Performance analysis of parcel sorting system configurations

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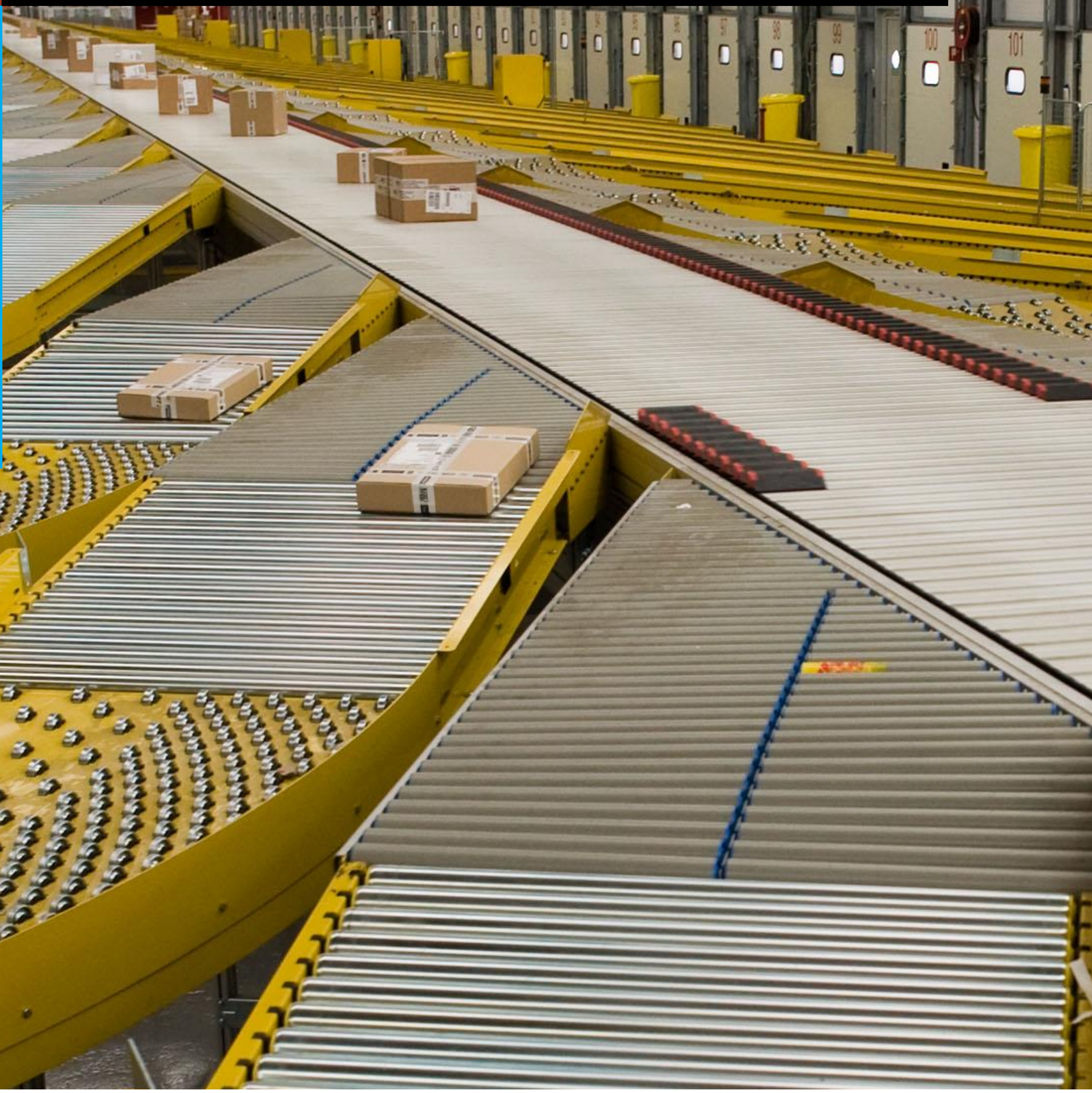

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Challenge the future

Performance analysis of parcel sorting system configurations

by

V. Groeneweg

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Preface

With this report in front of you, the proverbial journey of my master thesis finalizes. This journey of completing this thesis has been intense, the learning curve has been extremely steep, but I believe that the challenges have been overcome and as a consequence made me a better engineer. I am proud of the finished product.

It all started from my interest in engineering combined with logistics which was the reason for choosing the master. As completion of my master I wanted to choose a topic with a company which fit my interest which became material handling solution. Therefore, I contacted VanRiet and could already quickly start with the creation of an assignment. This firstly involved an extensive research in the available sorting solutions with their capabilities. However, it turned out that the assignment I was facing could give me at least another year of work. It started as a design methodology based on the requirements of the customer which I had to scope since *"You cannot solve all the world's problems within your thesis"* as I got correctly noted.

Further on in my research I got several times stuck into details. This is where I am thankful to my great supervisors at VanRiet. I would like to express my deepest gratitude to: Joyce Klaij, Teun Jelle Lasche and Ruben Burger for the many times we had discussions about new ideas or even moves I wanted to make within my research. I have to say you really helped me through the whole thesis process with keeping me focused to this moment of delivery. In addition, I want to thank Hans Veeke and Dingena Schott for the discussions and feedback especially get me out of the details and help to set my thesis in perspective.

With this thesis I may conclude my masters Transportation, Engineering and Logistics at the Delft University of Technology. I am grateful to my lovely parents, Kees and Jolanda, for their continuous support and patience throughout my study and especially within my thesis. Last, but certainly not least, I would like to thank my brother Eric for his ability to keep me grounded.

Vincent Groeneweg

Delft, April 19 2018

Summary

Within recent years, the parcel transport industry has experienced an increase in the volume of handled parcels due to the rapid growth in e-commerce (Clausen et al. 2015). The commonly known parcel handlers, such as DHL, DPD, UPS and TNT, collect the parcels from the sender and deliver these via one- or several parcel-hubs to the destination. Within these parcel-hubs the transport and sorting is often performed by an automated parcel sorting system (Bonini and Jain 2000). These systems are characterized by having multiple loading areas which are connected to a main-line conveyor. This is followed by the identification of the parcel which concerns scanning, measuring, weighing and eventually the sorting to the correct truck as visualized within Figure 1.

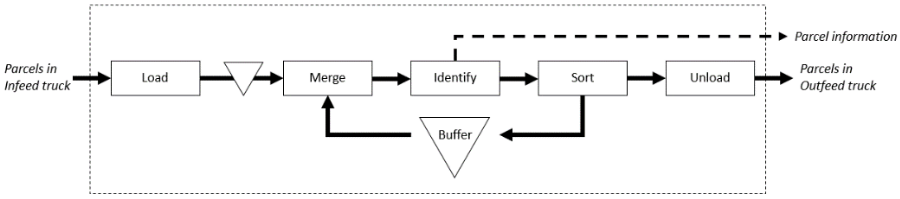


Figure 1: Functional process description of a parcel sorting system

Due to the described increase in parcel volumes the parcel handlers bear a higher pressure on their handling process (Fikse 2011). Conventionally, the method to enhance the capacity of the systems involved the improving of the system speed. However, the speed is facing the limits of physics, as with higher speeds, parcels may lose contact with the conveyor (Landschuetzer, Wolfschluckner, and Jodin 2013).

Within an ideal system the parcels would be placed, which is called merged, on the main-line without any gaps between the parcels. However, to perform the described functions a gap is required which is based on the parcel characteristics and the system configuration. Whenever the gap between the parcels does not match the required gap, the parcel may not be sorted correctly, called overflow.

Currently, the parcels are commonly merged onto the main-line with a gap based on the maximum required gap for the range of parcel dimensions. Therefore, the parcels are placed behind each other with a fixed head-to-head distance, which is called fixed-windowing, or an equal gap which is called fixed-gapping. In addition, the parcel may be merged with the minimum gap for the specific length and width which is called dynamic-gapping. Furthermore, the settings for fixed-windowing and fixed-gapping may be defined below the maximum requirements, which may result in a fraction of the parcels that cannot be sorted correctly.

The current method to define a system configuration includes a prediction of the system performance which is generally based on individually the sorter- and checkweigher configuration. Therefore, the impact of specifying the window by a fraction of the maximum gap-requirement or even dynamic-gapping cannot be estimated. This is the reason this research is initiated at VanRiet Material Handling Systems, a supplier of sorting systems, with the objective to retrieve insight in the impact of system configuration on the performance.

The main configurations which influence the performance of the system concern the checkweigher configuration, the sorter and the used gap-setting at the merge. This involves for the checkweigher, the number of scales, the scale-lengths and method how the weighing is performed. For the shoe-sorter, which is often applied within parcel sorting systems (Jodin and ten Hompel 2012a), the required gap is related to the sort-angle and the parcel width.

To assess the impact of the system configuration on the performance a model has been developed which simulates the parcel sorting process. Experiments are performed on the model to determine the impact of the configuration, overflow and the input-pressure. The performance within these experiments represented by the throughput, in handled parcels within steady-state, including the rate overflow.

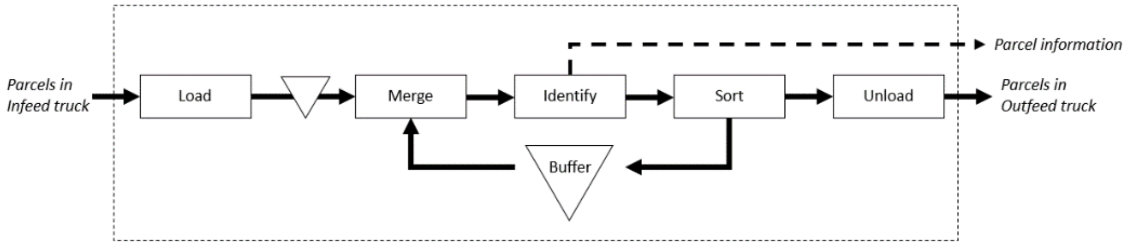
It is retrieved from these experiments that the checkweigher generally limits the throughput for the system. Besides this, it appears that the sort-angle impacts the parcel throughput by around 1% while this is 6% in a system without a checkweigher. In addition, the configuration of the checkweigher generally impacts the throughput by 5%. The highest impact is addressed to the windowing-method and window-setting. It appears that these, for the defined reference scenario, reduce the parcel throughput by at least 17% compared to dynamic-gapping when no overflow is permitted.

However, the impact of fixed-windowing and fixed-gapping compared to dynamic-gapping may be reduced by defining a setting below the maximum requirement. When this is applied, a fraction of the parcels may become overflow, while the throughput increases. This involves, for the reference scenario, a reduction to the performance with dynamic-gapping of at least 12% with fixed-windowing while this is at least 9% with fixed-gapping. Within a loop-sorter this increase in throughput generally does not appear due to the fact for a maximum arrival of parcels. Therefore, the parcels with a too small gap-setting may keep recirculating which reduces the throughput and may eventually result in blockage.

Results of the performed experiments, revealed insight in the impact of system configurations on the performance. This concerns that the appliance of the checkweigher mainly limits the throughput instead of the shoe-sorter. In addition, this research quantified the impact of the configuration which showed that the currently used windowing-method with fixed-gapping or fixed-windowing highly impact the throughput.

Samenvatting

In de afgelopen jaren ondervond de pakket industrie een toename in het aantal pakketjes als gevolg van de snelle groei in e-commerce (Clausen et al. 2015). De traditionele koeriers, zoals DHL, DPD, UPS en TNT halen pakketten op bij de klant en vervoeren deze via één of meerdere overslag-locaties (hubs) naar de bestemming. In deze hubs wordt het transport en sorteren vaak uitgevoerd door een geautomatiseerd pakketsorteersysteem (Bonini and Jain 2000). Deze systemen zijn kenmerkend voor het hebben van meerdere laadruimten welke verbonden zijn aan de hoofd-transportband. Vervolgens worden de pakketjes geïdentificeerd door de barcode te scannen, te meten en te wegen waarna de pakket naar de juiste vrachtwagen worden gesorteerd, zoals geïllustreerd in Figuur 2.



Figuur 2: Functionele proces beschrijving van een pakketsorteersysteem

Door de toename van pakketvolumes verhoogt de druk op het verwerkingsproces van koeriers (Fikse 2011). De traditionele methode om de capaciteit van systemen te verbeteren lag bij de systeemsnelheid. Het blijkt echter dat deze snelheidsverhoging bij de natuurkundige limieten komt omdat bij hogere snelheden de pakketten het contact met de transportband verliezen (Landschuetzer, Wolfschluckner, and Jodin 2013).

In een ideaal systeem zouden pakketten zonder tussenafstand op de hoofd-transportband kunnen worden geplaatst. Echter, om de bovengenoemde functies uit te voeren is er een tussenafstand vereist wat gerelateerd is aan de afmetingen van het pakket en de systeemconfiguratie. Wanneer de tussenafstand niet overeenkomt met de vereiste tussenafstand wordt het pakket mogelijk niet correct gesorteerd, ook wel overflow genoemd.

Momenteel worden de pakketten vaak op de hoofd-transportband geplaatst met een tussenafstand op basis van de maximaal vereiste tussenafstand voor de maxima aan pakket afmetingen. Dit wordt gespecificeerd met een vaste kop-tot-kop afstand, wat fixed-windowing wordt genoemd, of een gelijke tussenafstand, wat wordt aangeduid als fixed-gapping. Daarnaast kunnen de pakketten op de hoofdlijn geplaatst worden met de minimaal benodigde afstand voor het specifieke pakket, genaamd dynamic-gapping. Ook kunnen de instellingen voor fixed-windowing en fixed-gapping kleiner worden gespecificeerd als de maximale eis voor alle mogelijke pakketten. Uiteindelijk kan dit resulteren in een deel van de pakketten die niet correct wordt gesorteerd.

De huidige methode om een systeem configuratie te definiëren is gebaseerd op de verwachte prestatie van afzonderlijk de sorteer- en weegunit-configuratie. Daarom kan het effect van de specificatie van de tussenafstand als fractie van de maximale tussenafstand en dynamic-gapping niet worden bepaald. Om deze reden is het onderzoek bij VanRiet Material Handling Systems gestart, met als doel inzicht te krijgen in het effect van de systeemconfiguratie op de prestatie.

De belangrijkste configuraties die de prestatie van het systeem beïnvloedt, betreft de configuratie van de weegunit, de sorteerder en de instelling voor de tussenafstand bij het plaatsen op de hoofd-transportband. Deze configuratie omvat voor de weegunit, het aantal weegbanden, de weegbandlengten en de manier waarop het wegen wordt uitgevoerd. Daarnaast is de vereiste tussenafstand voor de shoe-sorter, die veelal wordt toegepast in pakket sorteer systemen (Jodin and ten Hompel 2012a), gerelateerd aan de sorteerhoek en de pakketbreedte.

Om het effect van de systeemconfiguratie op prestatie te beoordelen is in dit onderzoek een model ontwikkeld wat het pakket sorteer proces simuleert. Experimenten zijn uitgevoerd op het model om de invloed van de configuratie, overflow en fluctuerende aankomst van pakketten te onderzoeken. De resultaten uit deze experimenten zijn vergeleken op basis van de doorvoer aan pakketten in steady-state.

Uit de experimenten kan worden geconcludeerd dat de weegunit in het algemeen de pakket-doorvoer voor het systeem beperkt. Daarnaast blijkt dat de sorteerhoek de pakket-doorvoer met ongeveer 1% beïnvloedt, terwijl dit 6% is in een systeem zonder weegunit. Tenslotte is de impact configuratie van de verschillende weegunit configuraties voornamelijk 5% op de pakket-doorvoer. De grootste impact op de pakket-doorvoer komt voort uit de methode hoe tussenafstand wordt gespecifieerd bij het plaatsen van de pakketten op de hoofdlijn met fixed-windowing en fixed-gapping. Voor het referentiescenario kunnen deze methoden de pakket-doorvoer met 17% verminderen in vergelijking met dynamic-gapping, wanneer geen overflow is toegestaan.

Echter, de reductie op de pakket-doorvoer van fixed-windowing en fixed-gapping ten opzichte van dynamic-gapping kan worden verminderd door de tussenafstand kleiner te specificeren als maximaal benodigd is. Wanneer dit wordt toegepast kan een fractie van de pakketten resulteren in overflow, terwijl de pakket-doorvoer toeneemt. Voor het referentiescenario kan deze gereduceerde instelling het verschil in pakket-doorvoer ten opzichte van dynamic-gapping reduceren met tenminste 12% voor fixed-windowing terwijl dit bij fixed-gapping minimaal 9% is. Binnen een sorteerder met rondloop komt deze toename in pakket-doorvoer meestal niet voor. Namelijk, in een systeem met rondloop kunnen de pakketten met een te kleine tussenafstand kunnen blijven recirculeren als het systeem een maximale aanvoer van pakketten heeft. Dit kan resulteren in een verminderde pakket-doorvoer wat uiteindelijk tot blokkering kan leiden.

De resultaten van de experimenten hebben inzicht gegenereerd in de invloed van systeemconfiguratie op de prestatie. Dit betreft dat de weegunit hoofdzakelijk de beperkende factor is voor de pakket-doorvoer in plaats van de shoe-sorter. Bovendien heeft dit onderzoek de impact gekwantificeerd van de, momenteel veel gebruikte methoden van fixed-windowing en fixed-gapping welke de pakket-doorvoer beperken.

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Glossary

GOS	Gap Optimization System
KPI	Key performance indicator
LSL	Long Side Leading
pph	Parcels per hour
SSL	Short Side Leading
VanRiet	VanRiet Material Handling Systems
VDI	Verein Deutscher Ingenieure

1. Introduction

In recent years the parcel handling industry experienced a fast growth in the number of shipped parcels which is related to rapid-growth in e-commerce (Clausen et al. 2015). The provided service to collect a parcel and deliver it towards the customer is provided by a few large parcel handlers such DHL, DPD, UPS and TNT. Within these transport networks, generally one or more parcel-hubs are included which are mainly automated sorting system (Bonini and Jain 2000). Eventually, the transport process concludes with the delivery of the parcel to the final customer.

This introduction firstly gives a brief introduction of the system which is installed within the parcel-hub within section 1.1 followed by the company profile in section 0. Hereafter, the objective of this research is defined within section 1.3 with the research questions in section 1.4. Lastly, the outline for this report is described within section 1.5.

1.1 General process description

In order to perform the parcel transport in a cost-efficient manner the transport generally involves a set of parcel-hubs. Within these, the parcels with adjacent destinations are sorted towards one truck. Traditionally, this process was mainly a manual process. However, due to the growth in demand and the increasing labour costs this process is generally fulfilled by automated systems (Intelligrated and Naylor 2013). The sorting systems can vary from simple sorting systems which may handle a 1.000 parcels peak per hour, towards the larger parcel sorting systems which may handle up-to 15.000 parcels per hour (pph).

The parcel sorting system is a system which transports the parcels with several belt-conveyors and a sorting system towards the destination. The process starts with the parcels being unloaded from the truck onto the system inputs, so called infeeds. These infeeds transport the parcels towards the merge-area where the parcels from several infeeds are transferred onto the main-line as visualized within Figure 1.1. A system involves a variety of trucks where the parcel may be sorted to. Therefore, the parcels could be sorted towards a variety of outfeeds from the main-line. Whereafter the parcels are loaded into the appropriate truck. This operation is often performed by a shoe-sorter which is visualized within Figure 1.2 (Jodin and ten Hompel 2012a).

Figure 1.1: Merging of parcels from the trucks onto the main-line

Figure 1.2: Sorting with a shoe-sorter towards the outfeeds where the destination-trucks are positioned

1.2 Company profile

One of the suppliers of parcel sorting systems, VanRiet Material Handling Systems (VanRiet), initiated the assignment for this research. VanRiet has for over sixty years of experience in the design, production and installation of material handling solutions. The main facility of VanRiet is situated in Houten, but the company even has facilities in Poland and China resulting in a total of around 160 employees. With the growing interest in their systems, the company even experiences a large growth, which is reflected by a position within the top 100 of production companies of the Netherlands (MT.nl 2017).

