fresh water is added via the clay bath / brine separator.

The input of the system can be regulated through the speed of the input belt. The input belt that feeds the machine line has to be equipped with a belt scale or camera system to measure the throughput capacity of the washing line in real time. For most machines in the washing line the output of each machine depends on the width, angle and belt speed of the product belt. To get an even product flow, the output of each machine that uses an output belt can be regulated. This applies to the destoner, drum washer, FPR and brine separator / clay bath. All of those machines are commonly equipped with a bar belt for the output. This bar belt removes the product from the tank while letting the water leak through. Figure 40a below illustrates the important parameters of an output belt where (1) represents the product layer and (2) represents the bar belt. Figure 40b shows a free body diagram with the relevant forces. The output belts are installed in the machines at a fixed belt inclination θ, which differ per machine type and sometimes even per model. The belt speed to remove a certain product capacity from the machine depends on the inclination angle. The potatoes are assumed to form a single layer for optimal dewatering. The height of the product stream on the product belt is equal to the average product size, which for potatoes is the thickness h.

For belt inclinations smaller than the boundary angle θ_b the product will not roll down the slope of the output belt because the product has enough friction with the belt. This boundary angle can be calculated from the gravitational force F_G, friction F_S and normal force F_N which cancel each other out so there is no net resulting force F. This calculation is added in appendix N. The belt speed can then be calculated through equation 22 below. For all calculations throughout this section, the capacity Q will be in SI units, $[kg/s]$ instead of in $[TPH]$.

$$v_b = \frac{Q}{\rho_{p,bulk} h w} \qquad \text{if } F = 0,\ \ \theta \leq tan^{-1}(\mu_k^0),\ \ v_R = 0 \tag{22}$$

When the inclination angle exceeds the boundary angle, the product will start to roll down the slope of the output belt. The belt speed can then be calculated through equation 24 below. The kinematic friction coefficient μ_k, described in equation 23 below, decreases due to the increasing speed when the potato starts to roll. The decreasing friction coefficient lowers the friction and because gravity stays the same, a resulting force will create an acceleration down the slope. This way the speed will increase exponentially. Factors that are not taken into account here are the potatoes colliding with each other. Because of this the rolling speed can not easily be calculated and has to be determined through testing and/or modelling.

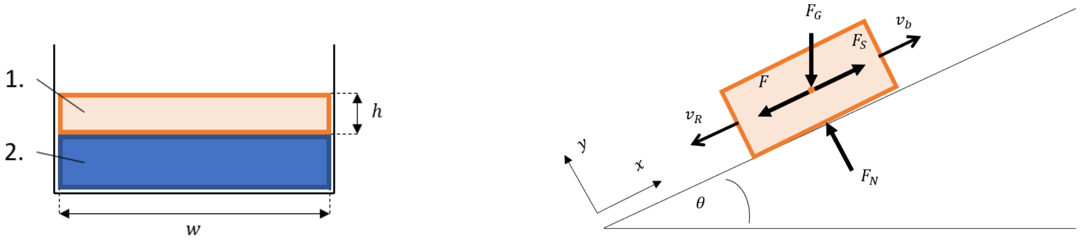
$$\mu_k = \mu_k^0 - c_\mu v_R \tag{23}$$

$$v_b = \frac{Q}{\rho_{p,bulk} h w} + v_R \qquad \text{if } F = 0,\ \ \theta > tan^{-1}(\mu_k^0),\ \ v_R > 0 \tag{24}$$

As can be seen in table 23 below, the belt inclinations are constant for most machines. For the destoners, the belt inclination is smaller for the bigger models. This is caused by the fact that the bigger models need a bigger tank, without the machine increasing in height. To realise this, the width and length of the tank need to be enlarged for bigger models. When the length of the tank increases and the height stays the same, the belt inclination decreases. For the brine separator / clay bath all models have the same belt inclination but the FPR-V-320. This is because the FPR-V-320 is not part of the standard machines and only produced as a special for a single customer that specifically asked for these parameters.

The initial kinematic friction coefficient μ_k^0 for potatoes on a bar belt is not described in literature yet. Nevertheless, Yurtlu et al. (2011) have researched the kinematic friction coefficients of potatoes on stainless steel which lays around $\mu_k^0 = 0.35$, depending on the potato variety [126]. This would lead to a boundary angle of $\theta_b = 19.3°$. Bar belts have way more grip on the potatoes than plain stainless steel plates and therefore come with a way higher kinematic friction coefficient. Because most product belts are equipped with cleats, the product is assumed not to slide or roll down the belt for any belt inclination and thus $\theta_b = 90°$. Because these cleats are relatively thin compared to the space in between them, their thickness is not taken into account. The belt speeds for the different machines and models are calculated through equation 24 and displayed in table 23 below, both for the original and the corrected capacity. The speed of the output belt can be automatically calculated from the machine parameters and the mass flow that is measured by the sensors in the belt that feeds the washing line and adjusted in real time by the DT. Higher belt speeds lead to increased wear and tear, therefore belt speeds are to be maintained as low as possible.

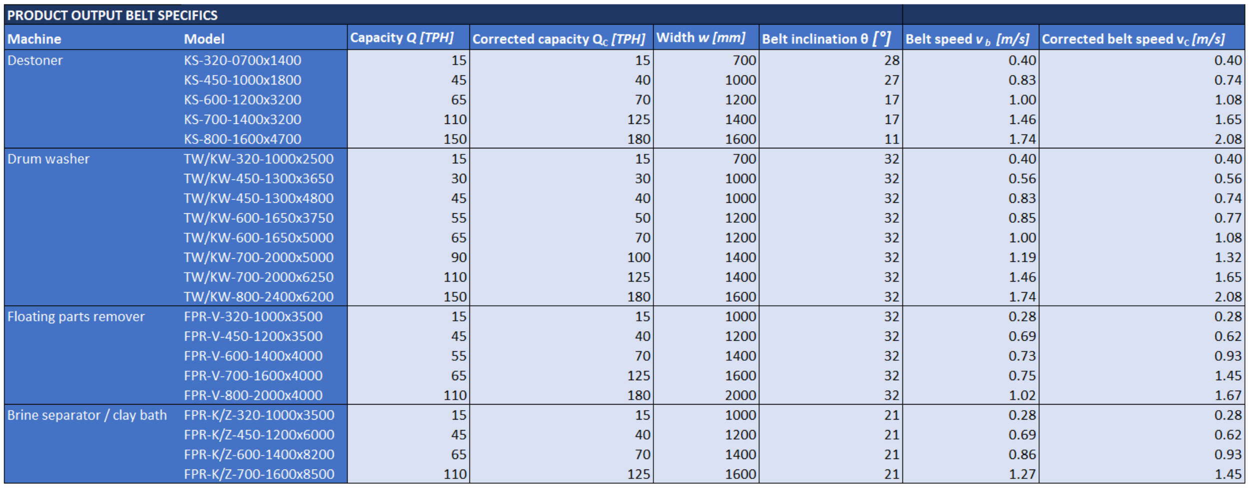
Another important reason to measure flows throughout the machine line is to check if the operator does not overload the system. Because Tummers machines are famous to be able to operate above their maximum capacity, customers often try to process bigger amounts of product than the machine line is built for. Even though the Tummers machines usually do not break down when operating above their maximum capacity, the wear in some parts of the machine increases significantly. An example of such a part are the toothed belts that wear out and break earlier when the machine is fed over its maximum capacity. Next to that the performance of the machines decrease. A destoner for example will let through more stones into the product stream when it is handling capacities that lay beyond its maximum. At larger throughputs, the stones do not get the time to sink to the bottom of the destoner tank and therefore end up in the washing drum. When the input of the washing line is measured it can be logged so that Tummers mechanics can log into the system to check for overloads when a customer experiences extensive wear or other machine malfunctioning.



(a) Intersection of the product belt.

(b) Free body diagram of product on a belt.

Figure 40: Schematic drawing of the product belt.



PRODUCT OUTPUT BELT SPECIFICS							
Machine	**Model**	**Capacity Q [TPH]**	**Corrected capacity Q_c [TPH]**	**Width w [mm]**	**Belt inclination θ [°]**	**Belt speed v_b [m/s]**	**Corrected belt speed v_c [m/s]**
Destoner	KS-320-0700x1400	15	15	700	28	0.40	0.40
	KS-450-1000x1800	45	40	1000	27	0.83	0.74
	KS-600-1200x3200	65	70	1200	17	1.00	1.08
	KS-700-1400x3200	110	125	1400	17	1.46	1.65
	KS-800-1600x4700	150	180	1600	11	1.74	2.08
Drum washer	TW/KW-320-1000x2500	15	15	700	32	0.40	0.40
	TW/KW-450-1300x3650	30	30	1000	32	0.56	0.56
	TW/KW-450-1300x4800	45	40	1000	32	0.83	0.74
	TW/KW-600-1650x3750	55	50	1200	32	0.85	0.77
	TW/KW-600-1650x5000	65	70	1200	32	1.00	1.08
	TW/KW-700-2000x5000	90	100	1400	32	1.19	1.32
	TW/KW-700-2000x6250	110	125	1400	32	1.46	1.65
	TW/KW-800-2400x6200	150	180	1600	32	1.74	2.08
Floating parts remover	FPR-V-320-1000x3500	15	15	1000	32	0.28	0.28
	FPR-V-450-1200x3500	45	40	1200	32	0.69	0.62
	FPR-V-600-1400x4000	55	70	1400	32	0.73	0.93
	FPR-V-700-1600x4000	65	125	1600	32	0.75	1.45
	FPR-V-800-2000x4000	110	180	2000	32	1.02	1.67
Brine separator / clay bath	FPR-K/Z-320-1000x3500	15	15	1000	21	0.28	0.28
	FPR-K/Z-450-1200x6000	45	40	1200	21	0.69	0.62
	FPR-K/Z-600-1400x8200	65	70	1400	21	0.86	0.93
	FPR-K/Z-700-1600x8500	110	125	1600	21	1.27	1.45

Table 23: Belt speed and corrected belt speed for different machines with different parameters [107, 102, 104, 105]

5.2 Optical sorters

Optical sorters are installed in almost every modern potato processing lines. Depending on the application of the processing line, multiple different optical sorters can be installed throughout different places in the machine line.

Processing lines for potato fresh packs often include an optical sorter between the washing and the packaging line. This optical sorter removes remainders of waste which the washing line failed to remove from the product stream like stones, haulm and clods but is also able to detect and remove rotten, disfigured, damaged or green potatoes which can not be removed by the washing line. Other waste particles that often pass through the washing line and therefore need to be removed by the optical sorter are bones, golf balls and pieces of wood or glass. Batches of potatoes that are grown on farmland near golf courses sometimes contain up to 300 golf balls per single batch. Pieces of metal, cardboard or plastic also sometimes end up in the machine line, for example when maintenance is performed. All these different categories of waste can de removed from the product stream by the optical sorter because of their visual differences with healthy potatoes.

The most basic optical sorters work with a monochrome vision sensor. This camera retrieves visual information in one single channel. It only detects the intensity of light and gives it a value that represents a grey value. Red Green Blue (RGB) vision sensors are able to measure in three different channels. Instead of only measuring grey values they are able to measure light intensity in three different wavelengths: red, green and blue and therefore are able to detect waste more efficiently [77]. Red Green Blue Infrared (RGBI) vision sensors measure on four different channels because they also measure light intensity in the infrared scope [34]. More advanced cameras are equipped with lasers next to the RGB vision sensor. With each laser they are able to measure on an extra wavelength up to a maximum total of fourteen channels. All these vision sensors are considered multi-spectral because they measure in less than twenty different channels. The newest technology is able to measure on more than twenty different channels and therefore considered hyper-spectral. Chemical Imaging Technology (CIT) is a sensor that is able to measure on 240 channels. This sensor analyses the chemical signature of the measured object independent of color, shape, surface or density. The data is not processed on single intensity points but on the first derivative of full spectra. Using the first derivative of the data prevents filth in the machine or change of product from causing problems during the separation. CIT uses Near Infrared (NIR) spectroscopy on different locations to get a three dimensional measurement. NIR spectroscopy uses infrared radiation to stimulate covalent bonds in mostly organic compounds. This way overtones and combination bonds are created in the fundamental vibrations of the molecules. These overtones and combination bonds are measured by the CIT sensor. [44].

One of the latest developments in optical sorting uses a combination of two RGB cameras and one CIT sensor to remove waste from the product stream. This sorter called the Sherlock Separator is a large single product sorter which can be used to sort potatoes and carrots among other foodstuff. Via thee way sorting foreign material and product that is unsuitable for processing can be separated from the product stream. Just like other optical sorters, the machine is supplied with the data that belong to the desired product and then take out every object that comes with a measurement that differs from that standard data. Next to separating waste from the product stream, this machine measures and logs the size and color defects of the product. This makes this separator ideal to be placed behind a peeling line. When too much skin is detected on the product the peeling time is increased and when no skin is detected at all the peeling time is reduced to ensure not too much of the product is wasted during the peeling process. The built in CIT sensor makes this machine ideal to be placed in a machine line that processes potatoes into fries. As previously described, glassed potatoes are not suitable to be processed into french fries. Because the chemical structure of glassed potatoes is different without the potatoes being visibly different, the Sherlock Separator is able to remove glassed potatoes which other optical sorters are unable to do. Next to glassed potatoes, potatoes with sugar ends are also unsuitable to be processed into fries. Potatoes with sugar ends contain high sugar contents in the outer layer of the tuber. When fried, these sugar ends burn and turn black. Because consumers do not want burned and discolored spots on their fries, potatoes with sugar ends need to be removed from the product stream before being fried. Sugar ends can only be detected after the potato is peeled because the high sugar contents lay beneath the peel. Because of seasonal high ratios of glassed potatoes and/or sugar ends, the optical sorter can not take out all of them. A clay bath still needs to be used to remove the majority of these defected potatoes. In contrast to other optical sorters the Sherlock Separator is also able to retrieve pieces of transparent materials like plastic or glass from the product stream, this comes in very handy in the Netherlands and in the West of Germany where music festivals are held on farm land. During the music festivals small liquor bottles end up in the soil and later in the product, when it is harvested. When the empty bottles do not contain a cap, they fill up with water and sink to the bottom of the destoner, FPR or clay bath to be removed from the product stream. If the caps are screwed back on the empty bottles they are not retrieved by the washing line and need to be removed by an optical sorter. Even though the Sherlock Separator is one of the best optical sorters available and guaranteed to remove over 98% of all waste particles it encounters, tuber processing lines that are not for high quality purposes still often include one of the more basic optical sorters. This is caused by the fact that the Sherlock Separator costs around €600,000, which is a very big investment for smaller or low quality tuber processing applications. The Sherlock Separator is able to process up to $Q = 80TPH$ [55].

Because of the high price, cheaper and less advanced optical sorters are used in factories that process lower capacities or for less advanced applications. Cheaper machines to detect and remove stones, clods, haulm, potatoes with clay caps and other waste can be bought for around €35,000. These optical sorters are equipped with RGB cameras and therefore are not able to detect glassed potatoes, potatoes with sugar ends and transparent plastics. For tuber processing factories in low income countries, manual separation of waste is still more profitable, both because of low wages as because employing locals comes with lots of secondary benefits like for example political ones [55].

Modern optical sorters keep log of all these statistics which can be monitored but also be used to get an insight into the functioning of the washing line. Some of the control strategies discussed below will make use of feedback loops based on the data obtained by the optical sorter.

5.3 Destoner

To be certain to get all the stones out of the stream, even the lighter and smaller ones, it is important for the product to stay in the tank as long as possible. Therefore the tubers are fed into the destoner on the opposite angle as where they enter the washing drum. For the same reason the propeller can be slowed down to a minimum until tubers are detected on the stone conveyor, then the propeller speed is raised a little to ensure optimal stone removal without tubers ending up in the waste stream.

When applying the destoner for industrial applications, it is better to transform the control of the destoner from manual to smart. A camera can be added to the stone belt that retrieves the stones from the bottom of the tank. If the camera detects potatoes on the stone belt, the system will slowly raise the speed of the propeller until no more potatoes are detected. When a certain threshold is breached in the stone detection rate of the optical sorter, the propeller speed is slowly lowered to ensure optimal stone removal until potatoes are detected on the stone belt again, this way a double feedback loop is implemented in the controls. When stones with a density similar to that of the product are encountered by the optical sorter, this feedback loop makes sure the propeller speed is not lowered too far. Also floating stones, lava rocks for example need to be identified separately by the optical sorter. When these kind of stones are detected the propeller speed does not have to be changed because they are lighter than potatoes and water and therefore can not be removed by the destoner but need to be removed by the FPR [23]. But there are more factors that play a role in the performance of a destoner. A parameter that can also be included in the control system is the density of the water in the destoner tank. Water that contains a lot of dirt is heavier than clean water and therefore has a bigger buoyant pressure on the stones and potatoes in the tank. A density sensor can be added in the tank to measure the pollution level, the control system can then take this information into account and lower the propeller speed when the water in the tank is strongly polluted or raise the speed for cleaner water [53]. This way a closed loop system is realised to control the machine. Another factor that plays a role is wear of the propeller. When the propeller wears out over time, more rotational speed is needed to generate the same amount of thrust. A wear detection method can be based on this phenomenon. When the propeller speed needed to power the destoner exceeds a certain threshold, the DT will show a warning to replace the propeller. Figure 42 below shows a control scheme for the destoner.

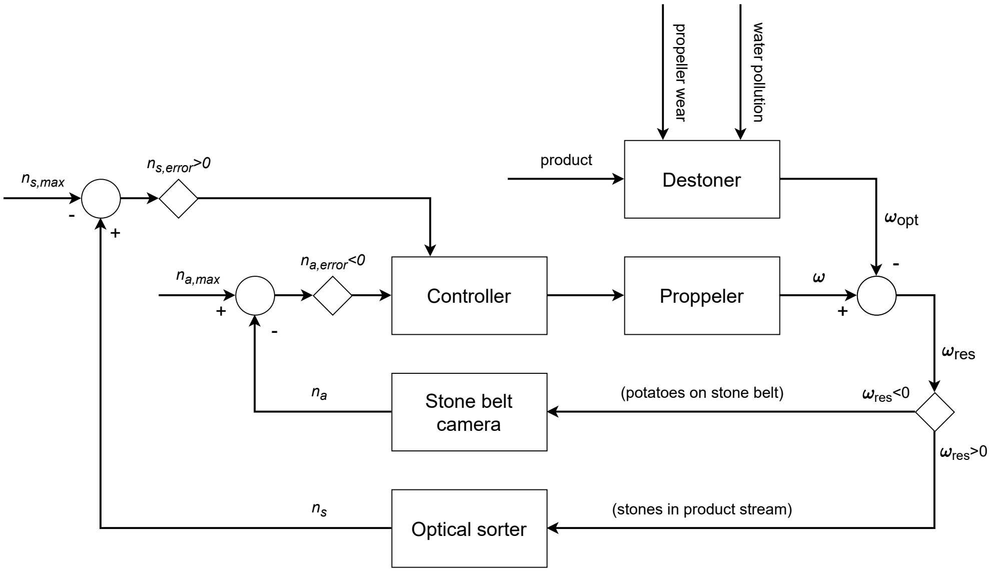


Figure 42: Control scheme for the destoner.

5.4 Drum washer

As previously discussed the drum washer is the machine that determines the vast majority of washing quality. The other machines in the washing line are mainly designed to remove waste, spread or dry the product. There are multiple settings of the washer that can be adjusted to make sure a consistent washing quality is realised while processing different batches of product with different levels of pollution. The KPI that has the biggest influence on the washing quality is the residence time t, which is discussed in section 3.2.

Some of the parameters that influence this residence time depend on the machine and therefore can not be changed during operation. These include the drum diameter d_d and length l_d. Each factory processes his own variety which keeps the density ρ_a quite constant. Nevertheless the potatoes come with different solid contents per batch and therefore slightly different product densities because the potatoes are grown in different arias that come with different growing conditions. Two batches of potatoes from the same variety that are grown next to each other can have big differences in solid contents due to for example difference in soil, rainfall, irrigation, pesticide treatments and fertilizers [65].

Other parameters that influence the residence time can be changed by the settings of the washer. The degree of filling $\phi = \frac{V_a}{V_w}$ is the ratio between the volume of the product and the water in the drum. This ratio can be changed by the settings of the dosing disk. If the dosing disk is lowered, the potatoes can leave the drum at a lower level and the degree of filling decreases. If the dosing disk is raised, the product leaves the drum at a higher level and the degree of filling increases. The position of the dosing disk is set by an electrical actuator. The water height $\ell = \frac{A_{filled}}{A_{tot}}$ is the ratio between the filled area and the total area in the cross section of the drum. This ratio can be adjusted by changing the water level in the washer. The water level is constant throughout the whole washer/destoner and integrated FPR. An overflow system consists out of two concentric pipes that determine this water level. To lower the water level the inner pipe can be lowered further down into the outer pipe and to raise the water level the inner pipe can be moved upwards. Obviously the residence time is also determined by the input capacity Q. This capacity can be changed by lowering the speed of the belt that feeds the product into the destoner.

If the product is not washed thoroughly enough, clay caps or other residual soil will keep sticking to the product. This has to be prevented at all times. Potatoes that are washed for the fresh packs need to look nice and clean when sold in transparent plastic bags in the grocery store but for most other processing applications the peel is removed from the potatoes and with it the remainders of soil. Because these remainders of soil pollute the felt rollers of the roller dryer and decrease the drying capacity of these felt rollers, remainders of soil lead to accelerated replacements of the felt. In the steam peelers that remove the peel from the potato and the conveyor belts throughout the rest of the peeling line, residual soil induces wear significantly. Therefore it is very important to ensure the minimum washing time needed to properly clean the potatoes is met. The optical sorter is able to detect residual soil like clay caps when the product is covered in dirt. This product will be discarded as animal feed. When the optical sorter detects too many filthy tubers n_c and the threshold is crossed, the residence time needs to be extended. This can be done by lowering the product input capacity, further closing the dosing disk or raising the water level. Which parameter to change depends on the product and the application of the line. When the product is for example grown in sandy soil, the water level needs to be raised to rinse more sand from the product. When clay caps stick to the product, the dosing disk can be closed further to enhance the rubbing effect between the tubers. If the water level or dosing disk are at their maximum position the speed of the product feeder belt will be decreased.

Next to the residence time, the pollution of the washing water is an important KPI for the washing drum. If the washing water is polluted with too much soil, the product will not be washed clean enough and the discharge valves underneath the washer can get clogged. A pollution sensor can be added into the different cones underneath the washing drum to detect the amount of soil in the water. If the water contains too much pollution, the discharge times t_s per individual valve can be lowered. When the pollution levels are low, the discharge times will slowly be raised to minimise the fresh water input needed to maintain the water level in the washer.

Via the logic which is described above, a double closed loop control system can be made. Figure 43 below shows the control scheme for smart control of the drum washer.

The rotational washing drum is powered by two motors at the head and tail of the drum. One of the two motors is acting as the master, this motor is fed by a frequency converter. The rotational frequency of this master motor is strictly copied by the other motor that acts as the slave and is also powered by a frequency converter. This way perfect rotation around the axis of the drum is guaranteed without any torsion of the drum. Because the frequency controllers are already in place, the rotational speed of the drum can easily be adjusted by the machine operator without the need to add additional sensors or actuators. For most industrial applications the motors are set on maximum speed to wash the product aggressively. For some washing line applications like for example when potatoes from a bruise sensitive variety are washed for the fresh pack industry, it is important for the machine operator to be able to lower the rotational speed of the washing drum to prevent the potatoes from getting damaged. Because the bruises do not show immediately on the potatoes but become visible over time, the optical sorter is not able to detect them. This, combined with the fact that the rotational speed of the drum only matters for very specific applications, leads to the fact that the rotational speed will be controlled manually instead of smart [23].

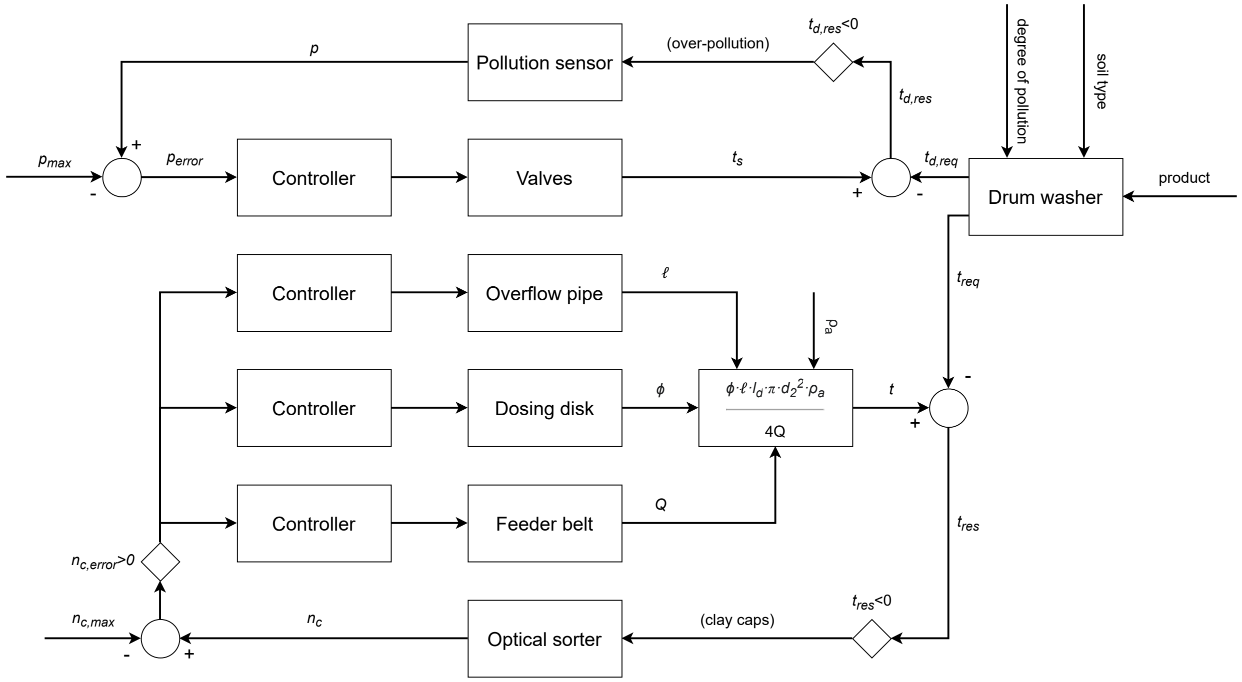


Figure 43: Control scheme for the drum washer.