1.3 Research motivation and objective

With the rapid growth in the e-commerce sector the parcel handlers bear a higher pressure on their handling process (Fikse 2011). This results in a continuous higher demand on the performance of the sorting-systems. Conventionally, the method to enhance the capacity of the systems involved the improving of the system speed. However, it turns-out that this is facing the limits of physics while with higher speeds parcels may lose contact with the conveyor (Landschuetzer, Wolfschluckner, and Jodin 2013), resulting in rates of damaged or miss-sorted parcels.

The system speed is only one factor in the maximum capabilities of the system. Besides this, the space which is set between the parcels sets the limit. This distance is generally based on the requirements for the system functions, as for example the sort-angle and the speed which define a certain distance (Intelligrated and Naylor 2013). However, it is currently unknown what the impact is of a reduction of this distance, so called gap has on the performance of the system. Therefore, this research is initiated which examines the impact of different configurations on the maximum performance.

Different concepts are available to perform the sorting within a system. From these, the shoe-sorter is often applied within the parcel industry since it encounters a high throughput with a gentle sorting movement (Rushton et al. 2010). Therefore, the scope of this research is limited to the shoe-sorter.

1.4 Research questions

Based on the defined objective the research questions are outlined which are examined within this research. This is represented by the main question and consecutively answered by the sub-questions:

> *What is the sensitivity on the performance of parcel sorting systems including a checkweigher, subjected to stochastic input characteristics?*

1. *What factors within a parcel sorting system configuration limit the performance?*
2. *What KPIs may be used to predict the performance of a parcel sorting system?*
3. *What is the impact of system configurations on the performance of a parcel sorting system?*
4. *What is the impact of unsorted parcels on the performance of a parcel sorting system?*
5. *What is the impact of varying input-pressure on the performance of a parcel sorting system?*

1.5 Report outline

The report starts with chapter *2. Research context*, therein an outline of the general functioning of a parcel sorting system is described. This involves an overview of installed equipment, the characteristics of the parcels and a brief literature review. This is followed by chapter *3. System analysis* which describes the design procedure of a system, the functional limitations of the installed equipment with the current method to estimate the system capacity. The system analysis gives insight in the current problems to estimate the capacity, including the limitation, which are described within chapter *4. Problem definition & research outline*. Hereafter, a model is created to attain the research objective in chapter *5. Model definition*, which is used within chapter *6. Experiments & results* to examine experiments. Eventually these experiments lead to the conclusion on the defined research questions within chapter *7. Conclusion and recommendations.*

2. Research context

In order to retrieve insight in the functioning of the system the context of this research is firstly examined with a general system description. This includes the customer and the equipment which are involved within a parcel sorting system. Furthermore, the reader is given insight in the parcels and their characteristics which are handled by the system. Lastly, a brief literature survey about capacity analysis of sorting systems is included which was retrieved from literature prior to this research.

2.1 System description

The parcel sorting process starts from the sender where the parcel is picked-up by small trucks. To reduce transport costs, these parcels are batched based on their destination within a parcel-hub, the send-hub. This batching involves the transportation and sortation of the parcels from the infeed-trucks (input) towards the outfeed-trucks (output). Hereafter, the outfeed-trucks transport the parcels towards the succeeding locations. This may be direct or indirectly via multiple hubs, towards the receive-depot as visualized within Figure 2.1. Eventually, at the receive-hub the parcels are sorted towards smaller trucks which finalize the parcel transport towards the receiver.

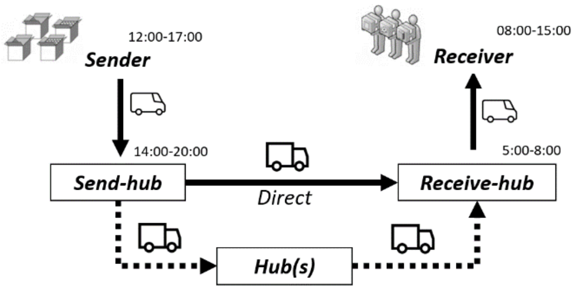


Figure 2.1: Parcel-hub within its environment

2.1.1 Functional description

Within a parcel-hub the sorting system forms the link between the infeed-trucks and the outfeed-trucks. One infeed truck typically has parcels for a variety of outfeed-trucks. Therefore, the parcels from the infeed-truck are transported and sorted towards a variety of outfeed trucks. This is visualized within the representation of a parcel sorting system as visualized within Figure 2.2.

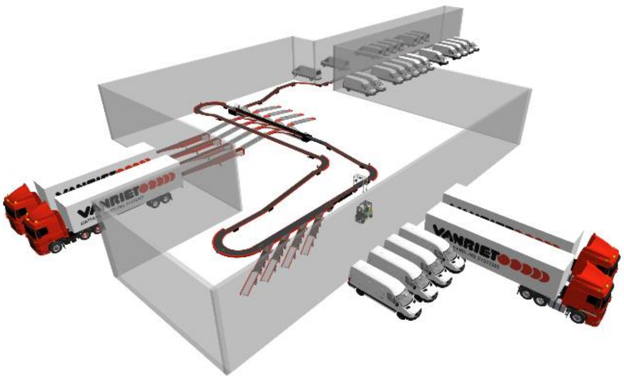


Figure 2.2: General representation of a parcel sorting system

The presented system includes the described infeeds, merge, sorting and outfeeds. In addition, the system includes an identification unit on the main-line to identify the destination of the parcel. To gain more insight into the system as a whole, it is converted into a functional description as visualized within Figure 2.3. Besides the defined functions transport is involved within this process which is represented by the arrows within the representation. Hereafter, the listed functions are described to give insight in the functioning of the system and the used equipment.

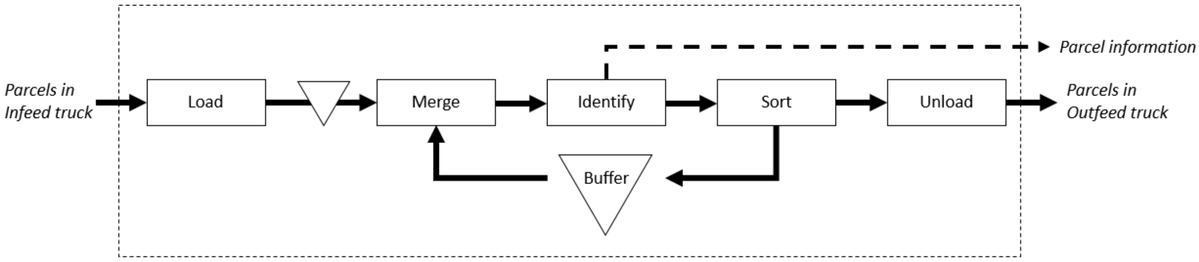


Figure 2.3: Functional description of a parcel sorting system

Load

The loading of the system occurs from multiple trucks which load the parcels onto the system at the infeed. Generally, a system includes a variety of infeeds where parcels may be unloaded from one truck or either multiple trucks.

How the parcels are loaded onto the system is specified by VanRiet. This involves the orientation, which is defined as Short Side Leading (SSL) meaning the longer side of the parcel is in the parcel direction as visualized in Figure 2.4. The requirement is stated since it is expected from practice that the reliability decreases whenever the parcels are placed with Long Side Leading (LSL).

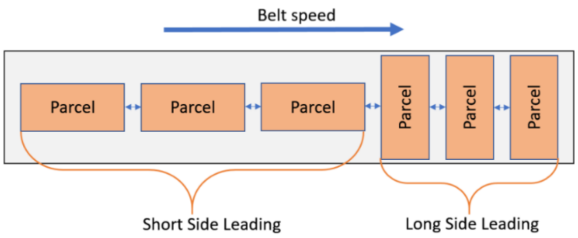


Figure 2.4: Parcel input orientation

Merge

The previously described infeed generally has multiple infeeds connected to one main-line where sorting occurs (Intelligrated and Naylor 2013). In order to achieve this, the parcels from several infeeds are transferred to the main-line, so called merging. This operation is executed by a control algorithm that sets the position and order of the parcels on the main-line. The algorithm reserves space on the main-line for the parcel, whereafter the parcel is merged at a defined time onto the main-line.

The space which is used for a parcel on the main-line highly depends on the settings within the control algorithm. This space consists of the parcel length and the distance between the parcels, called the gap. The total space a parcel requires, including the gap, is called the window as listed within Figure 2.5. Different methods are available to set the total parcel window which is further described within section 3.3.4. The gap can be exactly the required gap as defined by the equipment or even larger when it is specified larger by the settings, the window-gap

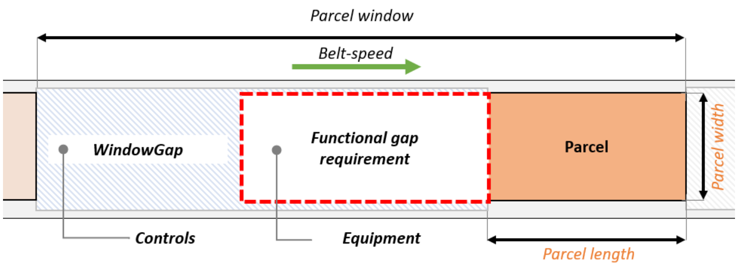


Figure 2.5: Gap explanation

Identify

After the parcels are merged onto the main-line, they are transported towards the following function which involves the identification of the parcel. This identification may consist on or more of the following aspects:

- Scanning
- Dimensioning
- Weighing

The scanning is required to retrieve the parcels identity from its barcode. With this information the system can retrieve the parcel destination which is then used to sort the parcel to the correct outfeed. An often applied solution is to install a laser-based scanner to read the barcode. A scan-unit generally scans multiple sides of the parcels, up to six sides. However, even one-dimensional scanning is available where the operators need to load the parcel with the barcode on the correct side of the system.

The parcel handling industry is characterized by pricing which is based on dimensions and weights of the parcel. Therefore, a parcel handler often implements a dimensioning and weighing systems. These systems ensure the parcel handler that the correct price is paid for their services. Often the identification-units are combined within one system, as visualized within Figure 2.6. The weighing within this system is performed by one- or two small conveyors, which in total is called the checkweigher.

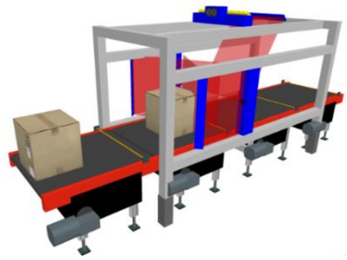


Figure 2.6: Identification-unit

Sort

After the parcel destination information is retrieved from the barcode, the parcel can be sorted towards the appropriate outfeed. The sorting operation may be performed by a variety of different sorting concepts. For a general overview a brief listing of the available sorting concepts is included within Table 2.1. Within this, the capacity is only included for the matter of comparison since the parcel length is un-specified. The decision to choose between the different principles within a system design is highly dependent on their abilities and costs.

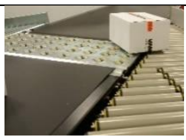
Type	Pusher	Pop up sorter	Shoe Sorter	Tilt tray sorter	Cross-belt sorter
Capacity	1.500 – 7.200	7.500	8.000 – 15.000	4.800 – 7.200	12.000 – 26.000
					

Table 2.1: Sorter comparison – Capacity in Parcels Per Hour from (Jodin and ten Hompel 2012a)

Since this research involves the shoe-sorter, this principle is further described. Firstly, a shoe-sorter operates as a common conveyor, represented slats that perform the straight transportation. Generally, numerous outfeeds are connected to the main-line, being on one side or both sides of the sorter, as visualized in Figure 2.7. The sorting is performed by the shoes that are positioned on the slats. Whenever a parcel needs to be sorted the required number of shoes are guided towards the outfeed, resulting in the parcel being gently pushed off the main-line.

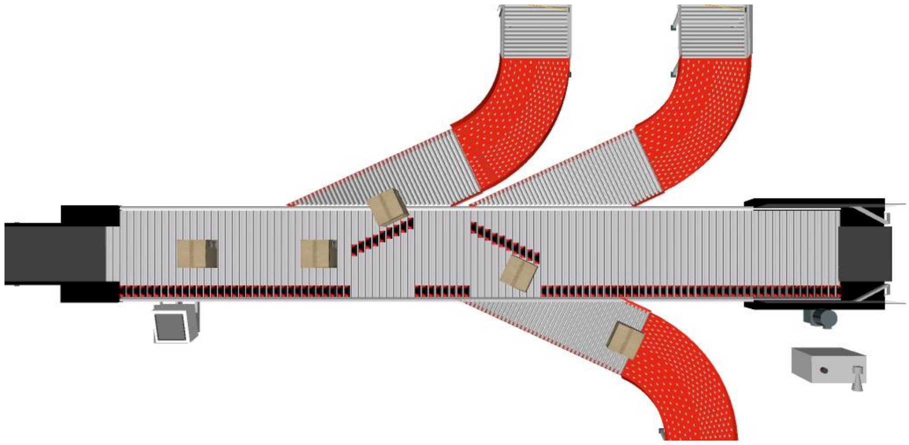


Figure 2.7: Top-view of a shoe-sorter

Unload

Eventually, the parcels are sorted onto the outfeeds which are aligned with the sort-angle of the shoe-sorter. After leaving the main-line, the parcel is transported towards the outfeed-truck where an operator unloads the parcel from the system into carts or directly into the truck. One outfeed may be linked to one or several trucks, depending on the system design and truck sizes. Opposing to this, one truck might even be loaded from several outfeeds.

Buffer

The last function which is involved within the operation is the buffer. This may be included as temporary storage, however this is generally not included within parcel sorting systems (Haneyah 2013). Within a parcel sorting system the parcels can generally directly sorted towards their destinations which leave out the requirement for a storage. Opposing to this, the system may involve an area where manual operations are performed to handle the parcels, like customs which can be described as a buffer-area. Hereafter, the parcels are again merged onto the main-line. Another example of a buffer principle is the ability to recirculate the parcels, which is further described within the following section.

2.1.2 Layout

A parcel may not be sorted to the outfeed when the state does not match the requirements. This may for example concern a parcel which is too large to be handled by the sorter, resulting in an unsorted parcel called overflow. Depending on whether the system is a loop sorter or a line sorter, the process for this unsorted parcel differs.

Line-sorters

The simplest layout concerns a line-conveyor where the overflow continues on the sorter until the end of the sorter as visualized within Figure 2.8. These line-sorters require manual labour to handle the parcels from the overflow to the correct outfeed. As an effect the investment for the system are smaller, however the fraction of overflow significant increases the handling costs since additional labour needs to be hired (Haneyah 2013).

Loop-sorters

The more complex configuration is characterized by the loop-sorter, from Figure 2.9, which transports the unsorted parcels back to the merge area. This concept directly reduces the throughput since main-line space is occupied by the overflow which may otherwise be used by newly merged parcels (Haneyah 2013).

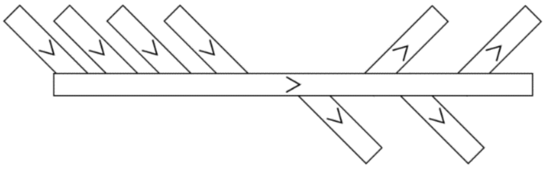


Figure 2.8: Line-sorter

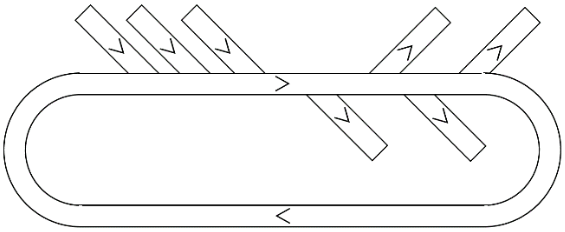


Figure 2.9: Loop-sorter

2.2 Input characteristics

The input of the system consists of conveyable and non-conveyable goods. The conveyables are the parcels that are handled by the automated system, while the non-conveyables need to be handled manually. The non-conveyables exceed the restrictions for the input characteristic of the system. However, within this research only the conveyables included.

The input characteristics may include a variety of factors which affect system performance. Firstly, the characteristics of the parcels may vary between different systems, but even between different times on the same system. This for example includes the dimensions, weight, firm fastness and frictional behaviour. From these properties the dimension are currently generally used to predict system performance while the weight, firm fastness and frictional behaviour may even affect the reliability within operation (Jodin and ten Hompel 2012a).

Currently the amount of detail of the expected dimension highly varies within design requests from parcel handlers (Peeters 2015). These may include only minimum, average and maximum dimensions. Next to this even outlines of the variation may be specified as visualized within Figure 2.10 and Figure 2.11. The figures give insight in the total variation in lengths and widths. However even relations may consist between the length and width which are not displayed by these figures.

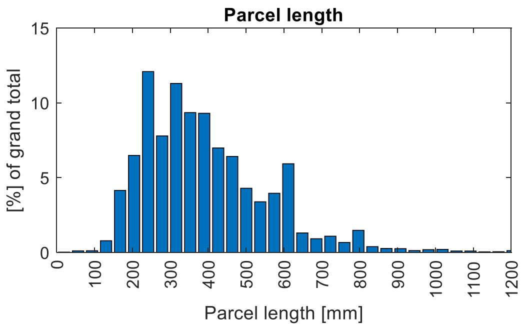


Figure 2.10: An example of a parcel length distribution

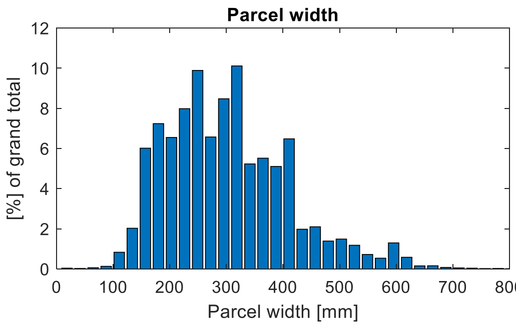


Figure 2.11: An example of a parcel width distribution

In addition, the arrival of trucks, and by that the parcels, generally varies through time which may be described as variation of the input-pressure (Intelligrated and Naylor 2013). Therefore, the throughput may vary caused by the variation of the input-pressure resulting in a throughput below the maximum capability of the system.

2.3 Literature survey

The context of this research is finalized with a literature survey about performance analysis within parcel sorting systems. Since a parcel sorting system is closely related to the principle of a baggage handling system this is even considered within this survey.

It is retrieved from this analysis that the performance analysis for these two systems generally concerns the two following categories:

- Parcel-hub scheduling problem
- Merge-algorithm

Within these it differs in the examined configurations, being only line-sorter or even loop-sorters. Furthermore, some only examine discrete carrier systems by fixed-windowing algorithms while others even include fixed-gapping.

Parcel-hub Scheduling problem

A widely discussed problem within literature on parcel sorting system performance is the assignment of trucks towards the infeeds and outfeeds. The arrival and sorting of parcels with the variation of truck arrival impacts the performance of a parcel sorting system. This involves the waiting times for the trucks and the number of parcels buffered on the infeeds and outfeeds. The effect of this is examined by Clausen (Clausen et al. 2017, 2015; Fikse 2011) by logging the throughput, throughput-time, occupancy and the average number of recirculations per parcel, resulting in the optimal number of infeeds and outfeeds.

The effects of variations on the input characteristics and the used gap-setting are not included within this. Fikse for example used a gap-setting of one parcel length for every parcel (Fikse 2011) and did not determine what the effect of other gap-settings.

Merge-algorithm

Another extensive researched problem is the creation and analysis of an optimal merge-algorithm. This matter involves the procedure to assign what parcel needs to be merged onto the available empty space, as visualized within Figure 2.12. The infeeds all include a sensor to retrieve a signal when a parcel is on the infeed, however these are often placed on the same length from the main-line. Generally, the time between the moment a parcel makes a reservation for space on the main-line and the actual merging is longer for infeeds downstream the main-line. Therefore, the algorithm gets quicker information of the arrival of new parcels on the upstream infeeds, commonly resulting in difference in throughputs for the different infeeds.

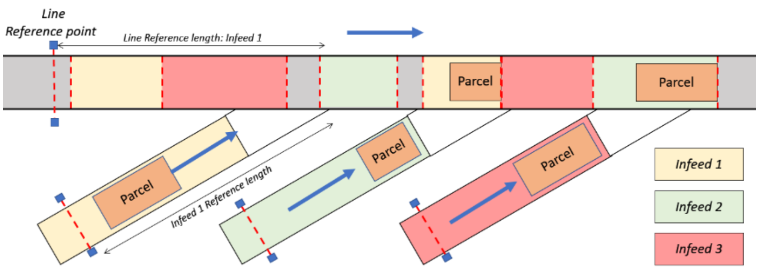


Figure 2.12: An example configuration of the merge

This problem does not necessary affect the system performance on the throughput, however this influences a balanced throughput-times for the different infeeds. It may for example occur that the parcels on an infeed down-stream cannot be merged since the upstream infeeds are constantly having parcels arriving.

Within literature a variety of methods are described which tend to have a high system outfeed while the throughput-time between the infeeds is balanced. Examples are First In First Out and the specification of a priority towards an infeed, which can be either statically or dynamically (Jodin and ten Hompel 2012a). From these last two dynamically can for example mean based on historical trends on throughputs.

Examples within literature that examine this problem mainly concern line configurations (Johnstone, Creighton, and Nahavandi 2015; Kim, Kim, and Chae 2017; Jing et al. 1998), however these do not include variation on parcel length. In addition, the impact of the system configuration including the used window-setting is currently not described within literature.

Concluding

Based on the literature survey is concluded that previous research focused on the optimization of the scheduling and merge-algorithm. It is noted that these studies do not provide the effects of changes on the functional limitations on the gap. Besides this, the effects of recirculation related to the parcel gap is generally undescribed within literature.

3. System analysis

Within the previous chapter a general overview is given of the system functioning from the perspective of the parcel handler. This involves what the system does within the environment and the used equipment to perform the transport and sorting. In addition, this chapter describes the system from a systematic-approach which is from the perspective of the system designer. The parcel handler approaches VanRiet with a design-request which involves specifications towards the system. This is the basis for the system design and eventually the installed system. Firstly, a general overview is given of the design procedure, after which the involved inputs and outputs of the design process are discussed within this chapter.

3.1 Systematic design procedure

The design of a sorting system involves the matching of a system configuration with the customer requirements which includes the analysis of the system functional limitations. Therefore, it may be summarized, as it is defined for an internal transport system as:

> *Designing of internal transport involves the selection of transport means, taking into account the technological requirements, combining them in a transport network and the determination of transport routes in the available space (Karkula 2015).*

A design procedure consists of a continuously diverging and converging process in combination with iterative steps. An example of a design methodology for a material handling system is defined by the Verein Deutscher Ingenieure (VDI) (Jänsch and Birkhofer 2006) which is included within appendix 0. This approach describes in detail the steps which need to be taken within a system design.

In addition to this approach, general design-methodologies are defined within literature. This research involves the process to rate if a system design matches the customer requirements. In order to retrieve insight in this, an overview of the design process is given with the innovation-model as described by In 't Veld (Veld 2002) as visualized within Figure 3.1. This method gives insight in the relation between the functioning system on the right and the iterative process to achieve the system-design. Within this, the first three steps concern the creation of a configuration based on the customer requirements. Veeke (Veeke 2003) defined this as function design, which eventually results in a configuration that matches the defined requirements. Whenever this is approved the design goes into the next phase including the detail design and eventually the production of the system. Eventually the system goes into operation as listed on the right within Figure 3.1 which includes the inputs, outputs and the achieved performance.

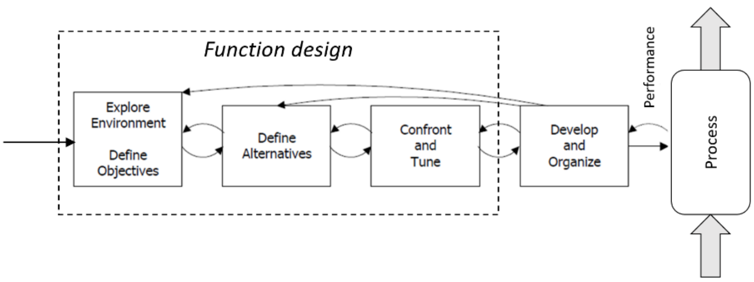


Figure 3.1: The innovation-model (Veld 2002)

The described process of function design is mainly concerned within this research. Therefore, a closer look is taken on function design and the inputs and outputs within Figure 3.2. This includes the customer requirements and the functional limitations of the equipment, which may even involve the estimations of operational factors. These are based on the performance of previous installed systems.

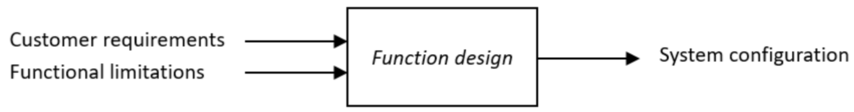


Figure 3.2: Function design as black-box

The described inputs of function design are further defined within this section. This starts with the current requirements and the functional limitations. Eventually, the current process to estimate if a configuration matches the customer requirements is describes, which involves the previously described confront and tune-step.

3.2 Current requirements and performances

The system is designed from a set of specifications that describe the requirements towards the system. This consists for example requirements on the layout and the performance for a defined input characteristic. Eventually within operation, the performance of the system is monitored towards the stated requirements. Currently the used requirements and performance measures mainly concern the capacity and reliability which are listed within this section.

Capacity

The main concerns of the parcel handler is to deliver the service to their customers meaning the transport within the specified time to prevent penalties for late deliveries (Fikse 2011). Therefore, the parcel handler is focused on the handled throughput in parcels per hour. This is listed within the system specifications as the peak-capacity the system should be able to handle. This is specified in combination with the predicted parcel characteristics, concerning only average or an outline of the predicted variation.

The capacity specification is tested within operation by having a constant pressure on the infeeds and measuring the throughputs on the outfeeds. However, it is noted that for monitoring within operation the current data does not fully cover the performance. Firstly, this does not list if the arrival-rate of parcels was limiting the throughput or the system capabilities. In addition, the monitor position may be on the main-line where the overflow may impact the throughput.

Lastly, the monitoring occurs by calculation the average throughput for a timespan, which is currently used as ten minutes intervals. The used timespan is of importance to list the achieved performance including the amount of detail. Whenever the timespan is chosen too small, this would result in high fluctuation, while too large timespans may leave out required detail (Fikse 2011).

From this insight is retrieved that parcel handlers wants to know if the installed system does match their specified performance. However, to improve the reliability of the system monitoring this should be improved. This involves the including of the arrival-rate of parcels, the specification of the used timespan, the measure position and the average parcel length.

Reliability

Whenever the system is in operation faults may occur which result in incorrect output. Within a parcel sorting system, the reliability is affected by a set of different factors. Generally, the parcel handlers specify within their design request the minimum required reliability for a set of faults that may occur. Examples of these factors concern miss-scanning, miss-weighing and miss-sorting which impact the rate of overflow.

3.3 Functional limitations

Generally, the design of a logistic system concerns three different aspects which concern the layout, controls and equipment (Blecker and Hamburg International Conference of Logistics 2014; Klein 2012). Within chapter 2.1 already different concepts are given for the layout. In addition, the functional limits of the equipment are described within this section which includes the gap-requirements for the system configuration. These involve the scanner, checkweigher and shoe-sorter. Besides these, the configuration of the controls sets limits on the performance which is described by the used windowing-method.

3.3.1 Scanner

The parcels are identified by the scanner which retrieves the parcel identity from the barcode. The commonly applied solution is to scan the parcels with a laser-based scanner. The simplest principle consists of a scanner which only scans the top of the parcel. This can be applied whenever it is ensured that the parcel barcode is on the top. Within a parcel sorting system, the position of the barcode is generally uncontrolled, therefore often a five- or even a six-sided scanner is installed which can scan the parcel front and back.

Whenever the scanner needs to be able to scan the front and back of the parcel a gap is required to scan these sides. This is related to the alignment of the scanners which is in a 45 degree angle towards the parcels as visualized within Figure 3.3. A correct scan is accomplished when, for the back-side, the succeeding parcel did not block the laser during the scan.

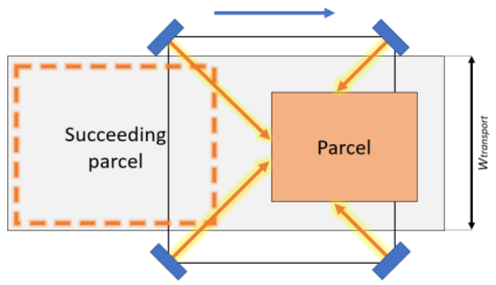


Figure 3.3: Automated scanning 4 sides of the parcel

When the gap between the parcels is too small the laser of the scanner is blocked, which result in an un-scanned parcel. Blockage of the laser can be prevented by usage of the minimum required gap, which is described by equation 3.1.

$$\mathrm{Gap}_{Scanning} = \tfrac{1}{2} * \mathrm{W}_{\mathrm{Transport}} \quad (3.1)$$

Lastly, the performance of the scanner is limited by its reliability which is often defined by supplier to be 99.9% (Datalogic and Brien 2014). This may be affected whenever the barcode is not of the sufficient quality according to the specification.

3.3.2 Checkweigher

The configuration of the checkweigher is often provided by the checkweigher-supplier based on the capacity, accuracy and maximum weight. To perform weighing with the required accuracy, the parcels should be stable on scale for a certain time. Therefore, the accuracy of the weighing is related to speed since this may impact the stability of the parcel (Mettler Toledo 2014).

The correct weighing of a parcel requires that only one parcel is on the scale for the described weigh-time. This weigh-time is directly linked with the system speed to the weigh-length which is required to perform the weighing. A simple checkweigher configuration consists of one scale with the length determined by the maximum handled parcel length and the weigh-length as displayed in Figure 3.4.

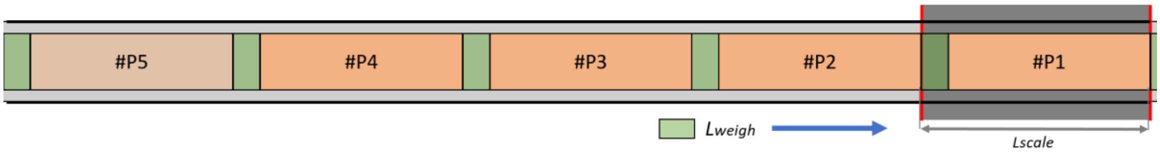


Figure 3.4: Maximum parcel on a scale

The system often handles a wide variety of parcel lengths. This results in a system with only one scale results in large required gaps for smaller parcels. The effect of the length variation can be reduced by installation of a second scale. The costs of the configuration would increase, however even the maximum achievable capacity increases since smaller parcels may be correctly weighed with a smaller gap. The throughput on a double-scale compared to a single-scale can be significantly increased since the double scale involves the ability to use it as three different scale lengths as visualized in Figure 3.5.

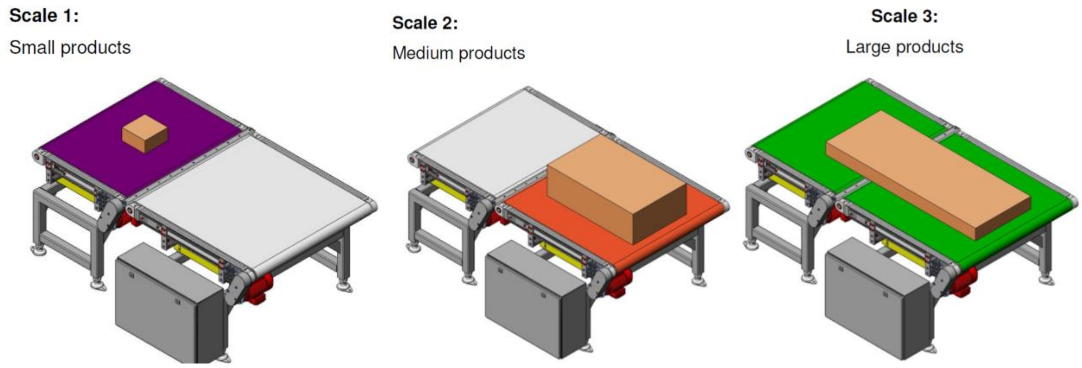


Figure 3.5 Usage of multipole checkweighers (WIPOTEC-OCS 2017b)

In practice two methods are available to perform weighing: conventional weighing and shared-gap weighing which are further described.

Conventional weighing

Firstly, within the conventional method the parcel which arrives at the scale triggers a sensor. Eventually when the parcel reaches the end of the scale, the parcel triggers the following sensor. Whenever only one parcel was within this time on the scale, this method concerns the parcel as correctly weighed. This method sets the limit of the parcel window, which involves the parcel length and the gap-back, as exactly the scale-length which is displayed within Figure 3.6. The method of weighing limits smaller gaps between parcels, since the window for all the parcels needs to be at least the scale length. This is achieved by appliance of an, in this research called, "fill-gap" which is required on top of the weigh-time as visualized within Figure 3.6.

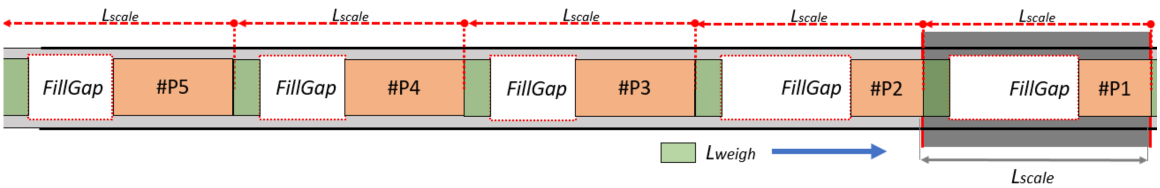


Figure 3.6: Conventional weighing

The requirements towards the gap can be specified within equations 3.2 and 3.3. Firstly, the gap in front of the parcel should be smaller as the weigh-length. As stated the minimum required gap-back is based on the parcel length and the scale-length.

$$L_{Gapfront} >= L_{Weigh} \tag{3.2}$$

$$L_{Gapback} >= L_{Scale} - L_{Parcel} \tag{3.3}$$

Shared-gap weighing

Opposing to the conventional method, a different weighing principle exists which reduces the required gaps and by-that improves the throughput (WIPOTEC-OCS 2017a). This principle, called in this research shared-gap weighing, requires only one photoelectric beam at the start of the scale, whereafter the software uses filtering techniques to monitor if the parcel is correctly balanced and weighed. The gap per parcel can be reduced since the required fill-gap may even be in front of the parcel. The effect of this method compared to the conventional method depends on the variation in parcel lengths. An example of this is visualized within Figure 3.7, which includes continuously two parcels of exact the same length. As a result, the parcels may "share" the required fill-gap, which reduces the total required fill-gap.

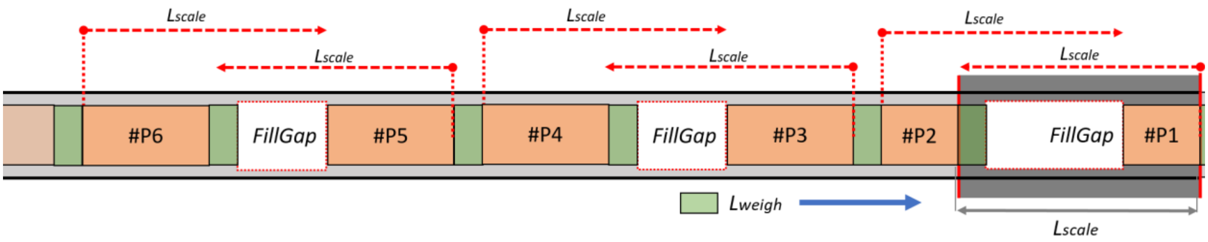


Figure 3.7: Shared-gap weigh-method

Like the conventional weigh-method this requires a minimum gap which is larger as the weigh-length. However, opposing to the conventional method this is specified for the gap-front and the gap-back. Firstly, the gap on both sides of the parcel still needs to be larger as the weigh-length as described by equation 3.4 and 3.5. Besides this, the parcel should be individually on the scale for the required weigh-time as specified within equation 3.6.

$$L_{Gap-front} >= L_{Weigh} \quad (3.4)$$

$$L_{Gap-back} >= L_{Weigh} \quad (3.5)$$

$$L_{Gap-front} + L_{Parcel} + L_{Gap-back} >= L_{Scale} + L_{Weigh} \quad (3.6)$$

3.3.3 Shoe-sorter

The configuration of the shoe-sorter influences the system performance by the used sort-angle and the sorter-speed, which is equal to the main-line speed. Furthermore, the sort-angle has impact on the required gap behind a parcel, which is called on the shoe-sorter the shadow.

Sorter-speed

The shoe-sorter firstly limits the system with the maximum system speed which is related to the used sort-angle (Intelligrated and Naylor 2013). This limit is related to the physics sorting which specifies the maximum speed per sort-angle. This specification, as used by VanRiet, is listed in Table 3.1. Within this, the decrease in speed for larger sort-angles is based on the maximum allowed impact of the shoes on the parcel.

Sort-angle [°]	Vmax [m/s]
20	3,2
25	2,5
30	2,0

Table 3.1 Maximum sort speed for an outfeed angle

It should be noted that from these specifications a wider sort-angle should not be used whenever a high capacity is required. However, in practice the specification of the shoe-sorter is often a trade-off with the available space, while a smaller sort-angle generally requires a larger site-space.

Shadow

The principle of a shoe-sorter is based on the parcels being gently pushed towards the outfeed. This is performed by the shoes, which follow the guidance towards the outfeed. Due to this guidance the parcels slightly rotate, which results in the parcel occupying a larger length on the main-line, so called shadow as visualized within Figure 3.8 and defined by equation 3.7.

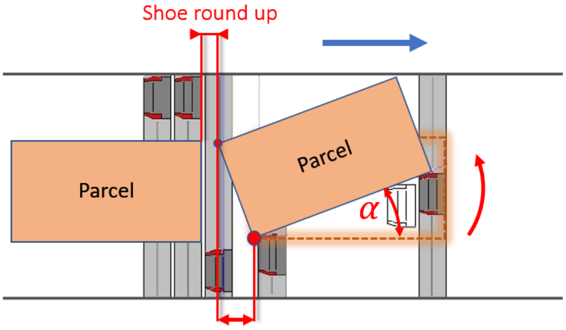


Figure 3.8: Shadow on a shoe-sorter

$$Shadow = W(Parcel) * \sin(\propto(Sort-angle)) \tag{3.7}$$

The parcel gap-back should be at least the length of this shadow to avoid collisions. Besides this, the sorting is performed by a number of shoes that push the parcel towards the outfeed. It is required that the succeeding parcel is kept untouched by the last shoe of the sorted parcel, therefore the total window for a parcel includes round-up towards the shoe-length. This shoe-round-up is based on the parcel length and shadow, which concludes in equation 3.8 for the required window and related the required gap from equation 3.8.

$$Window(Sort) = \left\lceil \frac{L(Parcel) + W(Parcel) * \sin(\propto)}{W(Shoe)} \right\rceil + N(Safe-shoe) * W(Shoe) \tag{3.8}$$

$$Gap(Shoe-sorter) = Window(sorter) - L(Parcel) \tag{3.9}$$

It should be noted that the calculation for the required window and the required gap, includes a number of safe-shoes. These are extra shoes that are required to prevent collisions that may occur due to operational factors like slippage on the shoe-sorter. The number of safe-shoes is commonly specified as two or three shoes. It is decided to use three shoes as specification within this research since this is often applied (VanRiet 2018).

3.3.4 Windowing-method

The previously described functions may define some requirements towards the gap for the parcel. These gap-requirements need to be matched to correctly perform the parcel sorting process. Therefore, the specification of the gap at the merge is of importance to correctly perform the following functions. This gap is specified by the used windowing-method and the setting which is implemented in the controls at the merge. Three different methods are available to specify the window on the main-line concerning: *Fixed-windowing*, *Fixed-gapping* and *Dynamic-gapping*. The method which is used affects the throughput and behaviour of the system.

Firstly, with fixed-windowing the required space per parcel is the same for all the parcels. Within this principle the window for the whole range of parcels is equal and is generally based on the maximum window requirements. As a result, a small parcel still requires the same space on the main-line as visualized within Figure 3.9.