5.5 Pintle belt

To remove as much haulm as possible without discarding potatoes on the haulm belt, the pintle belt has to be controlled in a smart way. The angle θ under which the pintle belt is positioned determines the performance of the machine and can be changed either manually with a steel cable winch or automatically with an electric motor. The product shape and capacity determines the rolling behaviour of the product. Potato varieties that for example produce very round potatoes, role down the slope more easily than very flat potatoes. If the belt is positioned too flat, the potatoes do not role down the slope of the belt nicely and get thrown over the barrier roller onto the haulm belt. When potatoes are detected on the haulm belt the controller needs to increase the angle. When the angle is too steep, the haulm stays in the product stream, falls down the slope and is not removed. When too much haulm, corn cobs, stumps or other plant waste is detected by the optical sorter that follows up after the washing line, the angle can be decreased. This way a double closed loop control system can be realised to optimize the performance of the pintle belt. Figure 44 below shows a schematic overview of the control strategy for the pintle belt.

5.6 Clay bath

Glassed potatoes but also rotten or hollow potatoes are not suitable for consumption. All these products are lighter than healthy potatoes and therefore can be removed by the clay bath if the density differs enough from that of healthy potatoes and from the clay solution. Because the density of the incoming product ρ_a, the throughput capacity Q and the glassed/healthy potato ratio differ per batch, the clay mixture ψ has to be changed based on the performance of the clay bath. Clay sticks to the product going trough the clay bath, therefore more clay needs to be added to the clay bath when high capacities are processed. On the other hand the product can still contain remainders of dirt when they enter the clay bath. When this dirt comes into the clay bath the density of the mixture increases and more fresh water has to be added. The input variable to determine the starting ratio of the clay bath is the underwater weight of the healthy and that of the glassed potatoes of the incoming batch. A sample is tested for every batch that comes into the factory. During these tests the glassed ratio and underwater weight of the healthy and glassed potatoes are determined. For every batch these measurements are used as the starting values for controlling the clay bath [23].

The Sherlock Separator, is the only optical sorter that is able to detect glassed potatoes. When this machine is following up on the washing line, the data can be used for smart control of the clay bath. When the amount

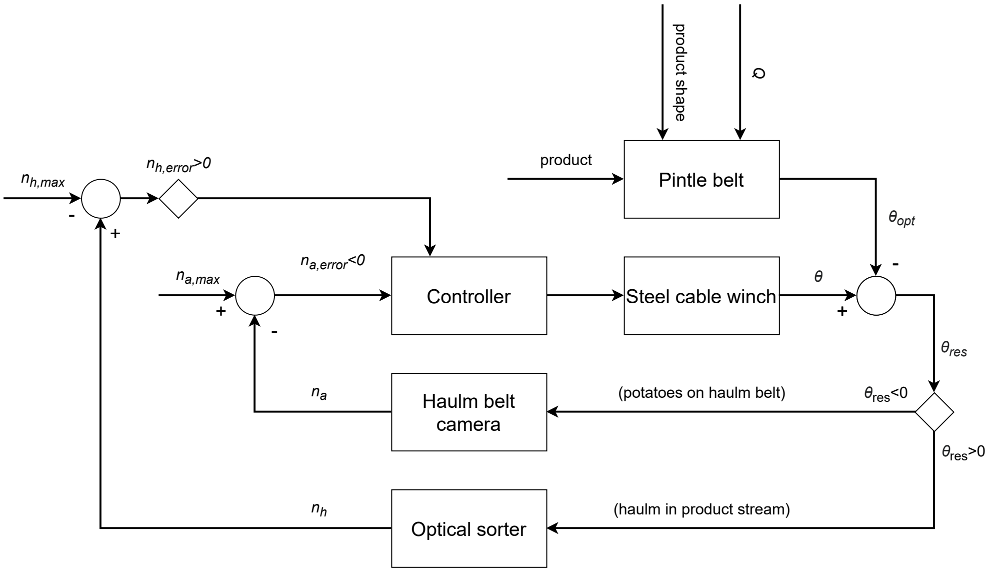


Figure 44: Control scheme for the pintle belt.

of glassed potatoes detected by the Sherlock Separator n_g exceeds the premeditated threshold, the controller knows that more clay needs to be added to the mixture. If no glassed potatoes are detected by the optical sorter, the clay ratio is slowly decreased to reduce costs and to prevent using too large a clay ratio with healthy potatoes ending up as waste as a result. A sensor can be used to measure the clay ratio. This way the clay ratio can be monitored. Some of the clay, dirt and other waste from the product stream sinks down in the clay bath. Therefore a pollution sensor needs to be placed in de bottom of the tank, just in front of the discharge valves. If the water in the bottom of the tank gets too strongly polluted the discharge times t_d need to be decreased.

Via these logics, a double closed loop control system can be formed. Figure 45 below shows a schematic overview of the control strategy for the clay bath.

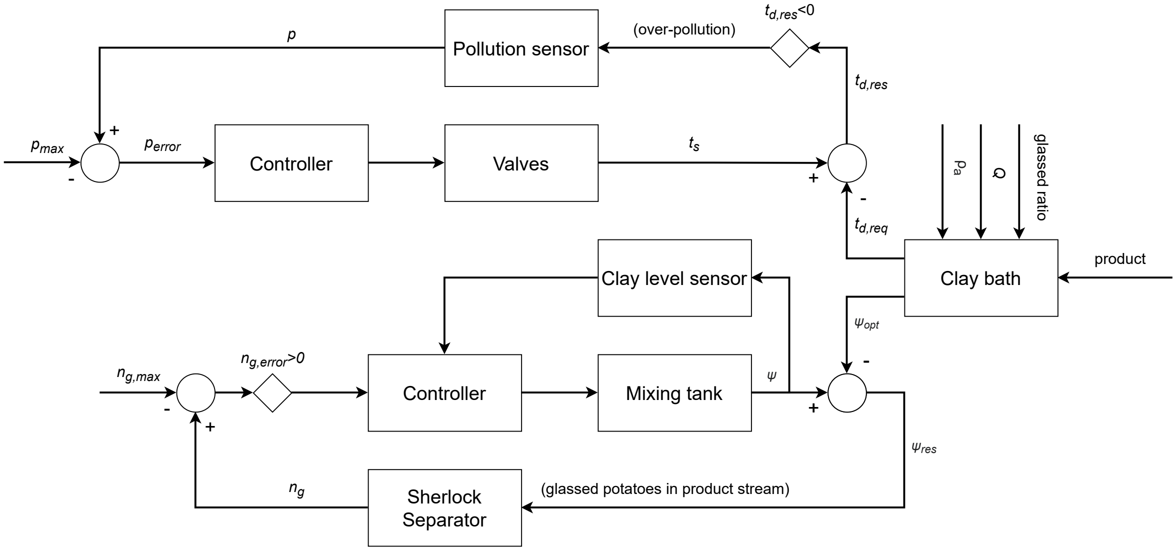


Figure 45: Control scheme for the clay bath.

The KPIs and other measurable parameters are listed in table 24 below per machine in the washing line. Next to all these KPIs the motor power is measured for all electric motors. The belt speeds for all machines are based on the throughput capacity Q as explained in the beginning of this section.

Machine	**KPI's**	**Measured parameters**
Input belt	Q	v_b
Destoner	n_s, n_a	p, f_r
Drum washer	n_c	p, $Q_{d,fresh}$, $Q_{d,recycled}$
FPR	-	-
Pintle belt	n_a, n_h	θ
Clay bath	n_g, ψ	Q_d, Q_{in}
Roller spreader	-	-
Roller dryer	-	f_r
Dewatering drum	Q_d, Q_{in}, Q_s	-
Water treatment	Q_{in}, Q_d, Q_s, p	-

Table 24: KPI's and other measured parameters per machine in the washing line.

5.7 Recipes

The system can be programmed with recipes as previously described in section 5. The most important recipe will be the reset recipe. After the washing line is installed on site, experts from Tummers assist during the first days of operation to fine-tune all the parameters and solve teething problems. The current situation is as follows. After a few weeks or months of operation, the product that comes into the washing line or the processing application changes. The machine operators then change all kinds of settings following the trial and error method to try to optimise the settings of the machine. Then when all the wrong settings are in place, they call Tummers with a complaint that the machine line does not do its job right. An employee of Tummers then has to go to the factory to see what the problem is and solve it. A huge share in the cause for these problems are that the operator has set the machines to the wrong settings. This problem can be solved by installing a reset recipe into the system. The professionals fill in all the right parameters during the installation of the washing line, which are then saved in the software and protected by a password which only Tummers knows. When the machine line after some time does not work up to the standards, the operator can select the reset recipe and the machine line will be reset to those settings. This button also comes in handy when the smart control system is installed. When the washing line is for example started again after some downtime, the operator can choose the reset button and during the processing of the product the washing line will automatically tweak its settings for optimal performance.

Other recipes can for example be for standardised throughput capacities Q. The operator can choose out of a list of predefined capacities and the machine will automatically be set to the right starting conditions. Other recipes can for example be installed for a washing line that feeds multiple factories with different applications. The washing line from example 1 in section 4.10 for example feeds both a fries and a rösti factory. Potatoes that are processed into fries can not break, be damaged or cut in the washing line. The potatoes turned into röstis however are shredded in the process and therefore these kinds of damage during the washing process do not matter for this processing application. The operator can be enabled to choose between the fries recipe, which sets the machine line to settings for more gentle washing and the rösti recipe, which sets the washing line to settings for more rough washing. With these recipes only the benchmarks are changed, the settings for the actuator signals itself are determined by the smart system.

5.8 Spare part packages

When the modular approach for designing the washing lines is implemented into the company, it would be commercially interesting to start selling standardised spare part packages. When a customer orders a washing line, the choice is presented to add a spare part package to the order. This spare part package includes a set of replacements for the wear sensitive parts and can be composed automatically out of the right parts from the standardised parts lists. The customer then has a stock of replacement parts for both preventive and predictive maintenance as for when a machine breaks down. The customer is able to order new spare part packages manually through contact with the Tummers spare parts department or through a periodical subscription. When the two-bin system is used, the customer will never be without the right spare parts which limits factory downtime. The system can also be equipped with an option to automatically order spare parts. When the sensors detect a broken or worn out part, a warning is shown in the DT system. When maintenance is then conducted to the machine, the mechanic states in the system which parts he has replaced and the system automatically orders new replacement parts from Tummers. For commercial purposes a distinction can be made between three different packages. The basic package, the advanced package and the complete package. The basic package is the cheapest and only includes spare parts that need to be replaced periodically. The advanced package is slightly more expensive and also includes the most common wear sensitive parts that are replaced through predictive maintenance. The complete package is the most expensive one and includes all wear sensitive parts for the entire machine line. The packages can be ordered together with the machine line but also after some time of operation. Because the price of the package is lower than the combination of costs of all the individual spare parts, the customer is tempted to buy a spare part package. This lowers the costs for the customer, makes sure he is never out of the right parts and brings in extra revenue for Tummers in a structured way.

6 Benefits of an adaptive tuber washing line

Changing the strategy for designing customer specific washing lines has lots of benefits for the different departments throughout the company. The biggest benefits that apply to all departments are the increase in clarity and automation and decrease in friction between the different departments. When a clear standard is created in the modular approach to design the washing lines, this standard comes with a lot of clarity for all the departments about what specific machines Tummers is selling. When this machine portfolio set up out of a set of standard modules and their specifics are known throughout the company, this takes away a lot of friction between the different departments. Misunderstandings about complex customer specifically engineered machines derived from faulty communication are limited. Working with a modular design of machines from a standardised portfolio enables automation of processes throughout the company that are now very time consuming. This clear standard, when extensively documented, also makes transfer of knowledge to new employees much easier. Even though smart control of the washing line has lots of benefits for the customer, it also has some benefits for the company. In this section the results from implementing the modular and smart design strategy for the washing lines for different departments throughout the company will be discussed per specific department. Afterwards the savings in man hours will be estimated for the modular approach and the payback time will be estimated for implementing the smart control strategy.

6.1 Marketing

The marketing department serves as the face of the company and presents the company and its products to the world. Among other things, they manage the website, present Tummers on trade shows, produce flyers and advertise the company. It has happened multiple times that the picture of a customer specifically made machine or machine-line was used in advertisement. The customer then was disappointed when they received their machine because it differed from what they had seen in the advertisement. When the washing line portfolio is standardised through modular design, the standard modules can clearly be shown on the website, in flyers and other advertisement. The customer then has a clear idea of what they get when they order a washing line. When the CPQ software is further implemented up to implementation step III, the online available configurator becomes a very powerful marketing tool. Customers are then enabled to configure a washing line specifically to their wants and needs to fit their application. Both 2D and 3D CAD drawings of the specially configured washing line and a list of the selected machines and their specifics are presented to the customer. Because the portfolio consists out of standardised modules, some of these modules can be produced op front to show to potential customers on trade fairs or to enable customers to visit Tummers to come take a look at them. These modules can then easily be sold afterwards when the module occurs in an incoming order. The package for smart control of the washing line is a great marketing opportunity to elevate Tummers above the competition with a washing line that automatically optimises its performance and efficiency while enabling preventive maintenance for most wear sensitive parts. Because the standardisation prevents mistakes throughout the entire company, damage to the image of the company is reduced which strengthens the competitive advantage in a tough market.

6.2 Sales

The sales department is the direct link between the company and the customer. They listen to the wants and needs of the customer and based on that advise them a specific washing line. The sales department makes quotations for customers and iteratively perfects them in constant consultation with the engineering department and the customers themselves. For each project the sales department has to divide the order in CTO and ETO parts. For these parts the salesmen determine the necessary amount of work hours per specific sub-department next to that they calculate the labour, material and other costs like transportation. This way the sales department creates a budget for the project. When the modular strategy is implemented, the configurator becomes an important tool that eases the work of the sales department drastically. When the tool is used throughout the whole department, the machine line that is advised to the customer no longer differs per salesman because of personal experience and preferences. This way a Tummers standard will be realised. Using the CPQ software to configure a customer specific machine line saves lots of work hours for the sales department because of automatically generated quotations, floor plans, CAD drawings and lists of machines and their specifications to present to the customer. Next to that the modular strategy provides a clear standard, this way the salesmen know immediately what specific machines they are selling to the customer and do not have to check with engineering if the specifications of a machine meet the exact wants and needs of the customer. Because of these clear standards and automatic quotation generations, sales does not have to perform a thorough cost analysis which also no longer has to be checked by company management. This way a lot of work hours can be saved and orders that contain a high share of ETO components automatically come with increased costs for the customer to prevent projects from becoming unprofitable.