Besides this, fixed-gapping involves the specific parcel length and a fixed setting for the gap. This gap-setting is mainly defined by the maximum required gap within the range of parcels. Therefore, like with fixed-windowing, the required gap for a parcel is generally larger as its functional requirement as displayed in Figure 3.10

Within the last windowing method, *Dynamic-gap* from Figure 3.11, the gap is based on the information of the specific parcel characteristics. The method requires information of the parcel length and width to determine the gap for the specific parcel. As an effect a dynamic-gapping principle may require measurement on the parcel length and width before it is merged onto the main-line.

Fixed window

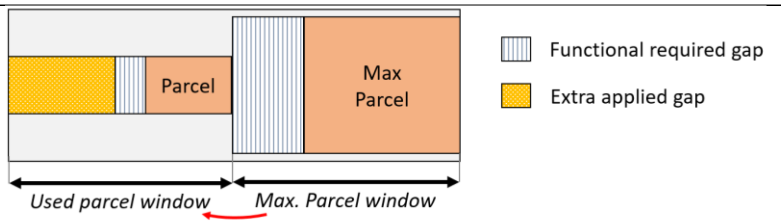


Figure 3.9: Fixed-window

Fixed gap

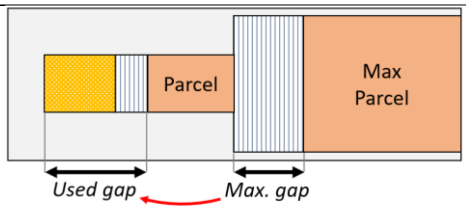


Figure 3.10: Fixed-gapping

Dynamic-gap

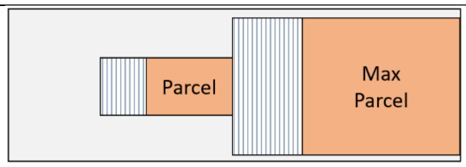


Figure 3.11: Dynamic-gapping

3.3.5 Conclusion

From this section can be concluded that the configuration sets limitations towards the parcel gap in different manners, what is listed within Table 3.2.

	Parcel specific	**Equipment configuration**		
Scanner		Belt-width		
Checkweigher	Parcel length	Scale-length	Weigh-time	
Shoe-sorter	Parcel width	Sort-angle	Shoe-width	#Safeshoes

Table 3.2: Gap dependency

The scanner, checkweigher and the shoe-sorter specify a required gap behind the parcel. In order to perform scanning, the gap is based on the maximum parcel width since the preceding or succeeding parcel can block the laser to successfully scan the frontside and backside of the parcel. In addition, the functional limiting gap for the checkweigher is based on the installed scale lengths, the required weigh-time and weigh-method. The conventional weigh-method requires the parcel having the required gap behind the parcel, while with the method of shared-gap weighing, the parcel may even have the fill-gap in front. Lastly, the shoe-sorter specifies the minimum required gap based on the parcel width and the sort-angle. More-over, a number of safe-shoes is added to the required gap since it is known from operation that the parcel may shift on the shoe-sorter and to avoid collisions.

3.4 Operational factors

In theory all the parcels are correctly handled. However, within operation it may occur that the parcel cannot be scanned, weighed or sorted which results in overflow. Depending on the layout the parcel from the overflow are either handled manually or recirculated. Both effects result in an increase in costs by required manual labour or a decrease in throughput.

In addition, it is supposed that the system generally does not fully utilize the main-line at the merge. This is related to the non-optimal reservation at the merge for the different infeeds, which are called reservation losses (Intelligrated and Naylor 2013). For the matter of insight both operational factors are further described, which is firstly visualized in Figure 3.12.

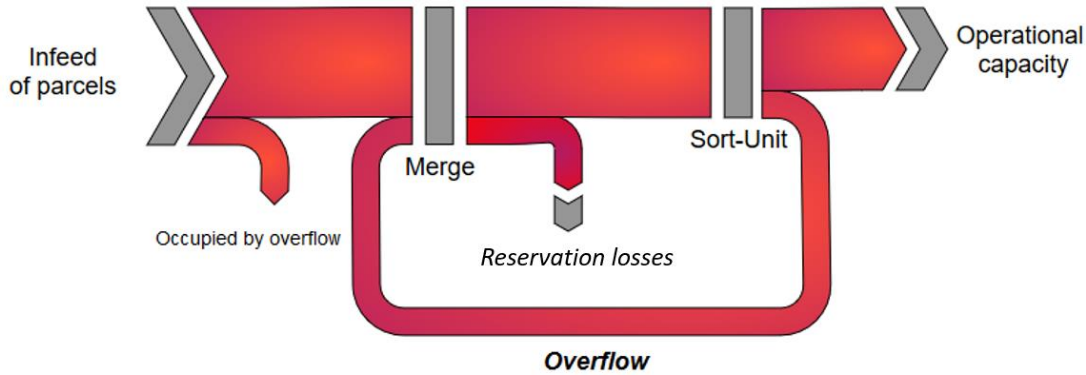


Figure 3.12: Operational factors within a parcel sorting system

Overflow

A wide variety of causes of overflow can be listed which vary from faults by the operator or either the system. A summary of causes is listed below, whereafter these are briefly outlined.

- Exceed maximum parcel dimensions
- Miss-read / Miss-weigh / Miss-sort
    - Reliability of equipment
    - Gap too small
        - Insufficient gap-setting
        - Slippage
- Outfeed-full / outfeed-blocked

Firstly, it may occur that a parcel is loaded onto the system which exceeds the maximum parcel dimensions. For safety reasons and reliability these parcels may be kept on the main-line by sorting these parcels to the overflow.

Besides this, the system may have issues to perform one of the required functions: scanning, weighing or sorting. The cause of this may be related to the reliability of the installed equipment. The reliability of the scanner might for example be affected by the quality of the parcel barcode. However, it may even occur that the required gap for the scanner, checkweigher or the sorter is smaller as the functional gap limitation. This too small gap prevents a correctly performing function and results in the parcel being sorted to the overflow.

The smaller gap may be caused by the gap setting at the merge or by slippage which is a significant disturbance in parcel sorting systems (Peeters 2015). It is expected that slippage occurs at transfers between two conveyors, however no validated data is available of these effects. An often-used solution to reorder the gaps is by the usage of a Gap Optimization System (GOS) consisting of multiple belts which correct the gaps of a parcel towards the defined gap-setting. However, the performance of this system is still not validated (Bruin 2013).

Lastly, the parcels cannot be sorted when the outfeed is full or either blocked. The outfeed becomes full whenever the operators were not able to empty it, by the rate it was filled by the sorter. Therefore, the specific outfeed cannot accommodate an additional item. Opposing to this, blockage occurs since the outfeed generally operates at a lower speed compared to the main-line. To prevent collisions of sorted parcels a time is required before a next parcel is sorted to the outfeed which is called blockage of the outfeed (Fikse 2011).

Reservation losses

Different algorithms are available to choose which infeed merges the parcel onto the main-line. As described within chapter 0. The controls do not have all the information of the parcels that arrive at the merge, resulting in sometimes making a reservation for an infeed that does not have a parcel ready. It is expected that the decrease on throughput highly depends on the used algorithm, the amount and position of the infeeds. However, currently no validated approach is available to estimate these effects within the design process.

3.5 Current capacity analysis

To match a system design towards the customer requirements currently a capacity analysis is performed. This analysis generally includes the limitations on the checkweigher and the sorter. Therefore, the current method to predict the capacity for the sorter and the checkweigher is described within this section based on the limitations as listed within chapter 0.

Sorter

Currently the capacity prediction on the sorter includes the input of the system speed, the sort-angle, the average parcel length and the maximum parcel width. This forms the basis to determine minimum required shadow and eventually the capacity.

To give insight an example calculation is listed within Figure 3.13 for a system with a 30° sorter and a maximum parcel width of 800 mm. This method is currently used to predict the capacity which is based on the fixed-windowing principle since it involves the maximum required gap.

The approach involves the calculation for the average required window. This involves the average parcel length and the maximum shadow. Firstly, the theoretical window is determined based on the average parcel length and the shadow of the maximum parcel width. As defined by the functional limitation shadow needs to be rounded towards complete shoes with several safe-shoes as safe-margin.

The concluding theoretical window only includes the requirements as stated by the shoe-sorter. However, the calculation generally even includes predictions of operational effects as slippage and wrong orientations. These effects are implemented within the calculation by the usage of predicted variations. A curve is for example predicted to require an extra gap of 25 mm, while a GOS is expected to have the ability to correct up-to 100 mm of this variation. Eventually, this results in a total operational impact, which is rounded towards the shoe-size and added on the theoretical window to retrieve the operational window.

Theoretical	Average parcel length	550	
	Sorter shadow	400	
		950	
	Round-up 1	50	
	Safe-margin	300	+
	Theoretical Window	1300	
Operational	Operational impact	100	+
	Operational window	1400	

Curves (5x)	125	
GOS	-100	
..	..	+
Slippage	25	
Round-up 2	75	+
Operational impact	100	

Figure 3.13: Current window calculation

This example results in a throughput of around 7000 pph with a speed of 2.7 m/s. However, this is often even reduced by a fraction which represents the impact reservation losses.

When occurs that the resulting capacity of a configuration does not match the capacity requirement, the engineers tend to modify the configuration. This may concern the usage a different sort-angle or either reducing the impact of the operational factors. Lastly, it might be chosen to reduce the fixed-gap such that it does not cover the whole range of parcel widths. This results in a fraction of parcels which shall be sorted to the overflow, however it cannot be predicted with the current method what the impact is of this decision on the operational capacity. Besides this, the effects of the variation within the lengths and width cannot be implemented within this calculation.

In addition, some remarks are placed to the current calculation method. This method concerns two round-ups which may even be reduced to one final round-up. Moreover, this prediction is initiated as capacity analysis, but is even used to determine the fixed-gap setting. It turns-out that this method does not necessarily result in the maximum required gap. This would concern the operational window without the parcel length which occurs to be the maximum when the first round-up is just below one shoe-width.

Checkweigher

The performance prediction as currently conducted at VanRiet for their designs generally does not include a separate calculation for the checkweigher performance. Therefore, the capacity of the checkweigher is currently specified by the checkweigher-supplier, which guarantees a capacity for a defined input characteristic.

The current approach, as used by the checkweigher-supplier, is based on the required window per parcel. This is calculation is based on the window-length which are defined by the minimum and maximum parcel lengths that can be weighed on the specific scale. The probability of the parcel lengths being within this range is used to predict the capacity as listed within Table 3.3.

Scale	Distribution factor [Sum %]
Scale 1 (900 mm)	9.9%
Scale 2 (1300 mm)	54.8%
Scale 1+2 (2100 mm)	35.3%
TOTAL	100,00%

Average window [mm]	1488
Capacity [pph]	6531

Table 3.3: Capacity prediction by the checkweigher supplier (SICK 2016)

However, as listed this prediction is based on the required window which a parcel requires on the related scale. This implies the usage of dynamic-windowing, while VanRiet generally tends to merge with fixed-gapping. Therefore, the suppliers even estimate the required gap per parcel for the range of parcels, which is used to predict the required gaps per parcel length. An example the required window and gap per parcel length is given in Figure 3.14 and Figure 3.15 for conventional weighing on the checkweigher configuration of Table 3.3.

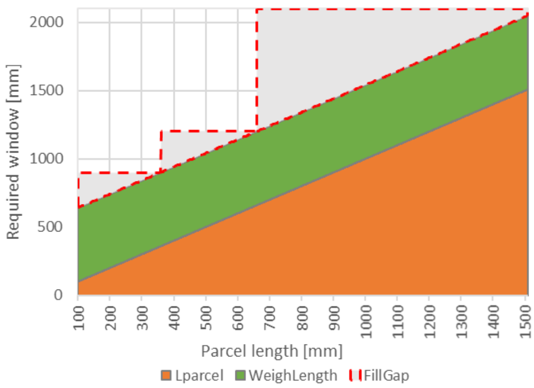


Figure 3.14: Required window for conventional weighing

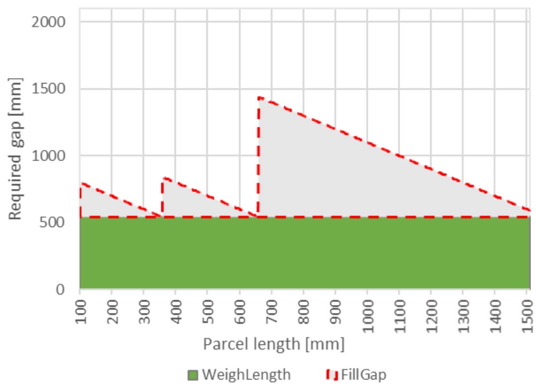


Figure 3.15: Required gap for conventional weighing

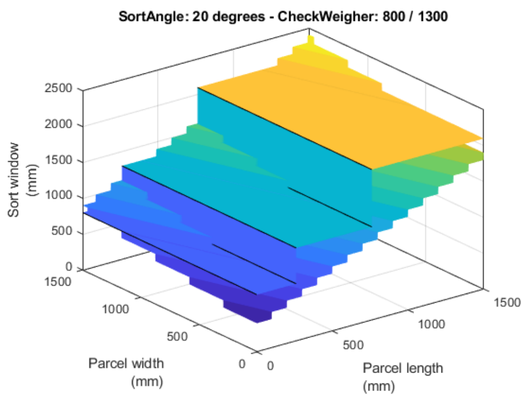
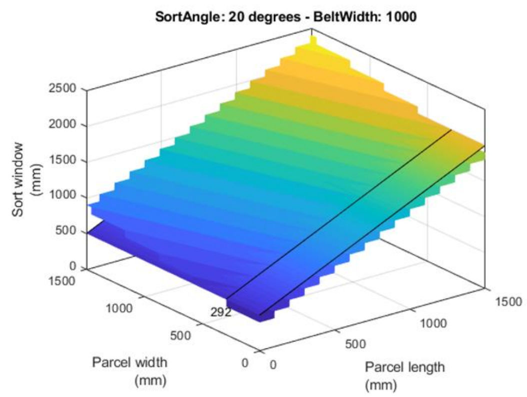
To correctly handle the whole range of parcels the fixed-gap setting should be specified following the maximum required gap. However, it occurs that this maximum gap is too large to reach the required capacity. Sometimes a supplier still accepts a too small gap-setting since to reach the described capacity which causes in a rate of overflow.

The impact of this too small gap-setting is currently unknown as even the maximum capacity with dynamic-gapping. This is because currently no combined approach exists to predict system capacity which includes the sorter and the checkweigher limitations. Lastly, the described weigh-method with shared-gapping is within operation dependent on the order of parcels, which currently cannot be implemented.

3.6 Window definition

The window which is required per parcel is related parcel length and width. Therefore, the required window may be visualized towards the whole range of parcel characteristics. For the matter of insight these inter-relations are visualized within Figure 3.16 which concerns conventional weighing on a checkweigher with two scales of 800 and 1300 mm, a sort-angle of 20-degree and a belt-width of 1000 mm.

This comparison shows that, with conventional weighing the sorter is limiting for the wider parcels. In addition, the impact of the scanner is listed which concerns the requirements when the maximum parcel width is in front or after a parcel. It is retrieved from this, that the scanner mainly does not set the limits required gap. This is since the maximum parcel width, including these parcels smaller as 292 mm do not appear. In addition, when this gap is not matched on the scanner it does not necessary result in a miss-scan. This is since bar-code of the parcel is not necessarily placed on the unreadable side.

	Checkweigher	Scanner
Sor-angle 20	 *Figure 3.16: Window limits for a sorter and the checkweigher*	 *Figure 3.17: Window limits for the scanner and the sorter*

The listed plots visualize that for the example configuration the limiting equipment differs through available parcel characteristics. Furthermore, it visualizes that the total required window on the checkweigher and the scanner only differs based on the parcel length. Opposing to this, the gap on the sorter is even related to the parcel width and increases within steps since it is related to the shoe-width.

4. Problem definition & research outline

Based on the previous section it is noted that the current method to predict the capacity lacks in the ability to include the whole configuration. The problem is firstly summarized; whereafter the outline for this research is presented. The problem is categorized in the input-characteristic, configurations and overflow.

Input characteristic

It appears that the amount of detail for the expected input characteristics highly varies. This may be represented by only the average and maximum lengths and widths towards detailed distributions. Currently, variation on the input characteristic cannot be included within the performance prediction. As a result, it is unknown what the impact is of current predicted performance with only averages compared to the actual performance with variation in lengths and widths.

Besides this, in practice the system faces a stochastic arrival of parcels, meaning the system is subjected to variation in input-pressure. This nature does influence the achieved performance of the system, however it is unknown how this affects the system performance.

Configurations

Concluding from the current system capacity prediction it is stated that this is separately based on sorter and the checkweigher. Therefore, the impact of a window-setting below the maximum or even the effect of dynamic-gapping could not be determined.

Overflow

In relation to the configuration a system might be configured with a loop which includes the recirculation of overflow. The impact of the rate of overflow which is caused by either miss-read or an insufficient gap-setting currently cannot be included within the capacity prediction.

4.1 Research scope

In order to perform a research generally a representation is made of a real-world example (Robinson 2004). Therefore, the simplifications need to be clarified which is described by the scope towards the system. This is visualized within Figure 4.1, which is followed by the description of the factors of a parcel sorting system which are included and excluded within this research.

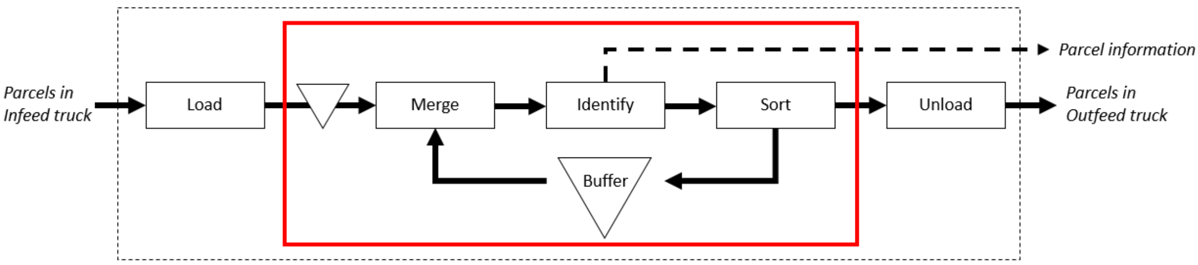


Figure 4.1: Scope description

Input

Within this research the maximum capacity determined for a system on the outfeed. Therefore, the configuration of the load and unload-section, concerning for example the number of infeeds and outfeeds, are out of scope of this research as visualized within Figure 4.1. The input of parcels may include variations in lengths and width. However, to compare results for different configurations a fixed input characteristic is used within this research. In addition, the variation of the input-pressure is included within this research.

Merge
Whenever a parcel arrives at the end of the infeed the merge controller specifies the time when the parcel is needs to be merged onto the main-line. Therefore, the parcel may be temporary buffered at the end of the infeed. This is included within this research since this buffering may impact the throughput when arrival of parcels is concerned.

The required space per parcel is specified at the merge-area based on the functional limitations and the window-setting, including the windowing-method. These factors are included within this research.

Within operation the merge controls concern the assigning of parcels from a specific infeed to the available space. This involves an optimization on performance measures as capacity and throughput-time for different infeeds. Since the number of infeeds is not considered, this optimization is left out of scope. Resulting, the merge policy only concerns the first parcel at the infeed-buffer.

Identify
The identification of parcels by the barcode, dimensioning and weighing is within parcel sorting systems generally applied on the main-line. Therefore, the identification is within this research considered on the main-line. The different weigh-methods including the configuration of the scale-lengths is included within this research. Opposing to this, it is retrieved from the system analysis that the scanner generally does not limit the throughput. Therefore, the focus within this research is set to the impact of the shoe-sorter and the checkweigher configuration while the impact of the scanner is not examined.

Sort
Since this research focuses on the shoe-sorter this is the only sorting principle which is examined within this research. As described, this system can be configured by different sort-angles which are included within this research.

Buffer
A temporary storage may be applied to the system to store parcels that currently cannot be sorted to the outfeed. These parcels use twice the system since these parcels are merged and sorted twice by the system. Within steady-state the system capacity would only be reduced by the factor of parcels that are sorted to this temporary storage. Therefore, this does not impact system capacity and is this out of scope.

Opposing to this, the main-line itself even performs as a buffer for the overflow parcels. Whenever these parcels are recirculated these parcels reduce system capacity. These recirculated parcels generally are uncontrolled recirculated, however the impact of this is still unknown. The impact of the fraction of overflow is therefore included within this research.

Operational factors
Within operation the position of the parcel may differ from the assigned setting at the merge. This differs caused by for example variation in slippage, what may be corrected with the application of a GOS. Besides this, within operation a parcel may rotate or not being aligned on the centre of the main-line. These effects may also be reduced by systems existing system and are for that not included within this research.

Scope summary
Resulting from this complete description the research scope can be summarized. This includes the factors that are examined within this research. Opposing to this, the described factors which are left out of scope are even listed in Table 4.1.

	In-scope	*Out of scope*
Input	Varying input-pressure	
	Length, width variation	Different length distributions
Merge	Buffer when system is overloaded	Merge algorithm
	Windowing method and setting	Number of infeeds
Identify	On main-line	Scanning
	Dynamic checkweigher configurations	
Sort	Shoe-sorter configurations	Number of outfeeds
Buffer	Overflow	Temporary storage
Operational factors		Effect of slippage
		Reservation losses

Table 4.1: Scope description

4.2 Performance analysis method

With the defined goal of the related scope the method can be defined to perform the research. The goal of this research includes the ability to predict the performance of the parcel sorting system. Firstly, the requirements are defined towards a model which should be able to perform the defined performance analysis. Hereafter, different performance analysis methods are outlined, resulting in the selection of the used method.

4.2.1 Model requirements

The performance analysis of this research is characterized in a variety of manners. Firstly, the model needs to have the ability to configure a variety of system configurations. These differ from different windowing methods and the configuration of the installed equipment. More-over, a parcel sorting system is applied to variability through time on the input characteristics. The model needs to be able to include the variability on input characteristics and input arrival since this may vary within operation.

Within this research even the effect of overflow is examined within a line- and loop-sorter. These may be caused by the reliability what concerns a degree variability described by a factor of reliability. As a result, the model needs to be able include this connection between the overflow and the merge process.

Summarizing a performance analysis method needs to be able to model the following statements:

1. Configurability
2. Variability
3. Interconnections

These statements need to be considered whenever the analysis method is selected.

4.2.2 Analysis methods

A wide variety of methods is available to study the behaviour of a system applied to different input parameters. From a top-level the physical experiments can be performed on the actual system or either a representative model as visualized within Figure 4.2.

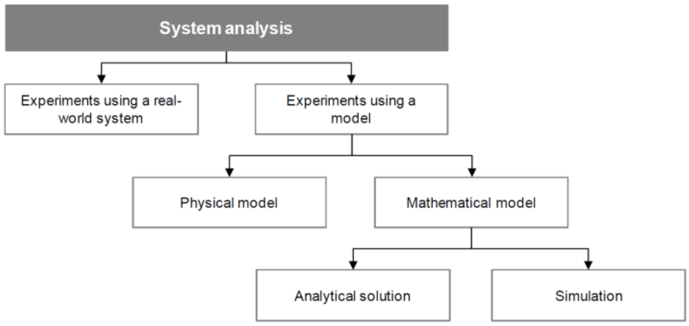


Figure 4.2: Simulation methods (Law and Kelton 1991)

Physical system or models

The usage of a physical system, being an actual system gives the clearest insight in the real-world functioning. Within such an experiment commonly one representation of the system is examined since high cost and time are required to experiment with different configurations.

Mathematical model

Besides a physical approach, a mathematical model can be used that represents the actual system. This approach has its advantages in the ability to analyse different system configurations without high investments (Robinson 2004). Within mathematical models an analytical or simulation model can be used which both include the logic and quantitative relationships between entities. Both methods are a representation of the actual system that implies the urge to validate in what matter the built model represents the actual system for the analysed effects (Law and Kelton 1991).

Analytical model

The analytical model is from history commonly chosen by its short process time. However, the complexity of an analytical model highly increases with an increasing system complexity (Law and Kelton 1991). Analytical approaches have the advantage to evaluate the inputs by a set of equations towards one solutions. Opposing, this is also the dis-advantage compared to simulation, which is the ability to model variability as subjected to the actual system.

Simulation

From a historical perspective simulation was often addressed as “method of last resort” (Fishwick 1994) addressed by long calculation times and costs of equipment. Due to the fast improvement of computer speed the method involved from “method of last resort” to the commonly used analysis method since it is the most versatile (Lucas et al. 2015; Kulwiec, Engineers (ASME), and Society (IMMS) 1985; Law and Kelton 1991; Fishwick 1994). Compared to an analytical model simulation has the advantage to, relatively simple, describe complex model, especially with the improving simulation software (Lucas et al. 2015). Besides this, simulation has the advantage to visualize events and has therefore a higher factor of transparency compared to an analytical approach (Robinson 2004). Simulation has opposing to analytical studies the ability to evaluate variations like these occur within the actual system. This is achieved by the usage of random-numbers to retrieve a value from a defined distribution, therefore variability can be examined within simulation. It has to be noted that, because of this nature, the simulation is only an imitation of the actual system (Robinson 2004). Resulting, a simulation model requires a degree of replications to predict the sensitivity and the performance of a system.

Generally, simulation studies may be described as continuous and discontinuous simulation. These differ in their representation having the state variables changing continuously or by the occurring of an event. From these the occurring of an event, for example the sorting of a parcel, characterizes a parcel sorting system.

4.2.3 Method selection

Within this research the effect on the performance of different system configurations is studied. Therefore, a mathematical approach should be used to perform this with low investments on time and costs. Besides the configuration the variation on input characteristics is considered with the variability on input-pressure. Based on the explanation of the different analysis methods a simulation study forms an appropriate method to include the effects of variations.

A variety of software packages are available to perform a simulation-study. These packages differ in their abilities and specialism and therefore software selection should be well considered. Generally, it is noted that the software influences the ease to model.

The available software packages vary from spreadsheets with the usage of random number towards specialized software. Within VanRiet Demo3D is a solution which is used to configure a system layout which has even abilities to perform simulations. In addition, Delphi TOMAS is included in the comparison since the researcher has experience with this program. Lastly, two specific simulation packages are included within the comparison being Simio and FlexSim.

The packages firstly differ in costs, while Demo3D is a paid software package, the other programs can be used, within this research, with an academic licence. Delphi TOMAS excels in the ability to convert a general process code into a program. Opposing to this, the other packages have advantages in the variety of available pre-defined functions. Besides this, the newer simulation packages cover a clear visualization which simplifies debugging and verification. Lastly, Simio has advantages in the availability of support within documentation and co-researchers using the program. The researcher therefore chooses to perform the analysis within Simio since it can be used with an academic licence, excels in the ease to perform experiments and includes an extensive support.

5. Model definition

A simulation model can be defined by following the steps as defined by (Robinson 2004) starting with the creation of a *Conceptual model* that is based on the *Real World (problem)*. Hereafter, the modeller starts the coding of the *Computer Model*, which is used to derive *Solutions and Understanding* of the system by examining experiments.

The creation of a conceptual model can be further detailed containing the following parts, which are partly discussed in the previous chapters (Robinson 2004):

- Develop an understanding of the problem situation (Chapter 2 and 3)
- Demine the modelling objectives (Chapter 4)
- Design the conceptual model:
    - Required inputs
    - Performance indicators
    - Process representation

From these steps the required inputs still need to be defined, which is firstly examined within this chapter. This is followed by the used performance indicators to analyse the different scenarios. As basis for the model a reference configuration is selected, followed by the representation of the process within a pseudo code. Furthermore, insight is given in the created model within the model design. Lastly, this chapter examines the testing of the model behaviour including the verification and validation.

5.1 Input definition

The conceptual model starts with the definition of the input, concerning the inputs of the model that should be configurable to answer stated objective. Furthermore, the input characteristics should be defined which are used to represent the system functioning.

5.1.1 Required inputs

The experiments conduct system configurations as also different parcel characteristics. Based on the research questions, the required inputs for the model can be defined. These are the inputs what need to be modified to examine the experiments. These inputs are split in four categories which concern the parcel input, equipment, controls and layout.

Parcel input

Firstly, the parcel characteristics need to be specified within the model. Besides this, the pressure of the parcel arrival also needs to be specified within the model. This is to represent the varying input-pressure as it occurs within operation.

Equipment

The system configuration involves what equipment is used within the system concerning the sorter and the checkweigher. These configurations are the sort-angle and for the checkweigher the number of scales and their lengths. Since different weigh-methods are available to have a correctly weighed parcel, as defined within section 3.3.2, these are both implemented within the model.

Controls
The controls which are examined within this research include the methods to define the window for a parcel on the main-line. These windowing methods are fixed-window, fixed-gap and dynamic-gapping as described within section 3.3.4. Besides this, the settings for the fixed window or either the used fixed-gap needs to be configurable.

Layout
Lastly, the model needs to include abilities for configuration changes on the layout. This involves the layout-type, as a loop-sorter including recirculation or a simple line-sorter. In addition, the overflow-rate may be differed within the experiments and therefore needs to be configurable.

Conclusion
The whole set of inputs for the different categories are summarized within Table 5.1. The model should involve these parameters to give the modeller the ability to perform the experiments which are required to answer the specified research questions.

Parcel	Equipment	Controls	Layout
Characteristic	Sort-angle	Windowing-method	Layout-type
Input-pressure	Scale length(s)	Window-setting	Overflow-rate
	Weigh-method		
	Include / exclude - Sorter - Scanner - Checkweigher		

Table 5.1: Summary of required inputs

5.1.2 Input characteristics
The parcel sorting system concerns a degree of unpredictability on the parcel characteristics. However, the parcel handlers mostly give an indication of the expected parcel characteristics. The effect for the amount of detail may be retrieved by specification of the distribution for the length and width. As described by Robinson (Robinson 2004), a modeller may represent the unpredictable variability within a model by the usage of different distribution types. From these the traces and a statistical distribution are described within this section.

Traces
The usage of traces uses actual data as input as retrieved from a real system. This method generally requires the most system-memory since all the input data needs to be defined to the model. The usage of traces creates the ability to validate a model, since it uses the real data. Opposing this, the method does not have the ability to perform a sensitivity analysis.

Within this research the data is available of the parcels that passed the identification-unit within two months of operation. This results in a set of around 485.000 parcels. From this data the recirculating parcels were filtered and data with an unknown input location (7.9%). Besides this, the parcel characteristics sometimes exceeded the restrictions or were miss-measured (1.6%) which were even distracted from the data before these are used as input for the model.

Eventually the filtered parcel characteristics involve an average length off 397 mm and a width of 303 mm.

Representative statistical distribution

The input data may be represented by a statistical distribution. This distribution has advantages compared to be based on only a few input parameters (Robinson 2004). The usage of a statistical distribution is especially useful whenever actual data is available.

The statistical distributions also have a disadvantage which is related to long tails what a distribution might include. Therefore, it may occur that an extreme value is sampled from outside the specified boundaries. This may affect the result of an experiment or even result in invalid inputs, for example whenever a negative length is sampled. This may be resolved by truncating the distribution, which set lower- and upper-limits for the distribution. It should be noted this has impact on the results which are retrieved from the distribution. Within this research is decided to truncate the distribution by setting the closed boundary value to a sample which is outside these boundaries.

Based on the available data an appropriate statistical distribution is defined which represents the available data. A variety of distribution types may be used to represent the data. From these the lognormal distribution is used within this research since it accurately fits the data. The input of this distribution is the mean (μ) and deviation (σ) of the related normal distribution as visualized within Figure 5.1.

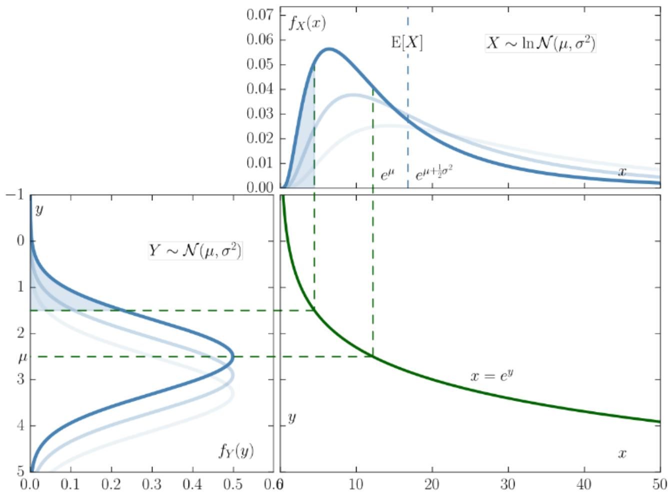


Figure 5.1: Relation between a log-normal and its normal distribution (Wikipedia 2017)

Based on this relation the actual mean of the lognormal distribution can be determined based on the input parameters, as defined by equation 5.1.

$$\mu_{lognormal} = \exp\left(\mu_{normal} + \frac{\sigma_{normal}^2}{2}\right) \qquad 5.1$$

To retrieve the distribution which fits the data the function *histfit* within MATLAB is used. The results of this function state the input parameters of the lognormal distribution which are listed in Table 5.2.

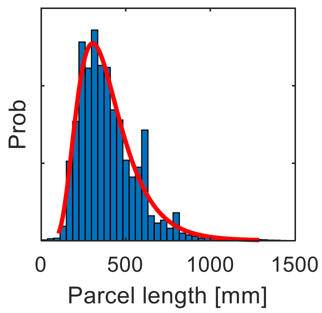
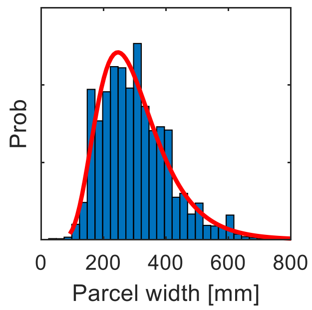
Site	Length	Width
		
μ normal [mm	5.903	5.65
σ normal [mm	0.397	0.36
μ lognormal m	396.38	303.73
Median mm	366.23	284.66

Table 5.2: Lognormal fit distribution on the available data

5.1.3 Input-pressure

In order to represent the variation on the input pressure different methods are available. These differ in their analysis goal. Firstly, the system may be tested to its maximum capabilities, what involves the arrival of a parcel whenever the parcel on the infeed is merged onto the main-line. This maximum arrival of parcel may be used to specific an input-pressure which is faction of this maximum arrival-rate.

Within the experiments the variating behaviour of the parcel arrival is examined. Therefore, the mean inter-arrival time from this input is used as input for the model. This mean is used as input to define a distribution from what sample for the inter-arrival times is be retrieved. As a result, the arrivals vary through time as this even occurs within operation.

The used distribution to describe this inter-arrival-time is an exponential distribution which involves the majority of the times being below the average, with occasional longer times (Robinson 2004). This distribution-type is used since it is a relatively simple distribution which is only defined by the mean. Due to this character and the absence of values below zero this distribution is often used to define inter-arrival-times (Robinson 2004).

5.2 Performance indicators

Performance monitoring gives insight in the functioning which may be expressed in absolute values or ratios. Within simulation studies these performance measures should be a combination of absolute and relative measures since the variability and assumptions affect the correctness of the measures (Kulwiec, Engineers (ASME), and Society (IMMS) 1985). Based current requirements from chapter 3.2 the performance indicators are defined which are used within this research, resulting in the conclusion where the used indicators are listed.

Throughput

The main criteria which parcel handlers specify is noted to be the capacity related to an average parcel length. This concerns the throughput which can be at maximum achieved within steady-state by the system. When sites with different average parcel lengths are compared the capacity may not give a clear insight of the performance difference between these systems. Since the average parcel lengths do not differ within this research this does not impact this research. However, when sites with different average parcel lengths are compared the utilization of the main-line should be implemented.

Overflow-rate

Currently the parcel handlers interested to what fraction of parcels cannot be scanned, weighed or sorted. Therefore, the rate of parcels which goes to the overflow is derived from the throughputs of the outfeed and the overflow as stated within equation 5.2.

$$Overflow-rate = \frac{Throughput(Overflow)}{Throughput(Outfeed) + Throughput(Overflow)} \tag{5.2}$$

Performance comparing

The performance of a system is commonly a relative measure compared a defined standard or reference system. To define these ratios a system maximum or required performance needs to be defined within the experiments whenever relative difference between scenarios is examined.

5.3 Reference definition

The basis for the simulation study is a reference scenario which represents a general parcel sorting system. As stated in the chapter 3 the configuration depends on the requirements as defined by the parcel handler. An analysis is performed on current installed systems to gain insight in the similarities and the differences. The results of the analysis are listed in appendix B and used to specify a reference scenario representing parcel sorting systems.

The systems that were analysed had mainly similarities in the system-speed and overflow-type being commonly a loop-sorter. Opposing to this, the sort-angle was beside 20 degrees even 25 degrees. The installed scale-lengths differ from a single scale of 1600 mm towards dual scales with the smallest scale of 700-900 mm and the largest scale being 1100-1300 mm.

The defined reference scenario with the main limitations on parcel characteristics and system configuration is listed within Table 5.3. Lastly, the weigh-length is specified based on the specification from a reference system which involved a weigh-length of 540 mm for a system with 2.7 m/s (SICK 2016).

Parcel	Value	Unit	*System*	Value	Unit
$Lenght_{min}$	150	[mm]	**System speed**	2.7	[m/s]
$Length_{max}$	1200	[mm]	**Sort-angle**	20	[°]
			Shoe-width	100	[mm]
$Width_{min}$	100	[mm]	**Scale-lengths**	800/1300	[mm]
$Width_{max}$	800	[mm]	**Weigh-length**	540	[mm]

Table 5.3: Selected reference scenario

Within the research some of these parameters shall be configured on their impact on system performance. One for example involves the ability to use a loop-sorter or a line-sorter. A visualization of the defined scenario for a line- or a loop-sorter is given within Figure 5.2.

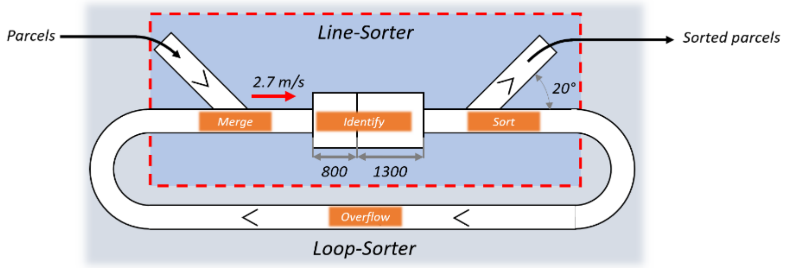


Figure 5.2: Reference scenario

In order to get insight in the used reference system including the input characteristics the functional limitations are defined. This involves the maximum required window and gap for the range of parcels. Within Figure 5.3 the steps within the required window are visible which are specified by the used scales of 800 and 1300 mm. Besides this, the maximum gap is listed for the maximum parcel width on the sorter with 20 degrees. The maximum required gap is derived from the required window and visualized within Figure 5.4 which shows that the maximum gap of 1340 mm is required at a parcel length of 760 mm. This is since the parcels larger as 760 mm need to be weighed on the scale combination, resulting in a required window size of 2100 mm. It has to be noted that these requirements are the requirements with conventional weighing which are smaller with shared-gap weighing.

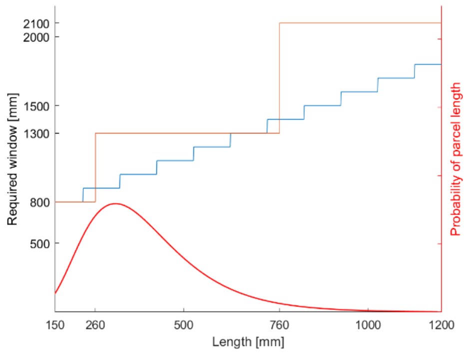


Figure 5.3: Maximum window for the reference scenario

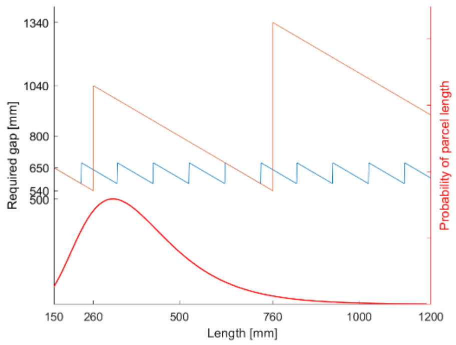


Figure 5.4: Maximum gap for the reference scenario

5.4 Conceptual model

With the inputs and outputs defined, the simulation-model is be created. The model is, as defined within the scope, created with one infeed that merges onto the main-line. Whenever the parcel is on the main-line the parcels are firstly handled by the checkweigher. Hereafter, if the parcel has a correct gap it is sorted towards the outfeed. The sort-angle is not visually implemented within the model, but only a parameter which is related to the required shadow.