6.3 Engineering

The engineering department is the creative motor behind the company. Here all machines are designed and supplied with CAD models, sets of technical drawings, parts and material lists. When the modular strategy is implemented throughout the company, the engineering department will benefit the most. The orders that come in from the sales department are divided in CTO and ETO components. For the CTO components a standardised set of CAD models, sets of technical drawings, parts and material lists can be generated. For the ETO components like flumes, platforms, frames or customer specifically changed machines the standardised design has to be changed or a new design has to de engineered. Because the far majority of the components ordered by the customer are assumed to be CTO, this standardisation will lead to huge savings in man hours. When a machine is improved by engineering, it is not only improved for a specific customer but for all future customers. The standard design is updated with the improvements and this new version is presented to customers by the marketing department. The modular design strategy leads to enormous relief from the workload on the engineering department. Because good engineers are hard to find caused by shortage on the labour market, Tummers currently struggles to divide all projects over the available engineers. Engineers are currently hired from external parties to fill up the gaps. Implementation of the modular approach will relieve this pressure and create the opportunity for engineers to work on improving the standardised machines instead of only working on customer specific projects. Because of the standardised machines, less mistakes are made during complex customer specific engineering. Platforms and piping can also be standardised to fit the standard modules.

6.4 Planning

The planning department schedules the incoming orders in the company agenda. It checks availability of employees throughout the different departments to plan the projects. This way the customer is presented a delivery time for the machine line and the workers throughout the different departments know what to work on and when. The estimation of hours needed per order that is performed by the sales departments is checked and improved before the project is started. Standardisation through modular design makes it way easier to estimate these hours, this way the the planning for the different departments will be better and estimated delivery dates are more easily met.

6.5 Project management

Project management oversees the different departments working on the project and checks the progress and collaboration with the customer and external parties. Project management for example arranges the transport of the machines to the customer and exchanges details about the machines with external parties that produce peripheral equipment. Standardised functional descriptions and specification sheets of the standard modules make it way easier to supply these external companies with the information they need. Standardised functional descriptions of the machines for example make it easier for ELTRA, which is a partner often worked with to supply the hardware and software to control the machine line. Also the standardised parts lists prevent events like the wrong parts being delivered to the customer for installing from occurring. This way project management does not have to move mountains to get the right parts to the customer in time for installing of the machine line.

6.6 Purchase & warehouse

The purchase department predicts which parts and materials are needed for manufacturing the machine lines in which amounts and order them from the suppliers. Parts that are often used are ordered from regular suppliers and new suppliers are sought for special parts that result from ETO components which can not be bought from the regular suppliers. Predicting which parts are needed becomes way easier when the modular approach is implemented. Parts being out of stock in the warehouse becomes more scarce and standardised parts can be bought in higher amounts. Because of these bulk offers parts become cheaper due to economy of scales. Also when parts are bought more often and in bigger amounts, the supplier can be asked to raise its stocks so supplying the parts can also be expedited. Modules that occur in regularly ordered machines can be produced in series and stored in the warehouse to speed up manufacturing and assembly and lower the costs per machine. An example can be drilling holes in the wear strips that are installed underneath the bar belts. Manufacturing these wear strips in batches instead of per machine reduces the time spend per single part drastically and therefore decreases the costs per part.

6.7 Work preparation

Work preparation provides the employees working in the workshop with manufacturing and assembly instructions. Standardisation through modular approach enables automation of generating these instructions. When all CTO components come with standardised instructions, the work preparation department only has to manually create the manufacturing and assembly instruction for ETO components. Automation and digitisation of this process recuse lots of paper instructions and drawings laying around the workshop because monitors can be placed that show the correct instructions and information at the appropriate places.

6.8 Workshop & assembly

In the workshop the different parts for the machine are produced. Sheet metal and parts that require turning and milling are produced in-house. Modules are built out of make and buy parts and assembled into machines. The complete machines are assembled in-house before being shipped to the customer. Because of the standardised modules, workshop and assembly personnel has to perform more of the same tasks and therefore less mistakes are made. Because of the standardisation of instructions it becomes easier to train the employees and dedicated work stations can be set up for performing these standard manufacturing operations. Manufacturing of semi-finished products in modules eases operations because parallel manufacturing is enabled. Special auxiliary tools can be made to ease manufacturing operations and searching for the right parts becomes way faster because the employees get acquainted to the regular parts.

6.9 Installation

The installation department assembles and installs the machine line on site. Most machines are assembled in-house but bigger machines are split in modules that need to be attached to each other on site. For the bigger washer models the stone belt for example needs to be adjusted to the machine on site because otherwise it protrudes too much during transport. Standardisation through modular design makes it easier for the installing personnel to know how to attach the machines. Cable trays and piping can also be standardised to fit the modules and ease installing on site even further. When lifting points and weights per machine are standardised, this makes installation a lot easier. This information can also be supplied to the customer for when parts need to be replaced.

6.10 Documentation

The documentation department creates all documentation that is delivered to the customer together with the machine line. This documentation includes a technical description, manual, manual drawing, exploded view, parts list, risk analysis and food safety statement for every machine, among others. Implementing a modular design strategy for the washing lines throughout the organisation has a lot of advantages for the documentation department. Nowadays the documentation department spends a lot of time checking and improving parts lists and manual drawings that come from the engineering department. Because every machine that is sold is different in some kind of way, engineering has to manually change the standard drawings and parts lists for almost each of them. Errors in this documentation are often made because the engineering department is overloaded with work. When the documentation department discovers errors in the drawings and parts lists, they send these documents back to engineering to be improved. Because this is not part of the core tasks of the engineering department, improving these documents is often delayed. The same applies for the food safety statements. When parts in the machines are changed customer specifically, they are often ordered from other suppliers. When these new parts are implemented in the machine, the documentation department has to search in the ERP system for the supplier and look for a food safety document. When the company does not have those documents yet, they have to be requested from the supplier. Sometimes these parts in the end turn out not to be food-safe, where after the purchasing department has to look for other parts that are food-safe. Because of this it takes a lot of time before the documentation is finished and ready to be send to the customer. Standardising the machines and building up the washing line out of standard modules will solve these problems. All different modules can be equipped with standardised drawings, parts lists, risk analysis and food safety statement. The documentation package for every washing line can be put together automatically by the CPQ software when the sales department configures the machine line. When this process is automated, the documentation department only has to check the documentation package and add documents for ETO components if they are ordered. [79].

6.11 Support

The support department handles the contact with the customer after the machine line is delivered and installed. When there are problems regarding an operational machine line the customer can call support which will help them solve these problems. Support either solves the problem through logging into the factory software, instructs the local machine operator or repair crew how to fix it or sends a Tummers mechanic to perform the maintenance. The modular design approach will ease support because of the standardised modules. For the standard modules often occurring faults are known and can be researched in a database to find the corresponding solution. The support employee does now have to research which specific parts are installed in the custom made machines installed in the factory that experiences the problems. Standardisation through modular design eliminates this task because a list of standard modules installed in the machine line in question can be easily found in the ERP software. Smart design of the washing lines also brings some advantages for the support department. The support department is able to log into the software that monitors and controls the machine line through a VPN connection to see into the current and past performance statistics to diagnose the problem. A point of action when this smart implementation is performed is that the support employees need to be schooled on sensors and how to install and maintain them because they currently are not experienced with this matter. Standardisation of modules raises the chance of the mechanic having the right parts laying in his van when arriving at the customer and detecting the error. The customer can be informed about inspections and maintenance of the washing line by the control software through data obtained by the sensors. Due to preventive maintenance breakdown of machines can be limited so that support will be called less frequently.

6.12 Spare parts

The spare parts department provides existing customers with operational machine lines with replacement parts. To be able to conduct immediate maintenance customers often have spare parts in stock for scheduled preventive maintenance or breakdown of wear sensitive parts. Customers order spare parts to replenish their stock when items are used during maintenance. When the modular approach is implemented throughout the company, modular spare part packages can be made according to the modules installed in the customer's washing line. This package can be bought together with the machine line and also later to replenish the spare part inventory of the customer. Because for some wear sensitive parts scheduled preventive maintenance is recommended to prevent failure resulting in factory downtime, customers can also subscribe to a periodical delivery of these spare parts. This way they will always have the right parts in stock to perform their preventive maintenance. Standardisation will make it easy for the spare parts department to determine which specific part fits the machine line of the customer. A list of which standard modules are installed at the machine line in question can be easily found in the ERP software. When the smart control strategy is implemented for the washing lines, the system will predict maintenance for some wear sensitive parts. When the part is detected to near the end of its lifetime, the system will show a pop-up to manually order new spare parts to replace those used during maintenance or order them automatically, depending on customer preferences.

6.13 Man hours

After a detailed presentation of the whole project about changing the design strategy for the washing lines to modular and smart, the following estimations were made for how many man hours can be saved throughout the different departments. These estimations are made during a discussion with experts from all these different departments. Table 41 in appendix R shows the percentage of man hours that can be saved after implementing this new strategy. The savings percentage is the percentage of hours that will be saved while working on a washing line when the modular strategy is implemented for the washing lines. Because the different departments of Tummers Food Processing Solutions do not only work on washing lines, but also on frying, flakes, cutting and peeling lines, these savings percentages need to be multiplied with the share a department is working on washing lines. This share is calculated as follows. The average amount of turnover a project brings per hour of labour is calculated from one of the examples in this report. Then the total turnover in 2021 is calculated from the ERP software for each product group as can be seen in table 40 in appendix R from which the labour hours are estimated. From the orders in the ERP software the percentage of the price of a project from each product group that comes from washing equipment is calculated. From this information the average amount of hours per product group spent on the washing lines can be calculated. Averaging these amounts of hours leads to a percentage of time spend on washing lines of 20%. Taking into account this percentage, the annual saving of labour hours per department, when the modular strategy is implemented, can be calculated. This saving of labour hours is estimates to come to a total of 8,611 hours per year. When in the future this modular approach is not only implemented for only the washing lines, but also for the other product groups, the share spend on the washing lines can be left out of the calculations which leads to five times as high total annual labour savings of 43,056 hours per year. This huge amount of hours for the company to be saved can be used for different purposes. For example more time is available for engineers to work on developing new machines or improving the standard designs of existing ones. Next to that less engineers need to be hired from external employment agencies as part time employees.

For the customer the reduced labour hours needed to complete the project, also have a positive effect. When constructing a quotation for the project, the sales department calculates the amount of labour hours needed to complete the project, and bills the customer for this estimation. A reduction in these hours therefore results in a lower price the customer needs to pay for a machine line. Figure 42 in appendix R shows a list of the hours spend on a project in certain departments and an estimation for the hours that will be saved on a similar project after implementation of the modular smart strategy. For this table the hours are taken for the fifth example in section 4.10 because this is one of the most recently finished projects that include a washing line. The hours are rounded to full hours for a clear overview. Most hours derive from the ERP software that keeps track of the hours that are spend on a project per different department and the rest is estimated during the meeting with the different departments as mentioned earlier. Calculating the savings in labour hours results in a staggering amount of 150 hours, which is 23% of the total amount of labour the customer is billed for. The hourly rate a customer is billed for the labour differs per specific task, some work is more expensive then other. If an average estimated hourly rate of €100 is taken, this leads to a total reduction in labour costs of €15,000 for this exemplary project.

6.14 Wear sensitive parts

Because the washing line is smart controlled, some of the wear sensitive parts will be replaced in different intervals. Table 43 in appendix R shows a list of all wear sensitive parts that change replacement intervals and the annual cost savings that result from it. Wear of belts and related parts will decrease with an estimated 5%. Because of the predictive maintenance of the propeller in the destoner, this part will be replaced more often. The felt in the roller dryer will wear out 20% more slowly because the washing quality is optimised preventing residual clay from ending up on the rollers [50].

6.15 Payback time

Downtime costs around €3,000 an hour for the average industrial potato processing factory because the fixed costs keep on adding up without commercial product being produced [50]. If due to the smart sensing system downtime can be prevented because belts for example experience reduced wear and preventive maintenance is performed to drive systems during scheduled maintenance informed by predictive maintenance sensors, factory downtime can be reduced by 10%. because most full-time operating factories experience around 5% downtime [80], this leads to an annual cost reduction of around €131,490. Next to that, the smart system reduces the amount of operators needed to keep the factory running. Instead of two operators working in the factory, this can be reduced to a single operator, saving up to €46,800 a year. Reducing the good-to-bad ratio's by a quarter, resulting in less product ending up in the waste streams of a $100TPH$ washing line can save up to €270,650 a year when 1% of the product ends up in the waste stream and potato prices lay at €130 per ton [119]. The reduction of wear in wear sensitive parts in the washing line, as previously stated, reduced replacement costs by €3,445. When less dirt, haulm, stones and other waste ends up in the machine lines following up on the washing line, this also leads to decreased wear. As an estimation therefore another €3,445 of savings is taken for this decrease in wear. Adding up these cost reductions as in table 25 below, results in a total annual cost reduction of €455,830. With the price of a complete sensor package laying around €122,000. The costs of the sensor package can easily be earned back within the half a year of operations, even if some of the cheaper sensors that are less robust need to be replaced sometimes.