The model representation is visualized within Figure 5.5 which includes the different installed equipment. For visual verification some elements are added towards the simulation. Firstly, the parcels (brown) arrive from the infeed including the required shadow (blue) which it requires on the sorter. Whenever the parcels enter the checkweigher the weigh-length (green) is added in front and after the parcel since this is, as specified, the minimum required gap on both sides of the parcel. Eventually, whenever the gap is not sufficient to perform the function the colour of the specific parcel changes. This is to indicate that the parcel cannot be sorted, which returns back to the original colour at the merge-point.

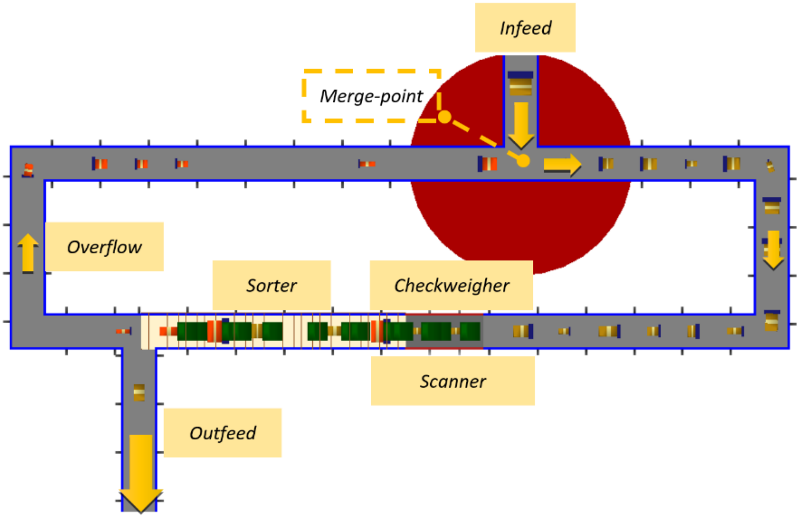


Figure 5.5: Visualization of the used model

Further-on in this section the reader is given insight in the functioning of the model. This firstly starts with the definition of the assumptions whereafter the process as performed by the different equipment is described.

5.4.1 Assumptions

A simulation-model is a representation of the real-world, which requires the modeller to make assumptions of the real-world. To give the reader insight in the functioning of the model compared to the actual system it is of importance to state the assumptions. This is even to list the intentions of the model, what gives the reader the ability to estimate if the model fits other purposes.

Input parcels

Within operation the trucks arrive to the system and load the parcel in batches onto the system. This results in a batch-arrival and may even have impact on the variation in parcel characteristics per batch. Within this research the arrival of parcels is parcel specific, so the impact of the arrival of batches is not included within this research.

Configuration

The merge configuration is modelled as one infeed which represents the whole set of available infeeds. In operation it may occur that another parcel is chosen to merge whenever the first parcel does not fit. The decision to choose a "best-fit" is not includes within the model. This since with a First Come First Serve algorithm the behaviour of the system is the clearest visible. While otherwise for example even the infeed buffer-length, which represents the number of infeeds, has impact on the performance.

The abilities of the scanner are included within the model by assuming the parcels are placed exactly in the middle of the main-line. The variation within operation may positively and negatively affect the scan-capabilities, therefore it is assumed that the placement in the middle is a correct approximation.

The weighing occurs by having the parcel being stable on the scale. The time it takes to ensure this is defined as fixed value. As a result, the weigh-length is within the model directly related to the main-line speed which may differ within operation.

5.4.2 Process Description Language

In order to create a simulation model which is representative for the actual system the covered process needs to be described. This is used by the modeller as basic representation of the system function. The created model is based on this functional description, therefore this basic description gives the reader insight in the system functioning. The method to represent the model is called Process Description Language (PDL) which represents the process with a pseudo code.

The different functions of the system are described using the previously defined functions within a parcel sorting system. Furthermore, some functions are added since these are required to perform the program logic.

The parcel sorting system is represented by a set of conveyors which are connected to one or two conveyors via nodes. The system functions are added on the system functional equipment by adding an extra procedure on the input or output-node of the conveyor. The conveyor is the main process of the system. Therefore, firstly the conveyor process is described whereafter the added processes follow for the defined functions.

General conveyor process

The process to transfer a parcel from the input node towards the output node of the conveyor is described by the following statement.

PROCESS
Insert Parcel in contentlist **Wait** the transport time based on the conveyor length and speed **Remove** Parcel from contentlist & **Execute** the event of the EndingNode

Infeed

The infeed provides the system with parcels that arrive based on the arrival specifications. This process may be directly started when a parcel is merged. However, these may even be created based on a specified arrival-rate.

Within the infeed the specific characteristics are assigned based on the used input distributions. Based on these, in combination with the windowing method, the required gap can be determined which is used to define if a parcel can be merged onto the main-line.

Eventually the parcel is placed within the UnreservedList and the physical buffer at the infeed which is represented by ParcelAtInfeed.

PROCESS
Create *Parcel* **Assign** parcel characteristics: Length & Width **Assign** Parcel MergeGapBack based on *WindowMethod, Sorter & Weigh requirement* **Insert** Parcel in UnreservedList and ParcelsAtInfeed **Execute** Merge

Merge

When the parcel is created it is checked if enough space is available on the main-line, based on the parcel length and it required gap. When this occurs, the parcel is transferred onto the main-line. Lastly, the parcel exits the infeed resulting in space on the infeed, so a new parcel is created.

PROCESS

Assign current EmptySpace available on main-line based on the ReservedList
  If a parcel in the UnreserverdList AND in ParcelAtInfeed fits available EmptySpace **Then**
    Remove Parcel from UnreserveredList
    Transfer Parcel from ParcelAtInfeed onto Infeed conveyor
    If WeighMethod = GapSharedMethod and WindowMethod = DynamicWindowing **Then**
      Assign Parcel MergeGapBack based on the ParcelLastMerged MergeGapBack
    If ArrivalMode is NOT InputPressure
      Execute Infeed

EndMerging

When the parcel is merged onto the main-line the parcel needs to be still within the ReservedList until the specified merge-gap tail exits the merge point. In order to include this, the EndMerging process is started when a parcel tail exits the merge point. Besides this, the parcel Gap-Front is assigned at this point. This process is also started when a parcel from the overflow exits the overflow, since these parcels even occupy space on the main-line until these reach the end of the overflow.

PROCESS

Wait until the Parcel required gap end quits the merge point
Remove Parcel from the ReserveredList
Assign Parcel Gap-Front and LastMergedParcel Gap-Back
Execute Merge

Identification

The process needs to check if the gaps for the parcels match with the requirements as defined by the sorter and the checkweigher. Therefore, the weigh- and sort-correctness are defined, based on gap-requirements and the available gaps. Within this, the sort-correctness is based on the widths of the parcels in front and after the specific parcel.

PROCESS

Assign Weigh- and SortCorrectness based on the available gaps, required gap
Assign Parcel destination based on the Weigh- and SortCorrectness and the Overflow-rate

Sort

The method how the parcels are sorted to the overflow differs for a line- or a loop-sorter. Within a line-sorter the parcels are recirculated towards the merge-point, while within a line-sorter the parcels are removed from the system.

PROCESS

Report Statistics
If Destination = Outfeed **Then** Transfer to Outfeed
If Destination = Overflow & Layout = Loop **Then**
  Transfer Parcel towards Mergepoint
  Insert Parcel in ReservationList and **Assign** the Parcel MergeTime
If Destination = Overflow & Layout = Line **Then** **Remove** Parcel from system

5.5 Model behaviour

Prior to the experiments the model behaviour is examined in order to determine the settings which are required for the experiments. This is required to ensure that the output of the model is of a sufficient accuracy. The setting consists of the warm-up length, the number of replication part, followed by the run-length.

Warm-up length

At the start of the simulation the system is firstly empty, so the system requires a moment to be fully functional. After this warm-up period the performance indicators can start their monitoring. This indicates that the performance indicators need to be reset after the warm-up period. The warm-up period is defined by visualization of the average throughput at the start of simulation for the reference configuration. The outcome is listed within Table 5.4 and shows that the system is fully functioning after 90 seconds of operation. Therefore, this is used as warm-up time for the system.

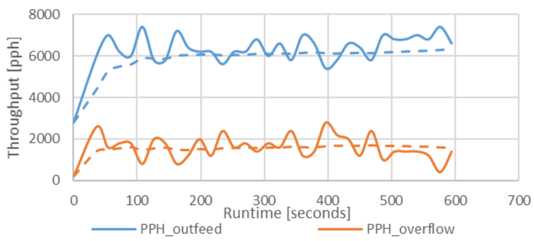


Table 5.4: Representation of the warm-up period

Number of replications

The principle of simulation is based on the usage of random numbers which retrieves input data from a distribution. Therefore, the results of replications may differ, giving the ability to simulate the variety which may occur within operation. Eventually the goal of simulation is to retrieve results within a sufficient accuracy.

One method to retrieve the number of replications is by definition of a minimum required confidence interval. This can be calculated by firstly calculation of the standard deviation based on equation 5.3 (Robinson 2004) which consists of the outputs from several replications.

$$S = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n-1}} \qquad 5.3$$

$S = standard\ devaition\ of\ the\ output\ data$ $\bar{X} = mean\ of\ the\ output\ data$	$n = number\ of\ replicaitons$ $X_i = result\ from\ replication\ i$

With this standard deviation the upper and lower confidence interval are determined based on equation 5.4. This confidence interval is based on the required level of confidence for the true mean of the run. A significant level (α) of 5% is often selected which gives level of certainty of 95% the mean is within the interval. Therefore, the 95% confidence level is used within this research. Within this equation $t_{n-1,\ \alpha/2}$ concerns the value from the student-t distribution for the specific replication with half of the significance level. In addition, with equation 5.5 deviation of the confidence interval is given for the cumulative mean for the replication (i).

$$CI = \bar{X} \pm t_{n-1,\alpha/2} \frac{S}{\sqrt{n}} \qquad 5.4$$

$$S_i = \frac{CI_{i,high} - CI_{i,low}}{2\ \bar{X}_i} \qquad 5.5$$

Eventually, the deviation of confidence interval is analysed for the number of replications as listed within Figure 5.6. This shows that after ten run-times the deviation is below 0.5%, what for this research of a correct accuracy. This test is even examined on a set of configurations which is added within appendix C.

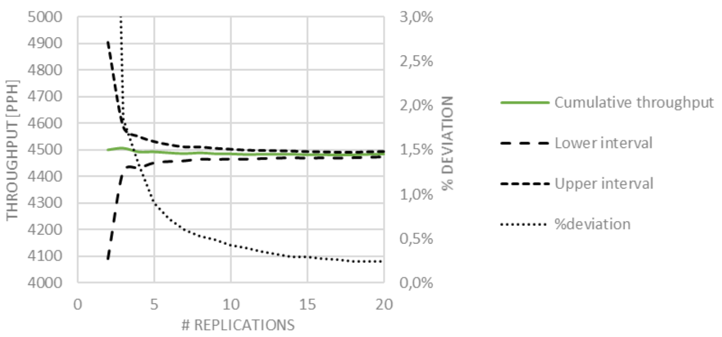


Figure 5.6: Deviation of confidence interval towards the cumulative average throughput

Run-length

Due to variation on input characteristics the output varies through-time, but after a certain time the fluctuation becomes stable. This moment within the simulation is called steady-state what is required to examine an accurate output. In order to retrieve the required run-length for steady-state the simulation is run for ten hours for the reference scenario with an overflow of 20%. Within this simulation a continuous plot is created of the average throughput which is visualized within Figure 5.7. This shows the variability of the moving average at the start of the simulation, whereafter average throughput become stable at around three hours.

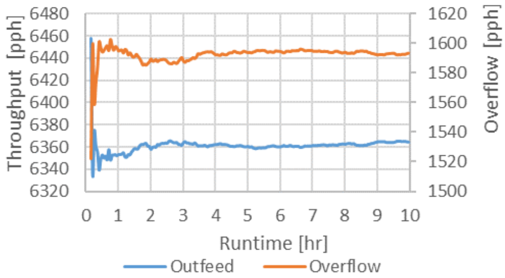


Figure 5.7: Run-length analysis

In addition, the run-length is determined for a loop-sorter with overflow caused by a too small gap-setting. This appeared to have a steady-state at longer run-lengths. Therefore, these experiments are run with a run-length of a full day.

5.6 Verification & validation

The simulation model is created based on the described process. Prior to the examining of the experiments, the model should be checked if it represents reality in the matter as expected. In order to do this verification is required which is defined as "*Determining that a simulation computer program performs as intended*" (Law and Kelton 1991). Following on this, the validation refers to the actual operational system as: "*Determining whether the conceptual simulation model is an accurate representation of the system under study*".

5.6.1 Verification

Throughout the model design verification is continuously examined within the different phases. This involves short visual verification to check if expected behaviour occurs. However, eventually even more other verification checks are required which are listed within this section.

Hypothesis matching

The verification of the system is tested with a relatively simple input distribution of two different parcels. This since the effects which occur can be quickly manually calculated. The scenario which is concerned is the reference scenario subject to an input characteristic of square parcels being of 200 mm and 600 mm parcel since need to be weighed on different scale lengths. This verification is to describe if the applied windowing-methods are implemented correctly within the model. Therefore, firstly the required windows are calculated based on the functional limitations as listed in Table 5.5.

Configuration			**Gap [mm]**		**Average window**			
Sort-angle	Checkweigher		L_{parcel}= 200	L_{parcel}=600	FW	FG	DG	DG Shared-Gap
20	0	0	400	600	1200	1000	900	
0	800	1300	600	700	1300	1100	1050	725

Table 5.5: Verification input table

The described average windows for the different windowing-methods are based on the parcel lengths and the defined gaps. This involves for fixed-windowing (FW) the maximum window. In addition, this involves for fixed-gapping (FG) the average parcel length with the maximum gap, while this concerns for dynamic-gapping (DG) the average window of the parcels of 200 and 600 mm.

Resulting from the experiments which are examined on the simulation model the model matches the outcomes for the mathematical approach. The differences for this analysis are listed within Table 5.7.

			% capacity difference mathematical/model			
Sort-angle [°]	Checkweigher		FW	FG	DG	DG Shared-Gap
20	0	0	0.00%	0.02%	-0.02%	
0	800	1300	0.00%	-0.03%	-0.01%	0.05%

Table 5.6: Verification output

Input distributions

Within this part is checked whether output of the model subjected to a statistical input distribution matches the expectation. This check involves the check if the fraction of parcels which is defined as overflow is correctly defined. To analyse this, the distribution is separately applied towards the length and the width distribution, while the other parameter is constant for all the parcels.

The distribution which is used to characterize the stochastic is a normal distribution with an average of 600 mm and a standard deviation of 100 mm. The model is represented by having a sorter with 30-degrees and a fixed-windowing method.

Firstly, the width is set as fixed-value 1000 mm, resulting with three safety shoes in a required window of for the average parcel length of 1400 mm. Therefore, the fixed window setting is set to 1400 mm which needs to result in 50% of the parcels being sorted to the overflow.

Besides this, the width variation is examined with the length set to a fixed value of 600 mm. Within this parcel width is retrieved from a normal distribution with an average of 1000 mm and a standard deviation of 100 mm. Just like for the length distribution this should result in an overflow rate of 50%, with the usage of a fixed window of 1400 mm. The results from this are listed within Table 5.7 and show that this matches the hypothesis.

Input characteristic				**Configuration**		**Result**
$L_{distribution}$	L_{parcel}	$W_{distribution}$	W_{parcel}	Sort-angle	FW	Overflow rate
Normal	600	Fixed	1000	30	1400	50.03%
Fixed	600	Normal	1000	30	1400	50.03%

Table 5.7: Verification of input distribution

Tracing of entities

The visual aspect of simulation tends to be a powerful method to accomplish verification and validation. Firstly, this includes stepping through the occurring events and checking if these behave as defined within the conceptual model. This is performed for different configurations to examine that the events, the defined parameters and the outputs perform correctly.

Next the logging capability Simio has the ability to visualize the simulation. This has been used to check if the defined gaps for the different windowing methods were applied correctly to the specific parcels. In addition, the parcels that could not be sorted correctly be sorted are checked with this visualization to review if this statement was correctly defined.

5.6.2 Validation

The verification proved that the results of the model matches the analytical hypothesis. However, this does not state in what matter the results match the results within operation. Therefore, within the validation the difference of the model results are compared with the result in operation. This states in what rate the assumptions to simplify the model impact the results.

Arrival pattern

First assumption is that the system exerts a maximum infeed of parcels. This differs from the operational system while the throughput highly fluctuates at the infeeds as visualized in Figure 5.8. The presented data involves one of the peak-throughputs which give insight in the operational capabilities of the system. In order to examine this, the monitoring is split in time-intervals of ten minutes with the throughput on the outfeeds and overflow separately listed.

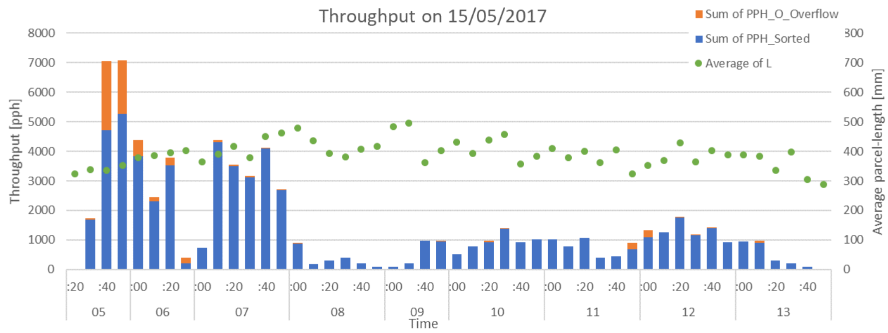


Figure 5.8: Outfeed and overflow throughput within operation

Based on Figure 5.8 the peak throughput on the main-line occurs at 05:40-05:50, being 7332 PPH for an average parcel length of 350 mm. It has to be noted that it is unknown if the system was continuously having infeed. Therefore, these operational capabilities may be still smaller compared to the system maximum.

With this operational data the capabilities as retrieved by the simulation model are compared to the operational system. This is performed by using the same parcel characteristics which were handled during the specified time-interval. In addition, the configuration of the model is matched with the operational system including the fixed-gap setting of 800 mm. With these inputs is run resulting in the outputs as listed within Table 5.8.

	Actual [pph]	Model [pph]	% Diff
Main-line	7086	8482	16%
Outfeed	5274	8096	35%
Overflow	1812	386	-369%

Table 5.8: Comparison of results

The results show that firstly the difference main-line throughput differs by 16%. This difference may be related to the assumption within the model with a constant infeed of parcels. In addition, the excluded effects of the merge-algorithm may even affect this within operation.

Besides this, it is found that the throughput on the throughput highly differs from the actual system caused by a higher rate of overflow. This may be related to blockage- or even full-outfeeds which is not included within the simulation model.

Input distribution

Since the input characteristics are described by an input distribution this differs from the actual results. Therefore, the difference due to the used distribution is analysed.

Within the simulation model, simplifications are made towards the input characteristics. These assumptions are tested on their impact which concern:

- Excluding length-width relation by using two separate distributions
- Usage of continuous statistical distribution instead of tracing
- Truncating distributions

The impact of these decisions is tested on the reference scenario with only a sorter and a sorter and checkweigher. The sorter is also separately included since the impact of the assumption on the width is within this clearly visible. The windowing-method which is used within this validation is dynamic-gapping since this is directly related to the parcel characteristics. The used input-types are tested for several cases to clearly see the impact of the made decisions towards to the statistical distribution.

The results of this analysis firstly involve a comparison of the defined input-type for the parcel characteristics as visualized within Figure 5.9. These results show that mainly there is no difference visible for the throughput in a system with only a sorter. This describes that the assumption to unlink the length and width relation does not impact the throughput.

However, within a configuration with a checkweigher can be seen that a difference of around 1.5% occurs for the used distribution compared to the actual characteristics. It is expected that this effect may be related to second peak which is found within the actual distribution as visualized within Table 5.2 this is not included within the used distribution. In addition, truncating the distribution did slightly reduce the difference since no overflow occurred.

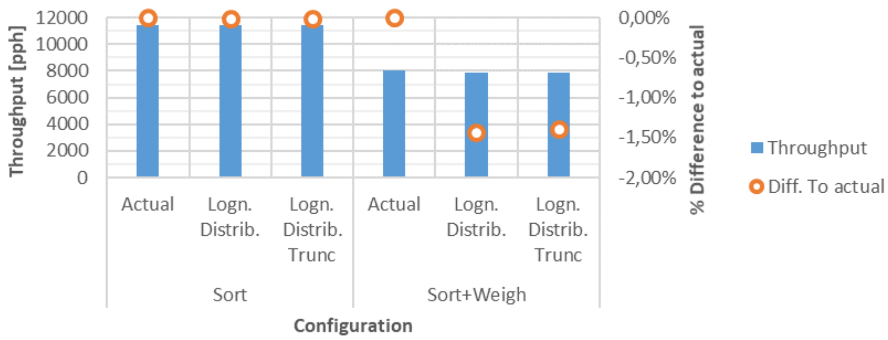


Figure 5.9: Comparison of L/W-input-type

6. Experiments & results

The created model is used to examine experiments which form the basis to answer the defined research questions. Firstly, based on the defined research questions the experimental plan is defined. Hereafter, these experiments are examined on the model which leads to the results. These results are analysed to give insight in the relations of the results which occur due to the changes on of the input or either the system configuration.

6.1 Experiment plan

Based on the system analysis the throughput of the system is dependent on several factors. This firstly involves the system configuration includes the sorter, the checkweigher and the used windowing method.

As described, the system commonly bears a rate of overflow which affects the performance of the system. The effects may differ for the used lay-out and the used windowing-method and window-setting, therefore this factor is included within the experiments. Lastly, a system has a maximum rate of parcels which it can handle, however within operation this arrival-rate commonly does not match this specific rate. Therefore, the last set of experiments concerns the effects of variation on the arrival-rate, which means the system bears different input-pressure.

Eventually the described experiments are summarized within the following list of three experiments which are examined.

1. *System configuration*
2. *Overflow-rate*
3. *Input-pressure*

Within operation it may occur that these experiments even have inter-relations. However, the goal of this research is to retrieve insight in the impact of the described factors. Therefore, the first experiment is applied a whole variety of system configurations, while the last two experiments are applied to the reference scenario.

6.1.1 System configuration

Firstly, to get insight in the difference of the maximum throughputs the system is analysed as a line-sorter, which leaves out effects of overflow. The result of this gives the maximum performance of the system configuration subjected to the input characteristics.Within the experiments that are examined the following parameters are configured:

- Physical configuration
  - Sort-angle
  - Checkweigher configuration
- Parcel width
- Controls
  - Weigh-method
  - Windowing-method

Physical configuration

The system configuration is firstly defined by the checkweigher configuration and the sort-angle. A system includes a sorter, however the checkweigher may be required within the system. Therefore, the impact of sorter and checkweigher configurations is examined as even a configuration without a checkweigher.

Firstly, the impact of the sort-angle is examined by usage of the system-speed of 2 m/s. This system-speed is limit for 30 degrees, what gives the ability to compare the impact of the change in shadow which is required by the sorter.

The scales of the checkweigher are assumed to be available in steps of 100 mm. These scale-lengths are related to the maximum handled parcel length and the weigh-length. However, since the two scales can be used for the weighing different scale combinations are feasible which are based on the same principle limited by the minimum parcel length.

With the minimum parcel length of 150 mm and a weigh-length of 540 mm this results in a required minimum scale-length of 700 mm. In addition, the required maximum scale-length for the reference maximum of 1200 mm, results in the combination of the two scales being at least 1800 mm. This scale-length is therefore also used as length when only one scale is applied since longer single scales would only result in a larger required gap on all parcels. However, the combination of the two scales may be larger as this length, as also occurs within the reference configuration with a total scale-length of 2100 mm. The maximum total scale-length as examined within this research is 2300 mm which is larger as currently applied within the configurations.

Parcel width

In addition to the previous experiment the sensitivity of the configuration is examined towards the parcel width. This evaluates the maximum impact of the parcel width on the limitations of the whole range of parcels. In order to retrieve this, the worst-case scenario is examined which concerns the parcels having the maximum parcel width. This scenario shows the maximum impact of the sorter requirements. However, this generally does not occur within operation since it is in contradiction with the principle of Short-Side-Leading as defined by VanRiet.

Controls

The impact of the used weigh-method is examined by comparing the checkweigher configurations which by usage of dynamic-windowing. As a result, the impact can be determined of using conventional weighing instead of shared-gap weighing. In addition, the impact is examined for the different windowing methods which define a fixed setting.

Concluding input parameters

Within the first category the physical representation is configured of the sorter by the sort-angle and the checkweigher scale-lengths. Besides this, the effect of different windowing-methods and conventional- or shared-gap weighing are examined. The variety of parameters which is changed within this first category of experiments is listed within Table 6.1 with the defined settings for the parameters.

	Parameter	Method	Settings
Parcel	Parcel width		[Distribution, maximum]
Sorter	Sort-angle [°]		[20,25,30]
Checkweigher	Min. scale length[mm]		[0, 700,800,900,1000,1100]
	Tot. scale length [mm]		[0, 1800, 1900, 2000, 2100, 2200, 2300]
	Weigh-method	Conventional Shared-gap	
System	Windowing-method	Fixed window Fixed gap Dynamic-gap	

Table 6.1: Input parameters for experiment 1

6.1.2 Overflow

The second experiment concerns the impact of overflow on the throughput of the system. This experiment is initiated since it is retrieved from operational data that it occurs that a fraction of the parcels are sorted towards the overflow. This fraction differs through time since it may be caused by a variety of factors as listed within section 0.

This experiment is divided into two parts which include:

- Overflow by an overflow-rate
- Overflow by a too small window or gap-setting

Overflow-rate

The first part concerns a fraction of the parcels what are sorted towards the overflow, as it may occur due to for example miss-reads of full outfeeds. This rate of overflow equally reduces the throughput with the specified rate within a line-sorter. However, within a loop-sorter the overflow recirculates within the system resulting in the parcels from the overflow occupying space at the merge what cannot be used by the parcels from the infeed. It is expected that the impact of overflow is related to the windowing-method. Therefore, the impact of overflow is examined for the three windowing methods. It is expected that the even the used weigh-method may result in a different behaviour to the rate of overflow. Conventional weighing and shared-gap weighing are because of that included within this experiment. Within this experiment the probability for a parcel to become overflow is equal for every single time the parcel enters the sorter. Therefore, the loop shall not be blocked which may occur when all the parcels cannot be sorted.

Gap-setting

The following part of this experiment includes the ability to use a setting for the fixed-window and fixed-gap which does not fully match the full range of parcels. The used fixed-setting may only be required for some specific parcel characteristics within the whole range of parcels. Therefore, a reduction of the setting may firstly result in an increased throughput. This tends to improve until the fraction of parcels that are sorted to the overflow becomes larger as the gap what it in total reduced.

It is expected that this may differ for a line-sorter compared to a loop-sorter. This is because the overflow within a loop-sorter recirculates which eventually may result in a dead-lock with no throughput. It is expected that a parcel which cannot be sorted may still be sorted when the shared-gap weighing is used. This is since with shared-gap weighing the parcel gap requirements are a combination of the gap-front and the gap-back. With conventional weighing it expected that the parcels within the overflow cannot be sorter since this method only sets a requirement towards the gap-back which is defined by the setting.

The window- and gap-setting which are used within this experiment are based on the minimum and maximum as defined within chapter 6.1. In between these limits a variety of settings are examined to list the behaviour for different settings.

Concluding input parameters

This experiment concerns the variation of the listed input-parameters on the defined reference scenario. Where this reference scenario is applied to the changes on the input-parameters as listed within Table 6.2.

	Parameter	Method	Settings
Checkweigher	Weigh-method	Conventional Shared-gap	
System	Layout	Line Loop	
	Windowing-method	Fixed window [mm] Fixed gap [mm] Dynamic-gap	[1200..2100] [540..1340]
	Overflow-rate		[0..1]

Table 6.2: Input parameters for experiment 2

6.1.3 Input-pressure

The previously listed experiments concern the maximum infeed of parcels which describes the maximum performance. Generally, the throughput of the system is directly linked to the pressure of parcels on the infeeds. However, it is expected to differ for fixed-gapping and fixed-windowing. Within these methods a too small gap setting may still lead to a correct sorting when no parcel arrived from the infeed. Therefore, the input-pressure may impact the rate of overflow and, by that, the throughput of the system. As a result, a too small gap-setting does not necessarily result in overflow as occurred within the previous experiment.

Within this experiment the impact of the gap- and window-setting are examined for fixed-gapping and fixed-windowing including changes on the input-pressure. From these the input-pressure is related to the throughput for the maximum gap-setting as retrieved from the previous experiment. In addition, the impact of the two weighing concepts is considered within this experiment.

This experiment concerns the impact on a line-sorter since the overflow is expected to differ compared to the previous experiment. However, within a loop-sorter the steady-state behaviour does still result in blockage when two parcels are placed too close to another. Therefore, a line-sorter is examined within this experiment.

Concluding input parameters

The described input-parameters are for the matter of insight summarized within Table 6.3. Which shows the changed input parameters which are changed within this experiment.

	Parameter	**Method**	**Settings**
Checkweigher	Weigh-method	Conventional Shared-gap	
System	Windowing-method	Fixed window [mm] Fixed gap [mm]	[1200..2100] [540..1340]
	Arrival-rate		[0.7..1.3]

Table 6.3: Input parameters for experiment 3

6.2 System configuration

Within this experiment the optimal-case is examined which concerns the maximum arrival of parcels for defined configuration. To analyse this, the system is firstly analysed on the physical configuration of the sorter and the checkweigher in combination with the system speed. Hereafter, the impact of changes within the controls are analysed concerning the windowing- and weigh-method.

6.2.1 Physical configuration

The sort-angle limits the throughput of configuration with the maximum system-speed and the related shadow. The impact of the sort-angle is examined by comparing the throughput for a system with the different sort-angles. The wider sort-angle may result in larger required gaps. The gap requirements on the checkweigher are dependent on the checkweigher configuration. Therefore, the impact of the sort-angle may differ for the different checkweigher configurations.

The effect of the sort-angle is analysed by comparing the throughput of system with different sort-angles and a system-speed of 2 m/s visualized within Figure 6.1. This concerns the maximum capabilities of the system with dynamic-gapping including shared-gap weighing. It is retrieved from this, that the sort-angle has an impact on the throughput of almost 6% in a system with only a sorter. However, within a configuration with a checkweigher the throughput is mainly limited by the checkweigher configuration which is visualized by an impact of the sort-angle which is mainly smaller as 1% for the configurations. In addition, can be retrieved from Figure 6.1 that appliance of a checkweigher within a configuration reduces the throughput.

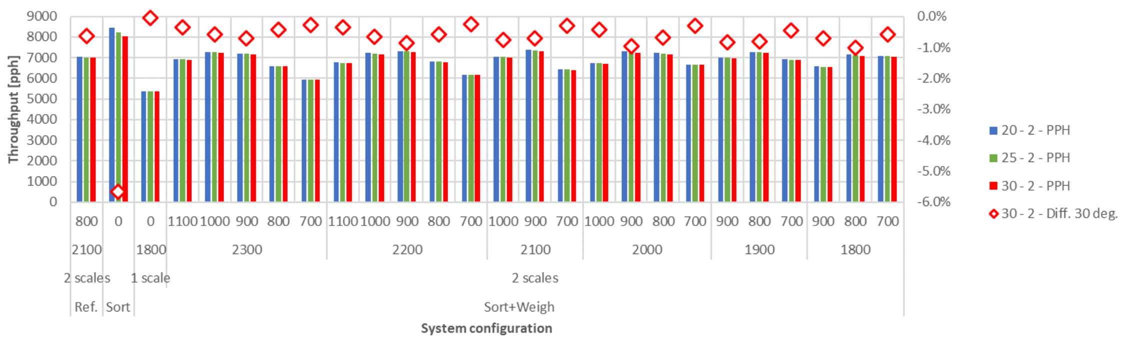


Figure 6.1: Throughput overview of different system configurations with shared-gap weighing

Based on Figure 6.1 a brief insight may be retrieved of the checkweigher configuration. However, this figure does not necessarily give a clear insight in the relations towards the throughput for the checkweigher configuration. It does show that the configurations with two scales of the same size have a smaller throughput; however the trend of the throughput for the configurations cannot be retrieved from this figure.

As retrieved from Figure 6.1 the sort-angle has a small impact on throughput. Therefore, the following experiment for the checkweigher configuration is only examined with a sort-angle of 20 degrees. In addition, the reference configuration is used which involves a system speed of 2.7 m/s. To analyse the impact of the checkweigher configuration this needs to be listed in a manner that it visualizes the impact of the used set of scale-lengths. A configuration with two scales results in three different scale lengths which impact the system throughput. This consists of the two scale-lengths and the combined length of the two scales. To visualize this impact, a length ratio is introduced which involves the ratio of the smallest scale towards the total scale length. Based on this, the impact of the checkweigher configuration is listed within Figure 6.2, where the lengths of the smallest scales are listed within the data-labels, while the length of the total scale-length are represented within the legend.

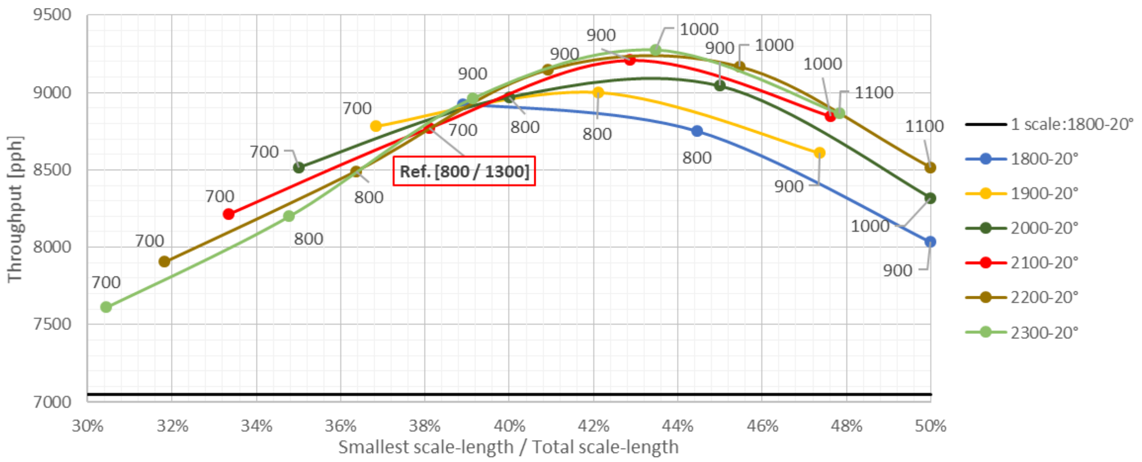


Figure 6.2: Throughput comparison for checkweigher configurations with shared-gap weighing

It is noted that for the configurations with a scale ratio between 40% and 45% the highest throughputs are achieved. This is expected to be related to the fraction of parcels that can be weighed on the smallest scale. Within the experiments this involves the scales with 900 mm and 1000 mm. This may be linked to the median of the parcel length of 366 mm which with the required weigh-length of 540 mm results for half of the number of parcels require a scale-length of at least 904 mm. Therefore, almost half of the number of parcels can be weighed on the scale of 900 mm, while even a higher fraction is weighed on a scale of 1000 mm. In addition, when the scale lengths become the same length the throughput decreases which is because this is eventually is equal to having two scale-lengths instead of the three scale-lengths.

As a result, from the comparison can be seen that the reference configuration is not the optimal configuration for the handled parcel length. Compared to the maximum throughput this differs with around 5% as visualized within Figure 6.3. Opposing to this, even a reduction up-to 18% is seen for a tested non-optimal configuration, while with only one scale the difference becomes almost 25% to throughput at the optimal configuration.

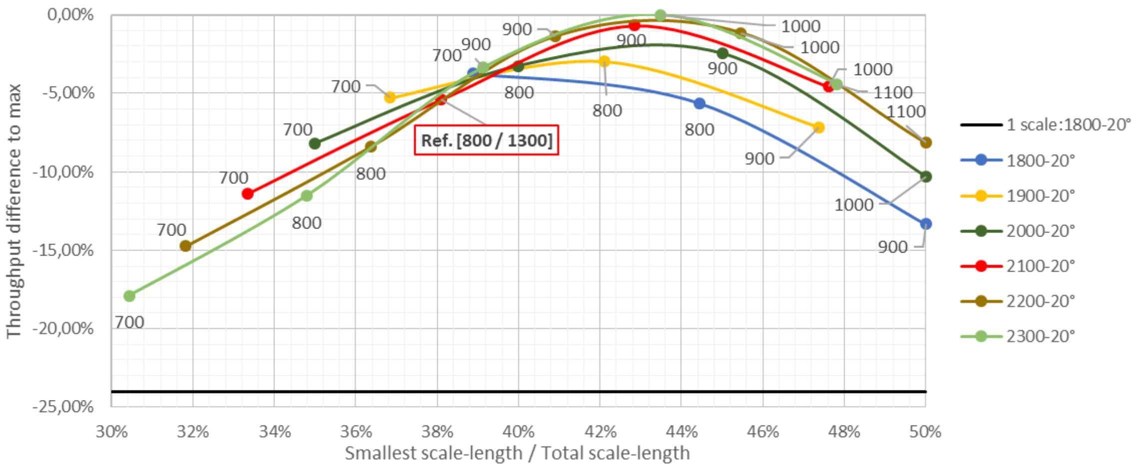


Figure 6.3: Impact on the throughput of checkweigher configurations to the maximum throughput

Moreover, is retrieved from Figure 6.3 that the tested checkweigher configurations generally have an impact on the throughput which is smaller as 5%. This is in displayed within Figure 6.4 which shows the rate of configurations for what a throughput difference occurs within steps of 2.5%.

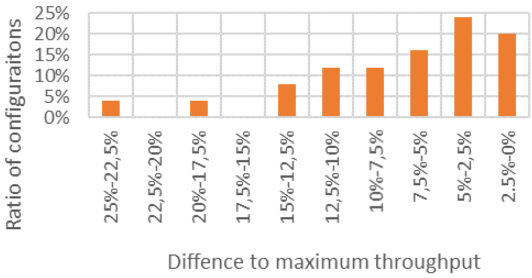


Figure 6.4: Difference to maximum throughput for checkweigher configurations

6.2.2 Parcel width

In addition to the previous experiments, the impact of the parcel width is analysed for the set of checkweigher configurations. This is to retrieve the maximum impact of the parcel width on the system throughput. Currently often the sorter capabilities are used to determine the system throughput. In addition to the previous experiment, this experiment shows the maximum impact the sort-angle may have on the system throughput.

As visualized within Figure 6.5 the impact on the throughput is at maximum reduced by 2.5%. This is compared to the used width distribution from the previous experiment. Within a system with only a sorter the impact of this width difference would reduce the capacity by around 17%.