Wear sensitive parts	-€3,445
Wear further upstream	-€3,445
Factory downtime	-€131,490
Product in waste stream	-€270,650
Operator wadges	-€46,800
Total	-€455,830

Table 25: List of the main reductions in annual costs for the consumer.

7 Conclusion

The goal of this research was to investigate how to optimally design a smart tuber washing line based on theoretical concepts, customer inputs and a modular approach. For this, the state of art regarding adaptive machine lines is researched. Afterwards the composition of the machine portfolio is determined. A parametric model of a modular tuber washing line configurator is composed after which also basic models are created to build up the first layer of a DT for smart control of the washing line. Finally the benefits of such an adaptive washing line are analysed. In this section the main research question is answered through answering the sub questions after which recommendations for further research are described.

7.1 Conclusions

Adaptive machine lines are configured customer specifically out of existing modules and controlled by smart systems. Being the future of machine line design, adaptive machines are growing in popularity. Reason for modular design becoming the rule rather than the exception, is the shift from ETO to CTO to standardise manufacturing and its side processes, as well as the service provided after the machine line is delivered to the customer. This increases clarity throughout the organisation of the machine line production company, speeds up manufacturing and enhances sales. One of the ways to model a modular machine line is through a modular kit model or jigsaw puzzle model. This model is a blackbox model based on a multi dimensional machine portfolio matrix that contains all available machine options that can be considered puzzle pieces. These different variations of puzzle pieces can be connected in different orders to create a machine line. Depending on a Multiple Input Single Output (MISO) model, multiple input parameters result in a single output parameter, namely, the machine line configuration. A set of relations between the inputs and outputs can be used to fill in the blackbox and form the model. Smart control of machine lines is also rapidly increasing in popularity. During industry 4.0 manually operated machine lines are replaced by smart factory lines where the machines are connected both to each other and to advanced technologies. In these smart factory lines machines are equipped with sensors that measure KPIs regarding efficiency and performance. These sensors are connected to monitoring equipment through the IoT to enable real time monitoring and logging machine operations in DTs. DT's are digital representations of the physical machine line which can be combined in a CPS. AI expends these possibilities with predictive maintenance and advanced control of machine operations with the help of machine learning algorithms. Even though smart factories come with advanced ways to optimise machine line performance and efficiency, there are some dangers and weak spots to keep in mind. An abundance of sensors rises the chance of errors to occur in the machine line and requires both operators and maintenance crew to be educated on how to work with smart technologies. Also the IoT opens up threats to the CS because hackers can get into the system leaking confidential information, causing harm to the machine line or safety issues for the personnel on the workfloor.

Before setting up a modular design method for the washing lines, the modules or puzzle pieces need to be defined. To do so, first the sales data from the past five years are retrieved from the ERP software and analysed to see which machine variations are most demanded. The drum washer is the most important machine in the washing line portfolio and available in five standard widths of which three can be ordered in two different lengths, each with different throughput capacities. The most common different machine line applications, being flakes, fresh packs, fries and starch each come with a most common throughput capacity and therefore with a most common machine size. Because each of the sizes comes with a substantial turnover, they are all taken into the machine portfolio. Tuber washing lines are most commonly used for processing potatoes and sometimes for washing carrots. Therefore this research project will focus on potatoes and take into account special requirements for carrot processing while leaving other tuberous products out of consideration. The capacities and therefore the size of all other machines in the washing line portfolio are based on the five different washer widths to make sure the modules can be connected in different orders and configurations. Because the original values for the maximum throughput capacities of the machines were not based on scientific relations, new estimations are made for the machine capacities. Next to the different machine sizes, the machines that remove waste from the stream can be equipped with waste belts either to the left or to the right of the machine. The washer can be fed from three different sides and other machines can be equipped with specific options like for example an emptying system or spraying bars.

When a model is made for configuration of the tuber washing lines, it is first considered as a blackbox model. The multiple inputs of this model are divided in four groups; the desired product a_1, input product a_2, factory layout a_3 and customer preferences a_4. The output of the system is the washing line configuration b. To couple the inputs with the corresponding outputs, the blackbox has to be filled in. The relations between the different input and output parameters are based on mathematical equations, material properties like density or surface hardness of the product to be processed and the amount and kinds of waste present in the input product. First the calculation capacity Q_c is calculated. When the input product contains high amounts of pollution or is grown in sticky soil, the maximum required calculation capacity is raised and when the input product is relatively clean or grown in sandy soils, this capacity is lowered. This way the machine line will be able to process the required throughput capacity while a decent washing quality is guaranteed. Not only the machine sizes but also the types of machines installed in the washing line depend on these input parameters. When the input product for example contains large amounts of haulm, multiple different haulm removal machines are installed in the line like pintle belts and an FPR. Based on all these input-output relations a decision scheme can be made that represents the configuration strategy. The next step is then to make a computer model that functions as a basic configurator. This model is made in LabView, which is a visual programming software that allows the programmer to perform test runs while programming. To iteratively improve and validate the model, five reference cases are researched. Each case has a different processing application for a different customer. Because existing cases are taken the outcome of the model is compared with the machine line the customer bought in real life. What stands out is that the machine configuration that comes out of the model regularly does not differ much from the purchased washing line. Most changes are CTO and therefore can be manually exchanged from the machine portfolio, some ETO products will always remain when a customer for example wants to use a flume system. In combination with a PVM and set of product variant matrices, this model forms the basis for a CPQ software implementation. The implementation of this CPQ software into a company has to be performed in three consecutive phases for the employees of the company and the customers to gradually get acquainted to it.

To implement smart control into the washing line, a control strategy has to be defined. The KPIs of the system form the basis for this control strategy. Some important KPIs of a tuber washing line are the throughput capacity Q, the amount of stones remaining in the product stream n_s, the amount of product ending up in the stone stream n_a and the drainage capacity Q_d. To calculate these KPIs certain parameters are measured, this can be the KPIs themselves or for example the belt speed and load on the belt to calculate the throughput. Because the KPIs indicate the performance of the machine line, actuators in the machine can be controlled based on this information for optimisation of this performance. This control can be performed either by open or closed loop control. With open loop control the machine settings are based directly on the functioning of a machine upfront. The belt speed of the product belt in the washer for example can be regulated based on the input capacity of the washing line. In closed loop control the functioning of the machine is measured through the use of sensors, based on the functioning of the machine the settings can be changed by the controller after which the sensor detects if the functioning has improved where after the controller acts accordingly. An example is the destoner where the amount of stones remaining in the product stream is measured. When this amount exceeds the threshold, the propeller speed is decreased to lower the upward current. Each machine has its own controller that is connected to all sensors and actuators installed in this machine and to the main controller. This main controller is connected to a server for storing all data. This data can be read out on local computers in the control room, mobile devices held by operators and mechanics or by the service department of the machine line production company through the use of a VPN. Recipes can be installed in the machines to be able to reset them to the initial settings or to set them to prescribed settings. The integration of sensors in the machines can also be used for predictive maintenance, for example to detect when the propeller in the destoner has to be replaced because it is worn out and does not induce enough current anymore.

Changing the strategy for designing customer specific washing lines has lots of benefits for the different departments throughout the company. The biggest benefits that apply to all departments are the increase in clarity and automation and decrease in friction between the different departments. When a clear standard is created by the modular approach to design the washing lines, this standard comes with a lot of clarity for all the departments about what specific machines Tummers is selling. When this machine portfolio set up out of a set of standard modules and their specifics are known throughout the company, this takes away a lot of friction between the different departments. Misunderstandings about complex customer specifically engineered machines derived from faulty communication are limited. Working with a modular design of machines from a standardised portfolio enables automation of processes throughout the company that are now very time consuming, for example setting up documentation accessory to each washing line sold, making quotations, construction drawings and parts lists. This clear standard, when extensively documented, also makes transfer of knowledge to new employees much easier. Working with standardised modules lowers the amount of different parts in the warehouse and enables synchronous production of modules in the workshop. Hence the workshop can be reorganised with dedicated production stations to further optimise production efficiency. While smart control of the washing line has lots of benefits for the customer, it also has some benefits for the company. At the customer side, the machine line has better performance and efficiency with less downtime. At the company side, the service department is able to log into the system that monitors and logs the data from the machine line in place and is thus enabled to more easily find the problems and their causes. The washing lines take up around 20% of the total turnover and therefore approximately 20% of the man hours spend at the departments that are taken into account in this research. When this adaptive design method is implemented throughout the company, the estimated man hour savings throughout these departments are estimated to add up to $8,611$ hours annually. This reduction results in reduced workload on the overloaded engineering departments and reduces the need to outsource certain engineering to external companies. It creates the opportunity to spend more time on improving the standardised machines but also lowers the cost and therefore the selling price of the washing lines. Because of the technical improvements of the machines, the lower selling price and the more professional image due to the decrease in mistakes and the new marketing options, Tummers will gain a larger market share with these competitive advantages. The smart control package for an exemplary complete washing line will cost around €$112,000$. Savings in replacing wear sensitive parts both in the washing line and in the machines upstream, the reduced factory downtime and product ending up in the waste stream and savings in operator wadges due to the smart control system, result in an estimated annual savings of €$455,830$. Even if some of the sensors need to be replaced a few times a year, the costs of this sensor package can easily be earned back in the first half a year of operations.

All these benefits are definitely outweighing the costs, both for implementing the modular design throughout the company as for installing a smart control system in the washing lines. Therefore the strategy for designing the washing lines is recommended to be turned into adaptive machine line design.

7.2 Recommendations

This research has developed a strategy for designing adaptive tuber washing lines. In this section recommendations for further research are proposed to improve the current state of the art regarding design of tuber processing lines.

Firstly it is recommended to bring this research to practice and implement the whole strategy throughout the company. During this implementation an advanced model has to be programmed in CPQ software. The model can then be expanded by adding transport equipment, platforms, building dimensions and recommendation for peripheral equipment. This way a water treatment system that matches the washing line can for example be recommended to the customer. Working together with permanent partners does not only bring sales opportunities but also improves the functioning of the whole factory because machine lines fit together in a better way. More parts of the organisation can be reorganised while using this CPQ software, an example can be automating the sales of spare parts. This strategy for designing adaptive machine lines is not only applicable for the washing lines. A similar research project can be carried out for the cutting, peeling, frying and flakes lines sold by Tummers.

After the adaptive design approach is implemented throughout the company, the results can be researched. The performance of the different machines in the washing line at different throughput capacities can be checked like the washing quality of the drum washer or the good-to-bad and bad-to-good ratios of the destoner or clay bath. These performances can be measured by analysing the optical sorter data or through the use of a so called 'electronic potato'. This electronic potato contains a set of sensors and has the same size and weight of an average potato. With the data from these sensors the time spend in certain machines but also the aggressiveness of certain machines can be measured. Next to the performance of the washing lines, the maintenance can be researched. This way the hypothesis of the smart control to lower wear of certain parts can be validated. Next to that, the sales data can be analysed after the system is applied. What is frequently asked for as ETO components? Is the amount of CTO parts sold increased with respect to the amount of ETO? Is the annual turnover increased? Is the net profit per sold washing line increased? Are there less faults in engineering and production? Has the downtime at the factories decreased? Also a survey can be held under the different departments at Tummers to see if the clarity within the organisation has increased, decreasing the friction between the different departments.

Because roller dryers are always advised to be preceded by a roller spreader, a new machine can be developed. This machine can be a roller dryer combined with a set of delta rollers inside. The product is then spread and dewatered on the delta rollers and dried by the felt rollers afterwards. This combined machine takes less space on the factory floor than when installing both the roller spreader and the roller dryer consecutively and will be cheaper too. Since this machine does not exist on the market yet, it will be patentable and form a unique product for Tummers to sell.

While there are multiple different ways to monitor conditions of conventional conveyor belts, there is no sensing equipment developed yet for monitoring wear in bar belts. Because bar belts are used very commonly for agricultural purposes all around the world, this would be a relevant research project. Instead of monitoring wear to be able to conduct preventive maintenance another design project could be a heavy duty bar belt that is able to withstand water and clay. Bar belts that are currently on the market are simply composed of belt strips with textile carcasses and therefore wear out quite rapidly. They are designed for machines like potato harvesters that are only periodically operational and not suitable for machines in continuous operation like tuber washing lines.

Another interesting research project is to go into further detail with designing a system for measuring water pollution. Photocells and Electrochemical Impedance Spectroscopy (EIS) sensors can be compared both with each other and with different sensor types for detecting sedimented soil blocking the valves underneath the washer and water pollution in the rest of the tank.

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Appendices

Some of the appendices include large diagrams, matrices, tables and figures from which the text can only be read through zooming in when looking at them online. Those elements are too big to print on A4 sheets and therefore can only be examined virtually.

A Scientific paper

Novel Design Approach For Modular Smart Machine Lines

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Abstract — **Adaptive machine line engineering based on modular design and smart factory engineering becomes the rule rather than the exception for production and processing lines. Adaptive machine lines are flexible industrial machinery characterised by the ability to intelligently adapt itself to the product to be produced. In contrast to conventional machine lines which are engineered specifically for each customer and controlled manually, adaptive machine lines are configured customer specifically out of existing modules and optimise their own performance and efficiency through smart control. This research sets up a method for designing adaptive machine lines for industrial purposes. Because of the need for a single model that can be used for both modular design as for smart control of machine lines, a new modelling method for modular design is proposed, called the jigsaw puzzle model. This cost efficient modelling method is then applied in a case study to create a design tool for adaptive tuber washing lines.**

I. INTRODUCTION

Factory owners are saddled with a lot of challenges to keep their factories running and profitable. Prices of raw materials and energy sources continue to rise and modern society is fighting against global warming. Therefore efficiency of processing lines has become more important than ever. Labour is also becoming more expensive because of the rising wadges and skilled personnel is scares (Fokusa & Zalane, 2021; King, 2015). Machine operators focus on keeping the machine line running and often lose track of efficiency and quality of the process. Next to that, partly due to the recent COVID-19 pandemic, parts are often unavailable or have enormous delivery times (Kamali, 2021). If the different machines in the machine line could be integrated with a system that automatically optimises efficiency and process performance while reducing and predicting wear, these issues could be solved.

Smart factory engineering poses a combined solution to all these problems. According to Sufian et al. (2021), in a smart factory the machines are connected both to each other and to advanced digital technologies. Through data that is obtained by a multitude of sensors and digital technologies, the manufacturing operations are managed and controlled. People are empowered with information that gives them better visibility into manufacturing processes and operations and therefore it becomes easier to diagnose issues and improve the system in relatively short time. Both productivity and flexibility are improved by smart engineering. The increasing developments and availability of sensors, actuators and control systems lead to increased popularity of smart factory engineering, kickstarted by the invention of the internet just before the turn of the century. This fourth industrial revolution, also known as industry 4.0 is based on future oriented production through smart machines that are interconnected through the internet. This future oriented production contains efficient, modular systems where products control their own manufacturing processes (Lasi et al., 2014; Lele, 2019; Pisaric et al., 2021; Schimanski et al., 2019).

A different term to describe the strategy that powers a smart factory is the Internet of Things (IoT). Sufian et al. (2021) describes an IoT system as a collection of an ecosystem of combined technology elements that collect, store and exploit data in order to provide information, trigger events and recommend actions. Connecting those machines and controlling them in an IoT system has become more accessible and affordable due to the considerable drop in the cost of sensors and computing and the improvement of the internet in the past few years. This is why smart factory design has become more and more common (Mantravadi et al., 2022; Zuehlke, 2010).

Essential for a smart factory to work is a central computer system connected to mobile devices that controls the factory with computer-based algorithms, also known as Cyber Physical System (CPS). The central computer system is where the data from all the connected machines is gathered. It processes the data, monitors the processes in the factory and makes decisions accordingly (Monostori et al., 2016). This way a Digital Twin (DT), a virtual representation of the real-life system, is formed. This DT represents both the physical appearance and the behaviour of the simulated system (Pisaric et al., 2021). The operators on the factory floor can log into the central computer system with a mobile device to be equipped with the right information on the spot (Zuehlke, 2010). The machines in the factory can be equipped with multiple sensors to acquire data. These sensors can for example be used to monitor wear, errors, safety issues and other deviations from the optimal functioning of the processing line. The information obtained by the sensors is send to the central computer through a Digital to Analog Converter (DAC) device. In a manufacturing line a dense grid of sensors can be used to make sure that no parts are missing and that every part is in exactly the right location after the final assembly (Wright, 2014).

Factory owners as the consumers of multi machine systems are not the only party in need of a solution to their problems during these complicated times. Companies that produce the machine lines need to provide customer specific, tailor made machine lines for a good price to keep ahead of competition. The increased prices of raw materials, energy and labour also affect their business. The need for tailor made machine lines for every individual customer leads to complex engineering. Because of the labour shortages, engineering departments are often overloaded. Mistakes are commonly made during the translation of customer specific wants and needs into a machine line, which results in faulty production, assembly and documentation. This complex engineering and lack of standard in the machine portfolio comes with lack of clarity and friction between the different departments throughout the organisation.

Smart design opens up a way to connect the different machines in a factory. Based on these connections, standardised machine modules can be developed. This method of modular design of machine lines can help tackle the issues occurring throughout the organisation of machine line production companies. Therefore in this research paper a novel method is created for modular smart machine line design, which is named the jigsaw puzzle model. This method will form a single model for both modular design and smart control of customer specific machine lines.

Modular machine line design is a principle where a system is divided into smaller modules. Each module can be independently designed, modified, replaced or exchanged with other modules. A standard portfolio is made of machines that fit together in different configurations. For each specific machine line design, a set of machines can be chosen from the portfolio and combined into a production or processing line. Each module included in this portfolio needs to have meaningful and/or structural functionality and be able to be joined to other modules. The alternative designs and combinations must cover the full range of requirements and the performance of each module must meet the specifications (Ito, 2008; Klushin et al., 2018). Though modular design the design method can be changed from Engineering To Order (ETO) to Configure To Order (CTO). This way all the steps in designing the machines need to be performed once instead of needing to be repeated for every individual order. These steps include engineering and constructing documentation, among others (Bultman, 2021; Schimanski et al., 2019).

Modular machine line design comes with lots of benefits when compared to conventional engineering of machine lines. In the late 1960s, the strategy of modular design was already assumed to be advantageous for both the manufacturer and the user. For the manufacturer the strategy of modular design is able to reduce both the manufacturing costs and the manufacturing time (Brahnkamp & Herrmann, 1969). Because the machine lines are standardised the clarity throughout the organisation improves. There are less different machine options and less different parts. This leads to less faults in production and documentation. This way both labour and material costs drop significantly (Kim et al., 2013; Neelamkavil, 2009; Schimanski et al., 2019; Upadhyay, 2020).

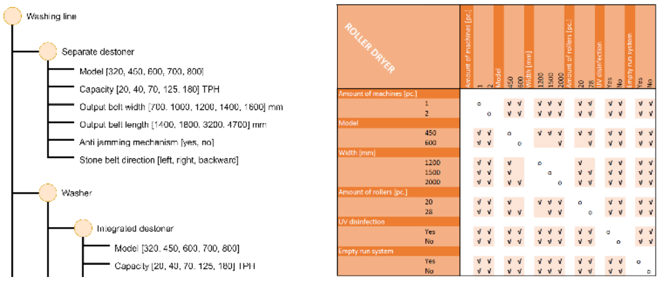
Adaptive machine lines are flexible industrial machinery characterised by the ability to intelligently adapt itself to the product to be produced based on a combination of these two core principles: modular design and smart factory engineering. Combining both design principles results in a machine line design that can be configured out of existing modules to fit the machine line application and change its own parameters according to relevant parameters of the input and desired output (Frost & Sullivan, 2017; Rodrigues et al., 2013).

II. JIGSAW PUZZLE MODEL

There are multiple different design methods used for designing machine lines. In the engineering department of machine line production companies Computer Aided Design (CAD) models are made to create three dimensional images, technical drawings, manufacturing instructions and parts lists for the different machines. This software can either be used to create CTO or ETO components (Tacton, n.d.). However for every new design, the entire design cycle has to be repeated. This makes CAD modelling a very time consuming method for designing customer and application specific machine lines.

CAD modelling can be upgraded with Configure Price and Quotation (CPQ) software. CPQ software is based on the method of parametric design. According to the method of parametric design, objects are shaped according to logarithmic processes. Parameters and rules between them determine which design follows up from which input parameters (Wassim, 2013). When modular design and parametric design are combined and automated, this leads to automated generation of design. In this method a parametric model can be used to determine which modules to combine into a final design (Tuijp, 2020). The CPQ software is programmed so that the user is able to answer a list of simple questions about the project. These questions concern the input parameters of the model. To answer them, the user does not necessarily need to have a lot of technical knowledge. The questions regard the wants and needs of the customer and the constrains that apply to the project. The answers to these questions are then compared with the predefined parameters of the modules to define a recommended machine line. The user is presented with a three dimensional CAD representation of this machine line, the machine line characteristics, a list of the applied machine models and options, parts lists and a rough quotation (Seiler et al., 2019).

The downside of CPQ modelling is that it takes a lot of time to set up a CPQ model that can be used for designing customer and application specific machine lines. Before being able to set up a CPQ model, all details regarding the standard modules need to be structured in a Product Variant Master (PVM). The PVM is a schematic hierarchical overview of all products and is used to set out the product range. The PVM consists out of two parts. The left side shows the different modules that occur in the portfolio in a hierarchical structure. The right sideshows the variable parameters of these modules and their different available options. An example to illustrate the PVM is shown in figure 1a below. After the PVM is constructed, the product variant matrices have to be made. These matrices show which machine options can be combined and which can't. A product variant matrix is made for every individual machine after which they are combined in a matrix for the entire machine line. Figure 1b below shows an example of such a product variant matrix. The combination of options that are available for the machines are indicated with a checkmark and the options that are unavailable are left blank (Hvam et al., 2008).



ROLLER DRYER	Amount of machines [pc.]		Model		Width [mm]			Amount of rollers [pc.]		UV disinfection		Empty run system	
	1	2	450	600	1200	1500	2000	20	28	Yes	No	Yes	No
Amount of machines [pc.]													
1	○		√	√	√	√	√	√	√	√	√	√	√
2		○	√	√	√	√	√	√	√	√	√	√	√
Model													
450	√	√	○		√	√	√	√	√	√	√	√	√
600	√	√		○			√		√	√	√	√	√
Width [mm]													
1200	√	√	√		○			√		√	√	√	√
1500	√	√	√			○		√	√	√	√	√	√
2000	√	√	√	√			○	√	√	√	√	√	√
Amount of rollers [pc.]													
20	√	√	√		√	√	√	○		√	√	√	√
28	√	√	√	√		√	√		○	√	√	√	√
UV disinfection													
Yes	√	√	√	√	√	√	√	√	√	○		√	√
No	√	√	√	√	√	√	√	√	√		○	√	√
Empty run system													
Yes	√	√	√	√	√	√	√	√	√	√	√	○	
No	√	√	√	√	√	√	√	√	√	√	√		○

(a) Example of a PVM.

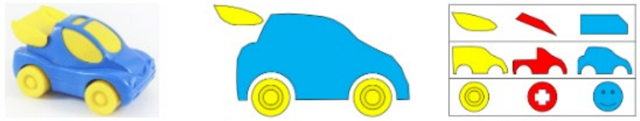
(b) Example of a product variant matrix

Fig. 1: Example for documentation of the machine specifications and available combination of options.

After the details of the available machines and combinations of them are described. A model can be made for the machine line configuration. Conventionally this is done through choice schemes. The disadvantage of this method is that for complex systems it leads to a huge choice scheme which has to be followed manually to design the machine line configuration.

After the machine line is designed, another model is chosen to monitor the machine line in real time and control its settings. For this application multiple different modelling methods can be used. A commonly used model for processing lines is a flowchart. In a flowchart for every machine the input and output streams are measured. By comparing the input and output streams of product and waste, the performance and efficiency of the machines can be monitored. Important is for every part of the machine to have an input/output balance that results in zero. A faulty mass balance can for example be caused by leakage, blockage or a broken sensor. Another commonly used way to design a monitoring system is through a Supervisory Control And Data Acquisition (SCADA) system. In addition to the flow chart, the SCADA model physically represents the machine line. The model can be used to control industrial processes locally or at remote locations (Inductive Automation, 2018). When a part of the machine line experiences an error it will be highlighted and can be clicked by the operator to get all useful information, this makes is easy for machine operators to see where and what the problem is.

The goal of this research project is to create a single model that can be used for modular design of a customer and application specific machine line while forming the first layer of a DT for monitoring and control of the machine line. A good basis for this new model is the modular kit model. For this model, according to Albers et al. (2019), the domain is understood as a modular kit so the individual products can be deductively derived from the modular system which inductively describes the modular kit. This is based on the modular kit reference model, which can be generated inductively from the reference product models. An example to illustrate this modelling method can be made for a modular design of a toy car. The modular kit model is a model that describes which parts need to be installed in which toy car. The modular kit contains all different options for the different car parts. These can for example be different chassis, wheels and spoilers. Based on the logic in the modular kit model, a tailor made reference product model can be configured out of these parts that represents the physical product model. Figure 2 below illustrates this example and the terminology of the different stages in this modular design method.



(a) Physical product model.

(b) Reference product model.

(c) Modular kit.

Fig. 2: Example of a modular kit design regarding a toy car.

To choose which modules to combine into the reference product model for a specific application, a morphological scheme can be used. According to, Mulder (2017) this design technique is about exploring all possible solutions to a complex design problem and is used while exploring new design ideas. The design problem is divided into sub-problems. Morphological schemes are visualised in a morphological matrix or morphological chart that systematically shows design options as combinations of design choices in multiple different dimensions that represent the sub-problems. The best solution in the morphological chart is chosen in a subjective way. This solution is chosen by grading each of the possible solutions from the matrix and grading them in different rubrics with different grading factors with respect to their importance in the final design. Figure 3 shows a morphological scheme for the toy car example.

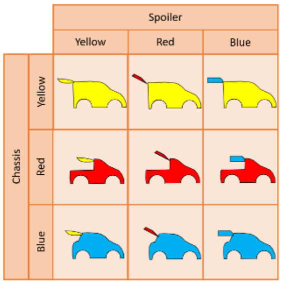


Fig. 3: Example of a morphological scheme regarding a toy car.

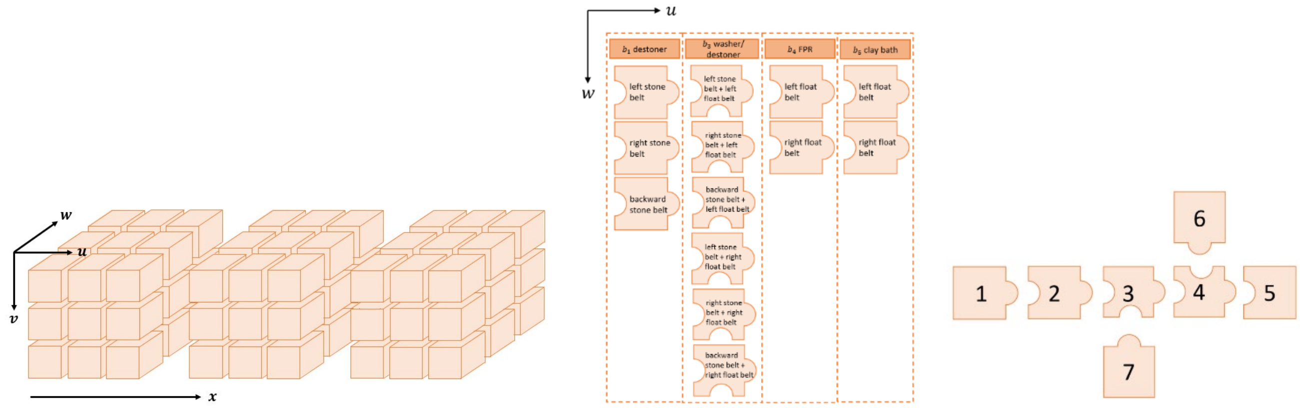
There are various different ways to visualise the modular kit reference model. Some examples are visualisation through block diagrams or two dimensional physical representations like in Figure 2. Based on the modular kit model, a new modelling method is created in this research project, which will be called the jigsaw puzzle model. This modelling method can be used for various modular design applications. The basis of the jigsaw puzzle model is that the design is a single specialised tailor made product in the eyes of the customer but in the eyes of the designer this specialised product is a combination of existing standardised modules taken from the module portfolio. The set of modules which Albers et al. named the modular kit, will be referred to as the machine portfolio. In contrast to the two dimensional modular kit, this portfolio can be structured in more than two dimensions as illustrated in figure 4a. Figure 4b shows an intersection out of this matrix. The dimensions represent different machine parameters. The first dimension, u sets out the different machines that can be placed in the machine line. The second dimension, v is the set of available sizes for each specific machine. The other dimensions, w, x, … can be machine options, for example the direction of a belt or the height of the frame. Combining these different dimensions in a multi-dimensional matrix sets out all the possible modules and represents the machine portfolio.

The different machines chosen from the portfolio can then be combined in different machine line configurations. This machine line is then put together like a jigsaw puzzle, which is illustrated in Figure 4c below. The different modules, visualised as puzzle pieces can be configured in different orders and exchanged with other pieces from the portfolio, visualised as the puzzle box, as long as the rules are obeyed. Just like with an actual jigsaw puzzle there are a few rules to make a complete configuration. The rules that come with this jigsaw puzzle model are as follows.

1. Pieces can only be translated, not rotated.
2. Pieces can only be connected to other pieces if their slots fit together.
3. The puzzle always has to be completed, no empty slots can be left.

During the designing process, machine lines can contain as many machines following up on each other as the designer desires. Also multiple machine lines can be designed to be installed in parallel, therefore this also applies to the puzzle pieces.

Figure 4c shows a complete machine line design represented by the jigsaw puzzle model. Other configurations of the pieces could have been made while following the rules. Piece 2 could for example be removed



(a) Four dimensional machine portfolio matrix
(b) Intersection of the matrix
(c) Visualisation of a complete design

Fig. 4: Examples of the machine portfolio matrix of the jigsaw puzzle model.

from between 1 and 3, or placed in between piece 3 and 4. Also an extra combination of piece 4 and 6 could be placed in between piece 2 and 3. This emphasizes the scalability and flexibility of modular design.

The jigsaw puzzle model solves the issue of a person not skilled at the art of modular design being able to work with a design model. This is caused by the fact that the terminology and visualisation of the model are clear and simple and the model is based on a simple set of modelling rules. Furthermore the multi-dimensional machine portfolio matrix expands the configuration options exponentially and makes it easier to define the machine portfolio in modelling software as when compared to modelling through modular kit design.

The next step is to define a model that describes which specific modules from the portfolio to choose for a customer specific application and in which order to install them. The choice for a specific machine line configuration can be described through a blackbox model. In such a model only the inputs and outputs are known while the decision making process in the blackbox is still undefined (Zhang, 2010). Figure 5 below shows a schematic overview of this black box model.

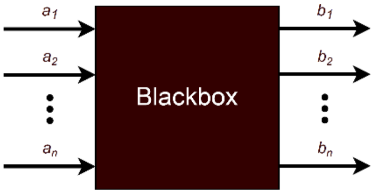


Fig. 5: Visualisation of the blackbox model.

The filling of the blackbox in many companies purely consists of the experience and personal knowledge of salesmen and engineers. This research focuses on changing that strategy to filling in this blackbox with a standardised model for modular design. The difficulty of defining the relations that fill up the blackbox and determine what outputs result from which inputs, comes from the fact that this single model has multiple inputs and multiple outputs. According to Woolf (2022), Multiple Input Multiple Output (MIMO) systems describe processes with more than one input and more than one output which require multiple control loops. These systems can be complicated through loop interactions that result in variables with unexpected effects. This MIMO model can be defined by a set of relations between certain in- and outputs. To set out these relations, described in equation 1 below, a decision scheme can be made. This decision scheme can be used as a clear overview for constructing a computer model.

$$b(u, v, w, x \ldots) \in [0,1,2 \ldots n], \qquad u \in U, v \in V, w \in W, x \in X \ldots \tag{1}$$

Because scientific literature lacks applied approaches for adaptive machine line engineering, this research will be illustrated with tuber washing lines as a potential application. To do so, a case study is performed at Tummers Food Processing Solution, leader in the world wide potato processing market.

III. CASE STUDY

Potatoes are the most consumed vegetable in the western diet. In the year 2019 22.54 kg of potatoes per person were available for consumption in the USA (USDA, 2020). Next to the potatoes sold in fresh packs in the supermarkets, potatoes are also processed into a wide variety of products. Fries, crisps and pre-cooked bags of potatoes are some of the best known examples but potato flakes and starch are other products that can be found in countless foods like soups, sauces and pastas but also in less obvious products like wine gums, frankfurter sausages and wallpaper glue. Even though potatoes are the most popular tuberous vegetable, other tubers like carrots, parsnips or red beets can also be processed into food by similar machine lines.

Before the tubers can be processed into all those various products, they need to be cleaned. Because tubers are grown inside the soil instead of on top of them, product batches contain relatively large amounts of soil, stones, clods, haulm and other waste when harvested. Each factory that processes tubers like potatoes contains a tuber washing line for cleaning the tubers and removing waste particles from the product. The market for tuber washing lines will be divided into two different categories: fresh packs and industry, which each come with their own requirements.

Potatoes and carrots that are processed into fresh packs are only washed, sorted and packaged. The customer wants fresh and clean vegetables. Breakage, bruising and slicing of vegetables in the washing line need to be prevented, therefore the machines have to handle the product gently. It is important for the skin to stay intact. This is both for the product to look good in the store as to protect it against viruses and bacteria. Furthermore the vegetables need to be washed thoroughly for the fresh packs not to contain traces of sand or other filth. Discoloured vegetables like green potatoes for example, have to be removed from the stream and the vegetables need to be dried before packaging. Washing lines for fresh packs regularly have low capacities and are not in continuous operation.

In industry, potatoes and carrots are processed into a wide variety of products. After being washed and sorted, the tubers are processed by different lines like peeling, cutting or frying lines for example. Tubers that are peeled have to be washed less thoroughly because sand and filth are removed with the skin during the peeling. The tubers are immediately processed after being washed. Because the product is often pasteurised, fried and/or packaged in vacuum, bacteria and viruses do not pose a big threat in these production lines. Breakage, bruising and slicing of vegetables in the washing line have less impact on product that is processed for industry. First of all the tubers are often peeled, which takes away all minor damage. Secondly the product goes through an optical sorter after being peeled and cut, this optical sorter removes all pieces that do not meet the requirements. Potatoes that are processed into starch or flakes have even less requirements. Tubers that are damaged do not need to be removed from the product stream, only green or rotten potatoes need to be removed. Tuber washing lines for industry are characterised by high capacities and are in continuous operation of more than 7000 hours per year. Because of this, the machines need to be engineered maintenance-free for minimal downtime.

Each machine that is part of a washing line portfolio has limited efficiency. It is the combination of machines following up on each other that makes the machine line highly efficient on removing all kinds of waste from the product stream. This is caused by the fact that the different machines are removing waste based on different separation principles. A Floating Parts Remover (FPR) removes waste based on its ability to float on water for example and a pintle belt removes waste based on its ability to roll down a certain slope. As modular design of machine lines is intended, the different modules can be installed in different configurations based on the application of the machine line.

As previously mentioned the configuration strategy for a specific washing line can be described through a blackbox model. In such a model only the inputs and outputs are known while the decision making process in the blackbox is still undefined. Figure 6 below shows a schematic overview of this blackbox model. In this model the inputs are details regarding the desired product, the input product, factory layout and customer preferences. These four types of inputs come from the customer side to determine which machines with which options to implement in the washing line. The filling of the blackbox in the current situation purely consists of the experience and personal knowledge of salesmen in the sales department. This research focuses on changing that to filling in this blackbox with a standardised model for modular design.

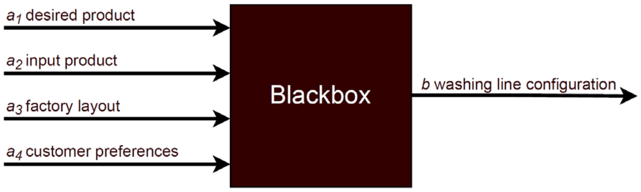


Fig. 6: Blackbox model for tuber washing line configuration.

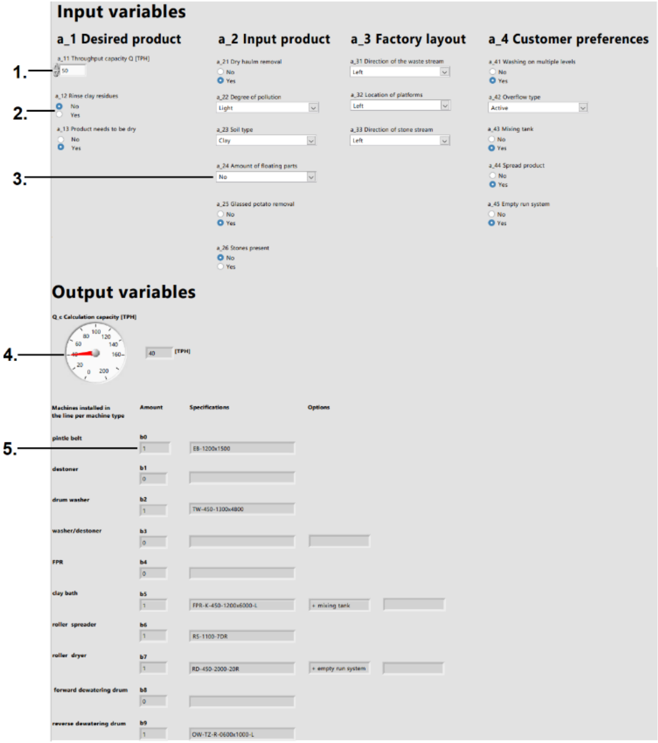
The machine portfolio matrix that structures the different available outputs of the blackbox model consists out of six dimensions. The first dimension u sets out the different machines from set U, which is a list of the ten different machine types. The second dimension v sets out the machine sizes from set V, which is the set of available sizes per machine type. The feeder and receiver belt are added as the head and tail of a machine to create a complete overview but are not part of the machine portfolio matrix. The third dimension w sets out the direction of the waste stream of the machine from set W, which is the set of available waste directions per machine type. The fourth dimension x sets out the motor location from set X, which is the set of available motor directions that can be chosen for two different machine types. The fifth dimension y sets out the type of FPR of a machine from set Y, which is the set of FPR types that can be chosen for two different machine type. The sixth and last dimension z sets out extra options that fall outside of the other dimensions from set Z, namely the addition of a mixing tank to the clay bath and emptying system to the roller dryer. The amount of specific machine models recommended to be installed in the machine line b can be described by equation 2.

$$b(u,v,w,x,y,z) \in [0,1,2], \quad u \in U, v \in V, w \in W, x \in X, y \in Y, z \in Z \quad (2)$$

IV. LABVIEW MODEL

There are multiple software tools that can be used to construct a basic digital version of the model for modular design of the washing lines. An interactive, visually attractive and easy to use software which can be used to construct this model is LabView. LabView works with two windows, one is a panel where all the input parameters can be filled in and the output parameters are shown and the other is a visual programming window. This visual programming window shows the structure of a graphical block diagram, the LabView-source code, on which different function-nodes can be connected by drawing wires. This way the data flow is used as a programming language. Using a visual instead of a text based modelling software for this first basic digital model, enables the programmer to perform test runs while programming to check if the model gives the right outputs with respect to the filled in parameters. The visual panel for the LabView-source code shows the different inputs needed for each function node and highlights modelling errors in real time, this eases working with the software for inexperienced programmers. This model can be seen as a configurator that as previously discussed can be used to configure washing lines according to customer and application specifics (National Instruments, n.d.).

To construct the model, first all the parameters are defined in the parameter panel. Figure 7 shows the input and output parameters, the numbers in the text correspond to the numbers in the figure. The input variables are created out of different tiles: numeric control tiles (1), boolean tiles (2) and system ring tiles (3). The output variables are created out of a gauge tile (4) for the calculation capacity Q_C and multiple string indicator tiles for the machine line configuration b. In the output section of the panel, the number of machines, specifications and potential options that are recommended by the model are shown.



Input variables

a_1 Desired product

a_11 Throughput capacity Q [TPH]: 50

a_12 Rinse clay residues: ● No ○ Yes

a_13 Product needs to be dry: ○ No ● Yes

a_2 Input product

a_21 Dry haulm removal: ○ No ● Yes

a_22 Degree of pollution: Light

a_23 Soil type: Clay

a_24 Amount of floating parts: No

a_25 Glassed potato removal: ○ No ● Yes

a_26 Stones present: ● No ○ Yes

a_3 Factory layout

a_31 Direction of the waste stream: Left

a_32 Location of platforms: Left

a_33 Direction of stone stream: Left

a_4 Customer preferences

a_41 Washing on multiple levels: ○ No ● Yes

a_42 Overflow type: Active

a_43 Mixing tank: ○ No ● Yes

a_44 Spread product: ○ No ● Yes

a_45 Empty run system: ○ No ● Yes

Output variables

Q_c Calculation capacity [TPH]: 40 [TPH]

Machines installed in the line per machine type	Amount	Specifications	Options	
pintle belt	b0 1	EB-1200x1500		
destoner	b1 0			
drum washer	b2 1	TW-450-1300x4800		
washer/destoner	b3 0			
FPR	b4 0			
clay bath	b5 1	FPR-K-450-1200x6000-L	+ mixing tank	
roller spreader	b6 1	RS-1100-7DR		
roller dryer	b7 1	RD-450-2000-20R	+ empty run system	
forward dewatering drum	b8 0			
reverse dewatering drum	b9 1	OW-TZ-R-0600x1000-L		

Fig. 7: Panel where the input and output parameters are defined in the LabView model for washing line configuration.

After all parameters are defined, the relations between them are defined in the LabView-source code. This source code is a very complex diagram that connects all the input and output parameters and defines the logic between them. This complex model is well structured and build up out of many different if-statements to define the corresponding output for every possible combination of input parameters.

When the model is set up as a complex combination of these if-statements and describes all possible input combinations, it can be iteratively checked and improved. To do this, multiple different situation examples are used. For each example a list of input parameters is determined after which these input parameters are filled into the LabView model. Then the model is ran. If the machine lines coming out of the model differ from that coming out of the choice scheme, the model is improved until it gives the correct machine line recommendations for all examples. The basic machine line configuration model is then finished.

V. SMART WASHING LINE CONTROL

As previously discussed, different product batches come with different kinds and levels of pollution. Next to that, different washing applications come with different requirements regarding the washing quality. Something important for every application is that the quality of the output product has to be constant and compliant with the standards. To make sure a constant washing quality is realised while processing different batches consecutively, machine operators are hired to keep an eye on the performance of the washing line, tweak settings of the machines and perform small maintenance jobs. Because of growing machine complexity, decreasing quality of machine operators and increasing possibilities for smart control, it would be advisory to install a network of sensors, actuators and controllers to control the washing line in a smart way, and thus realising an adaptive washing line.

Smart control has lots of benefits over manual control of the washing line. Sensors are installed in the different machines in the washing line to measure certain parameters that give important information about the functioning of the washing line, called KPIs. For each of the KPIs specific thresholds are determined. If the thresholds are breached, the system will know that action has to be taken to optimise the functioning of the machine. Control algorithms will calculate what needs to be done and the controller sends the right output signals to the right actuators in the specific machine (Sufian et al., 2021).

There are two types of control that can be applied to the machines. With open loop control the controller receives an input signal and then sends its output to actuators that make changes to the system. An example can be a transport conveyor that is fed with a certain product capacity Q. The controller then determines what belt speed v_b is needed for this capacity and sends a signal to the electric motor to power the conveyor. In closed loop control, a sensor is built into the system. This sensor checks if the behaviour of the system fits the input signal. If the system behaviour deviates from the desired behaviour and therefore from the input signal, the controller is corrected. In the same example a proximity sensor for example can be placed above the conveyor belt to measure the height of the transported product. If the pile on the belt is too high the controller gets a signal to increase the belt speed. This process is repeated either continuously or discrete. In continuous control the control loop is repeated continuously and in discrete control it is repeated on an interval basis. The structure for these two different kind of control loops are shown in figure 8 and 9 (Aström & Murray, 2009).

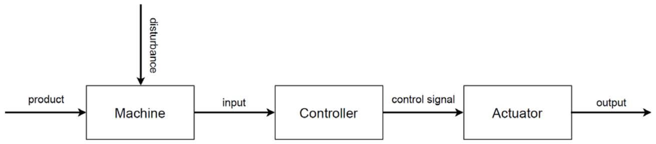


Fig. 8: Example of an open loop control scheme.

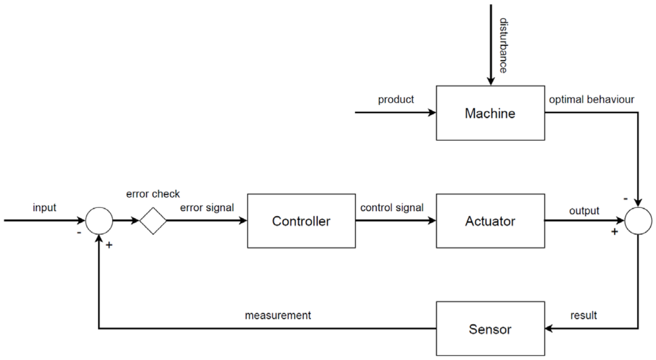


Fig. 9: Example of a closed loop control scheme.

Important KPIs that are often used in feedback loops for processing lines are good-to-bad and bad-to-good ratios. The good-to-bad ratio defines the amount of suitable product that ends up in the waste stream. In case of the tuber washing line this can be the amount of potatoes that end up on the waste heap. The bad-to-good ratio defines the amount of unsuitable product or waste that ends up in the product stream. In the same example this can be the amount of stones that remain in the product stream after the washing line. In smart systems these KPIs can be measured to analyse the functioning and efficiency of the machine line. Through feedback loops these KPIs are commonly used to detect malfunctioning of the line and correct the machine settings after sending the error signal to the controller.

The machines in a washing line can be equipped with multiple sensors to acquire data. The information obtained by these sensors is send to the central computer through a Digital to Analog Converter (DAC) device (Wright, 2014). Sensors can for example be used to monitor performance, wear, production errors, safety issues and other deviations from the optimal functioning of the processing line. The sensors can be connected in different network topologies. The network topology is the way the network of sensors and routers is structured. For the washing line the tree-network is the best fitting topology, figure 10 shows a schematic picture of this topology. In this network structure, every sensor is connected to a sensor node and for each machine the sensor nodes are connected to a router. The machine routers on their turn are connected to the main router. The main router communicates with the server to store all data, which is connected with the computers in the control room and with the mobile devices of the machine operators and mechanics. Professionals from the company that produced the machine line and the company that makes the software to control the washing lines are able to log into this system via a secured Virtual Private Network (VPN) connection. One of the benefits of this network topology are that the network is very flexible and sizable, which is ideal for a modular washing line. The fact that the network is structured with a router per individual machine makes it possible to analyse the performance of these individual machines. Downsides of this topology can be that it takes more cabling than other methods and that branches can be detached from the system when a router fails or when a connection is broken (Varga, 2017; WhatsUp Gold, 2021). These problems however, can easily be solved. When the sensors and routers are connected through a WLAN or internet connection, cabling can be reduced. When a router breaks down, the power is lost or the signal is blocked or interfered, the sensor can re-route to another router. This way a self-healing network is realised (Pang, 2020).

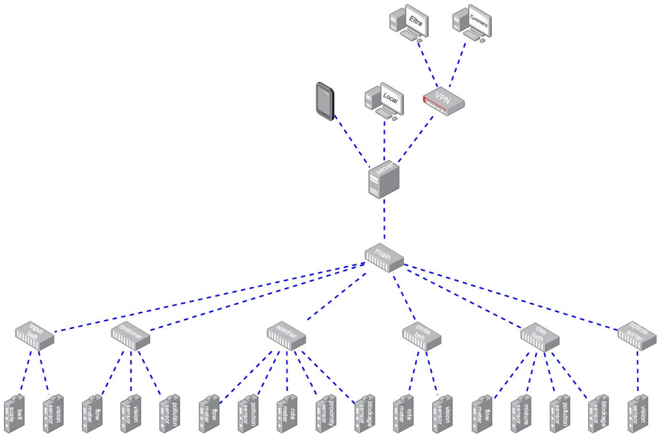


Fig. 10: Network topology for smart control of a tuber washing line.

VI. BENEFITS OF AN ADAPTIVE MACHINE LINE

Changing the strategy for designing customer specific machine lines to adaptive design has lots of benefits for the different departments throughout the company that produces these machine lines. The biggest benefits that apply to all departments are the increase in clarity and automation and decrease in friction between the different departments. When a clear standard is created through the modular approach to design the machine lines, this standard comes with a lot of clarity for all the departments about what specific machines the company is selling. When this machine portfolio set up out of a set of standard modules and their specifics are known throughout the company, this takes away a lot of friction between the different departments. Misunderstandings about complex customer specifically engineered machines derived from faulty communication are limited. Working with a modular design of machines from a standardised portfolio enables automation of processes throughout the company that are now very time consuming like constructing quotations, manuals, parts lists, CAD drawings and manufacturing instructions. This clear standard, when extensively documented, also makes transfer of knowledge to new employees much easier.

Smart control of the machine line has lots of benefits for the customer but also for the production company. If the machine line is equipped with sensors that monitor the wear in wear sensitive parts, they can be replaced when nearing the end of their lifetime. The replacements can be performed during scheduled maintenance and breakdown of parts is prevented, this way machine downtime is reduced greatly. Because the speed of the product belts in the machine line is controlled with respect to the throughput, the wear in these belts can be reduced. Belts are the most expensive wear sensitive parts in the washing line to replace. This is not only because the prices of these industrial belts are quite high but also because the belts are very heavy. Big belts need to be replaced with help of a crane. This operation takes about a day because the belts are positioned in a difficult place to reach and therefore a big part of the machine needs to be reassembled during maintenance.

Another benefit of smart control of the machine line is the reduction of product ending up in waste streams. Initial product that ends up in waste streams cannot be processed into saleable end product. Even though these bad-to-good ratios are commonly very low, decreasing this ratio even further leads to large savings. This is caused by the fact that processing lines commonly have large throughputs and prices of raw materials which are quite high. Losses are even higher because not only a share of the input product is lost, but also less saleable end product is produced.

The last customer benefit of smart control of the machine line is less dependency on machine operators. The smart system automatically optimises the process quality and efficiency without the operator needing to constantly tweak the settings of the machine line. This way not only the quality of the output product is improved with reduced use of resources, but also less machine operators are needed to run the factory. Bigger factories that contain multiple consecutive machine lines can now have a machine operator that controls multiple lines instead of a dedicated operator solely for control of a single line. This reduces costs due to wadges of machine operators.

Smart design of the machine lines also brings some advantages for the support department. The support department is able to log into the software that monitors and controls the machine line through a VPN connection to see into the current and past performance statistics to diagnose the problem. This way remote solutions to certain problems can be determined more easily and mechanics send to perform maintenance can be equipped with the right information, replacement parts and tools to perform the maintenance more efficiently.

VII. CONCLUSIONS

There are multiple different options to model a smart modular machine line. Different models need to be combined though to get a complete overview. The jigsaw puzzle model, which is created in this research, makes it possible to design a modular machine line and form a basis for a smart control system with a single model. First the available modules and options are set out in a machine portfolio matrix. Afterwards the relations between the relevant inputs and the output, namely the machine line configuration, are set up. To get a clear visual model based set up based on the data flow, LabView can be used as a modelling software. The jigsaw puzzle model can be expanded in CPQ software to automatise the design process even further by coupling the standardised modules with documentation like parts lists, technical drawings and prices. Next to designing a modular machine line, the model sets out the first basis of a DT for smart control of the machine line. The jigsaw puzzle model is created to design modular smart machine lines but can also be used for other design purposes. Some examples are modular architecture, furniture or for designing ports. The method of jigsaw puzzle modelling can be further expanded with modelling rules for creating a modular DT. The information of certain parameters in the model can then automatically be used for smart control of the machine line when the digital modular design model is linked to the SCADA system in the factory.

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B Name convention

To make it easy for all personnel to recognize machines and their characteristics immediately, a name convention is used throughout the company. Figure 46 below shows an example of a machine name. The different parts of the machine name are described as follows.

1. Machine type *(see table 26 below)*
2. Capacity index *(320, 450, 600, 700 or 800)*
3. Dimensional parameters *(for example the width and length of the product belt or the amount of rollers)*
4. Direction of the waste belt and water content *(L=left, R=right, A=backward, N=wet, D=dry)*
5. Extra options *(see table 27 below for examples)*, can also contain the direction of the corresponding waste belt

$$\underbrace{KW}_{1.} - \underbrace{600}_{2.} - \underbrace{1.65 \times 5}_{3.} - \underbrace{L}_{4.} - \underbrace{DDSL}_{5.}$$

Figure 46: Example of the name convention.

Code	Machine type
DS	Dry soil remover
EB	Pintle belt
FPS-K	Clay bath
FPS-V	Floating parts separator
FPS-Z	Brine separator (salt bath)
KS	Destoner
KW	Washer/destoner
OTZ	Dewatering drum
RD	Roller dryer
RS	Roller spreader
TR	Transport equipment
TW	Drum washer
UV-C	Surface disinfection with UV
WB	Soak tank
WTD	After washer

Table 26: Alphabetic list of codes and corresponding machine types.

Code	Extra option
DDS	Mechanical FPR
OA	Active overflow channel
OH	Manual overflow channel
LD	Empty run system
UV	UV lamps
F	Forward dewatering drum
R	Reverse dewatering drum

Table 27: List of extra options.