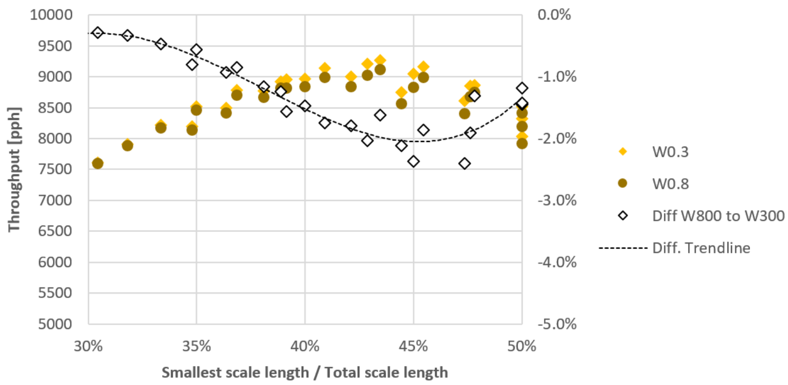


Figure 6.5: System sensitivity to the average parcel width, a sort-angle of 20-degrees and shared-gap weighing

6.2.3 Weigh-method

In addition to the impact of the configurations, the impact of the different weigh-methods is examined for the variety of checkweigher configurations. This involves for every checkweigher configuration the impact on the throughput of shared-gap weighing compared to the conventional method, still with dynamic-gapping. The results of this comparison are listed within Figure 6.6. However, within this the total scale-length is not listed since it is the purpose of this comparison to list what differences are achievable by applying the shared-gap weigh-method compared to the conventional method.

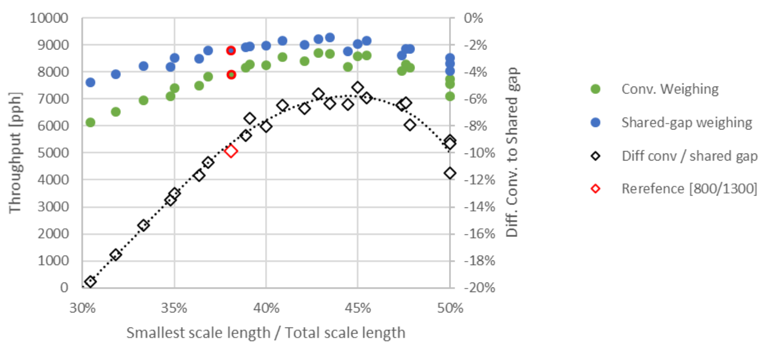


Figure 6.6: Throughput comparison on conventional weighing and shared-gap weighing

The listed differences are compared Figure 6.6 for the same configurations concerning the different weigh-methods. Therefore, the differences within throughput are determined based on equation 6.1 which describes the difference in throughput for the weigh-method on a specific checkweigher configuration : i.

$$TP_{difference}(i) = \frac{TP_{conventional}(i) - TP_{shared-gap}(i)}{TP_{shared-gap}(i)} \tag{6.1}$$

Based on the results can be seen that the difference between conventional weighing and shared-gap weighing is between 5% up-to 20% where it is highly dependents on the system configuration. It is retrieved from this experiment that the difference between conventional weighing and shared-gap weighing decreases when the scale-configuration becomes more optimal. This is as expected since these configurations require the smallest fill-gap.

6.2.4 Windowing-method

Within the previous experiments the system throughput is based on the functional limitations with dynamic-gapping. Opposing to this, the system can be configured with fixed gapping or either fixed windowing. These are based on the maximum gap- or window-requirement for the whole range of parcels.

The result of this experiment, which is examined for conventional weighing, is listed within Figure 6.8. This result shows that the throughput with fixed-windowing is only related to the maximum scale-length. In addition, the results for fixed-gapping show a trend with the highest throughput for lowest scale-ratios. This is since the fixed-gap is defined by the first parcel on a scale, which is generally the first parcel on the largest scale. Therefore, with a smaller scale-ratio the parcel length on the maximum scale becomes longer resulting in a smaller gap-requirement.

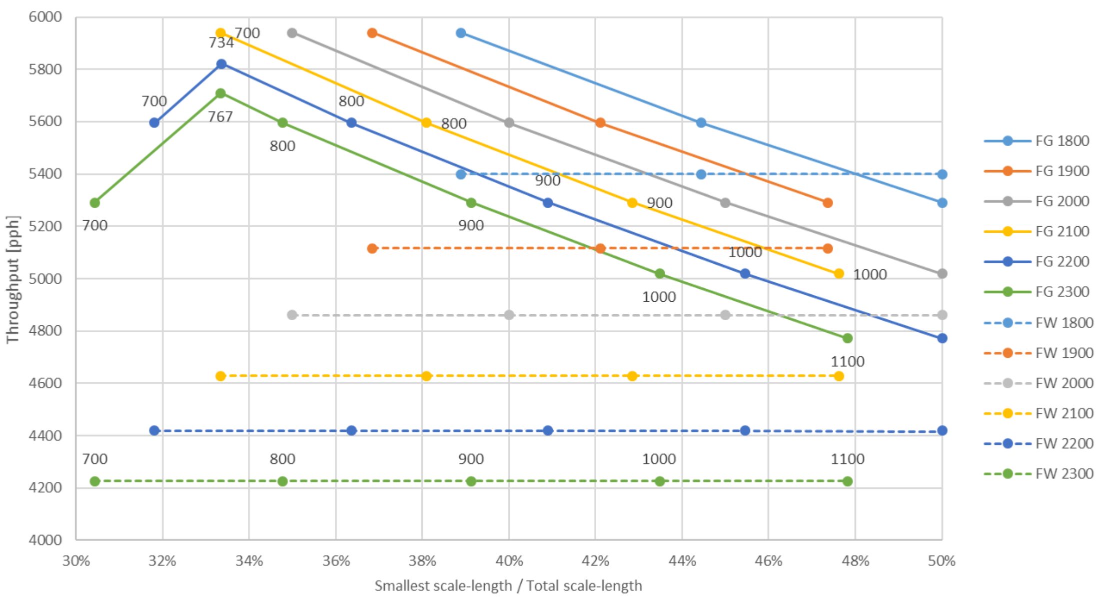


Figure 6.7: Throughput comparison for the windowing-method to the scale-ratio with conventional weighing

Remarkable is the configuration with a checkweigher configuration of [900/900] which has a higher throughput with fixed-windowing compared to fixed-gapping. This effect is related to the relative small-scales in combination with the scales being the same size.

Besides this, another effect is seen for the smallest scale ratios with a total scale length of 2200 and 2300 which decrease in throughput. This is because the fixed-gap setting is from this point determined by the first parcel which is weighed on the largest scale in-stead of the first parcel weighed on the total scale-length. This effect is visualized within Table 6.4 which shows the change towards the maximum required gap on the first-scale.

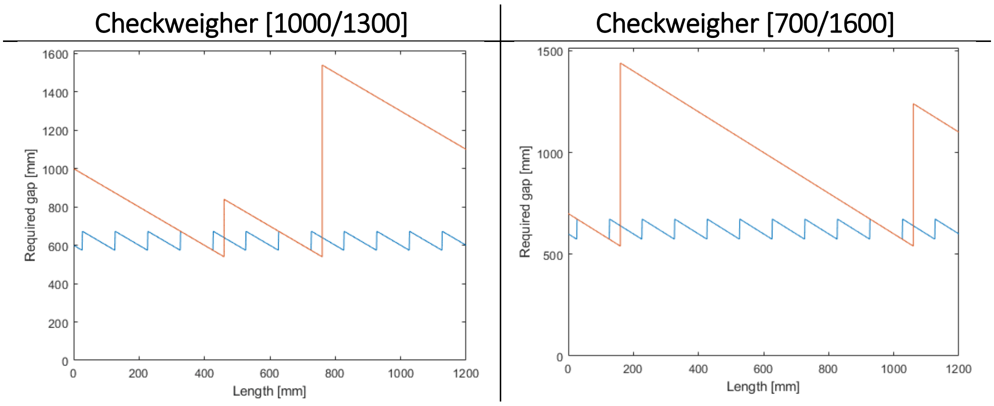


Table 6.4: Required gaps on two checkweigher configurations

The scale-ratio where this occurs can even be analytically retrieved from the gap-setting calculation. This involves the minimum parcel length that needs to be weighed on the specific scale (combination), which is determined by the maximum length of the previous scale. The equations which are used to define the gap are listed within Table 6.5. The equation for the maximum gap is listed by filling definition of the smallest parcel which needs to be weighed on the specific scale.

	Smallest parcel	largest ($L_{pMax,si}$)	Maximum gap
Scale 1	$L_{parcel,min}$	$L_{s1} - L_{weighl}$	$L_{s1} - L_{parc}$
Scale 2	$L_{pMax,s1}$	$L_{s2} - L_{weighl}$	$L_{s2} - L_{pMa}$ $L_{s2} - L_{s1}$
Scale 1+2	$L_{pMax,s2}$	$L_{parcel,max}$	$L_{s1+2} - L_{pMax,s2}$ $L_{s1+2} - L_{s2} + L$ $L_{s1} + L_{weig}$

Table 6.5: Calculation of maximum required gap per scale-length

With these equations the ratio can be defined where the gap required on the largest single scale becomes larger as the required gap on the scale-combination. The proof of the previous retrieved 33% scale ratio follows eventually from equation 6.6 which is derived below.

$$L_{gap,1+2} \leq L_{gap,2} \tag{6.2}$$

$$L_{s1} + L_{weighl.} \leq L_{s2} - L_{s1} + L_{weighl.} \tag{6.3}$$

$$2L_{s1} \leq L_{s2} \tag{6.4}$$

$$2L_{s1} \leq L_{S1+2} - L_{s1} \tag{6.5}$$

$$L_{s1} / L_{s1+2} \leq 1/3 \tag{6.6}$$

In addition to the previous experiment the effect of the windowing-method is compared to the dynamic-windowing principle. The results of this comparison are listed within Figure 6.8 and show that fixed-gapping instead of dynamic-windowing decreases the throughput with at least 20% for the examined configurations.

The throughput with fixed-windowing is based on the total scale-length. Opposing to this, the throughput for fixed-gapping differs based on the configuration with a decrease of around 40% for fixed-gapping and between 25% and even up-to 50% decrease for fixed windowing.

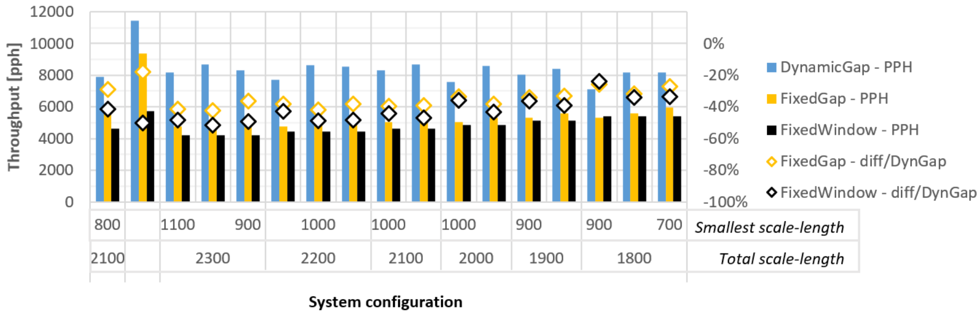


Figure 6.8: Throughput comparison on the windowing-method with conventional weighing

6.3 Overflow

The impact of the overflow is, as described, split in two parts. The first part concerns the impact of the ratio of parcels which are become overflow due to reliability as for example miss-reads. Besides this, the impact of overflow which occurs due to a too small window- or gap-setting is examined within the second part.

6.3.1 Overflow-rate

The effect of the overflow-rate is examined for the different windowing methods. Furthermore, for dynamic-gapping the conventional and shared-gap weighing are included. These different weigh-methods are included since the throughput differs within dynamic-gapping. Within fixed-windowing and fixed-gapping the weigh-method does not change the window or gap setting. Therefore, the weighing concepts are not of importance for windowing with the maximum required setting.

The impact of the overflow-rate is firstly analysed by comparing the impact within a line- and a loop-sorter system. Within this, the throughput on a line-sorter is directly related to the overflow-rate and the maximum throughput as retrieved from the previous experiments. Opposing to this, the recirculating parcels occupy space at the merge area which further reduces the throughput as visualized within Figure 6.9. The line-sorter is within this compared to the loop-sorter applied to same overflow-rate. To get a further insight, the difference between the throughput on a line-sorter and the loop-sorter is visualized within Figure 6.10. The percentage shows the difference in the throughput-fraction compared to a line-sorter. This fraction is related on the maximum throughput, so the maximum difference of 7.5% with an overflow-rate of 40% states a reduction of 47.5% throughput.

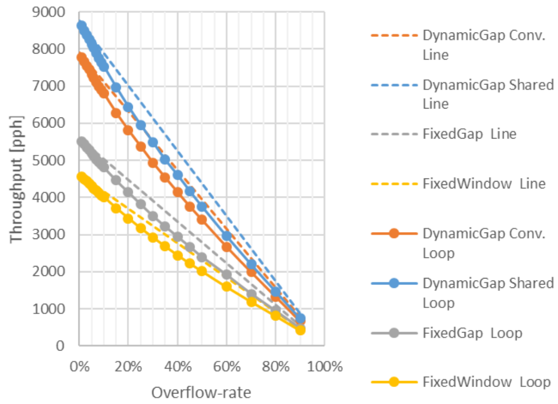


Figure 6.9: Throughput comparison between overflow for a line- and a loop-sorter

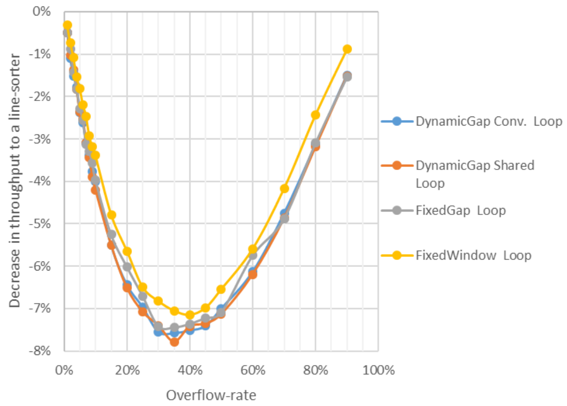


Figure 6.10: Difference in the impact of overflow for a loop-sorter compared to a line-sorter

These figures show that the throughput decreases with a larger fraction compared to the same rate of overflow within a line-sorter. This effect is related to the recirculating parcels which generally do not arrive at the merge that the parcel from the infeed exactly fits. This extra space which is required per parcel may have a relation with the average window-length and the loop-length. However, these relations are not examined within this research.

The decrease in the difference between throughput of the line- and the loop-sorter describes that the utilization of the overflow is higher with the higher rate of overflow. This effect visualizes that high rates of overflow require relatively small fractions of extra space to fit the parcels within the available space. It is expected that with fractions higher overflow-rates the recirculating parcels behave more as a "train". Therefore, the miss-fit of the window with the total loop-length is expected to level-out for a couple of recirculating parcels instead of one which reduces the effect of recirculation.

6.3.2 Gap-setting in a line-sorter

Within the previous experiments the fixed-gap and fixed-window setting were defined based on the maximum requirements. Therefore, all the parcels that are merged with this setting can be weighed and sorted. When a fraction of this maximum requirement is used as setting, some parcels become overflow which reduces the system throughput. In addition, a reduction in the window- or gap-setting reduces the space which is required for all the correctly sorted parcels which may increase the throughput.

Fixed-windowing

Firstly, the effect of using the reduced window-setting is examined on a line-sorter system. This reduced window results in a higher throughput as listed within Figure 6.11 with the maximum window-setting as reference-throughput. From these results can be retrieved that, for the used configuration, a decrease in the window-setting does have almost no effect on the overflow-rate as listed within Figure 6.12.

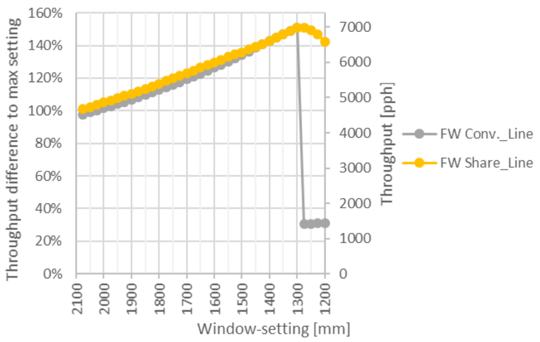


Figure 6.11:Throughput difference for fixed windowing

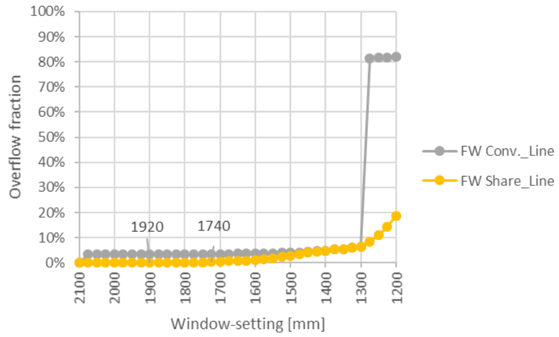


Figure 6.12: Overflow-difference for fixed-windowing

These results are directly related to parcel characteristics as retrieved from Figure 6.12 only a small fraction of around 3.5% requires this maximum window-setting. With conventional weighing this 3.5% is constant between the window-setting of 1300 mm and 2100 mm since it is directly related to the scale-length. Opposing to this, with shared-gap weighing the overflow occurs from a window of 1920 mm. This critical window can be retrieved by converting equation 3.6 for the minimum required gap with shared-gap weighing towards the minimum required window-setting. This follows from equation 6.7 towards equation 6.8.

$$L_{Gap,front} + L_{Gap,back} + L_{Parcel} >= L_{Scale} + L_{Weigh} \quad (3.6)$$

$$2 * L_{window} - L_{Parcel,max} >= L_{Scale} + L_{Weigh} \quad (6.7)$$

$$L_{window} >= (L_{Scale} + L_{Weigh} + L_{Parcel,max})/2 = (2100 + 540 + 1200)/2 = 1920\text{mm} \quad (6.8)$$

A remarkable point is at a window-setting of 1300 mm, where the overflow-rate significant increases including a large reduction in throughput. This effect is related to the range of parcels which is weighed on the 1300 mm scale. This includes the fraction of parcels between 260 mm and 800 mm which is substantial, resulting in an overflow-rate of around 80% for conventional weighing. Opposing to this, with shared-gap weighing the overflow-rate gradually increases for a decreased window-setting. This is since the functional requirement with shared-gap weighing is related to the combination of the gap-back and the gap-front.

Fixed-gapping

Following on the effects of fixed-windowing, the reduction on the gap-setting within fixed-gapping is examined. The results of this reduction are listed within Figure 6.13 and Figure 6.14 which describe, like the previous comparison, the related rate of overflow and difference in throughput to the maximum required gap-setting.

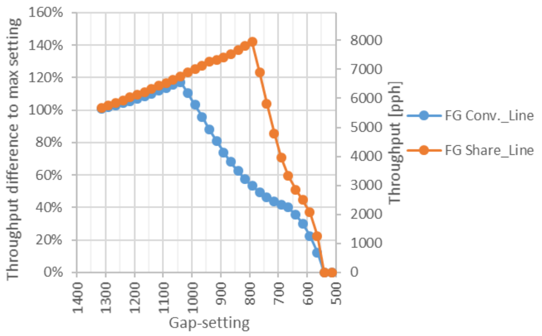


Figure 6.13: Throughput difference for fixed-gapping

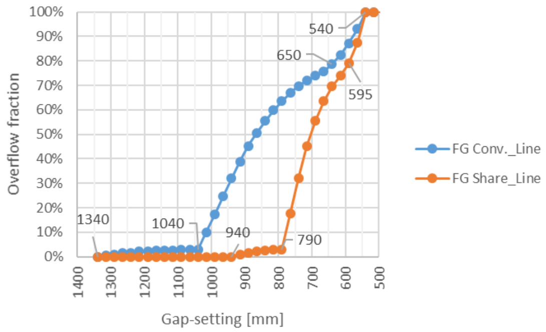


Figure 6.14: Overflow-difference for fixed-gapping

The figures show that the rate of overflow is below 3% up-to a gap-setting of 1040 mm for conventional weighing and 790 mm for shared-gap weighing. For smaller gap-settings the overflow-rate significant increases due to fraction of parcels which is weighed on the 1300 mm scale. This gap-setting can be retrieved from equation 6.9 for the checkweigher requirement. This equation is converted, to retrieve the minimum fixed-gap setting as described by equation 6.10. Within this, the length of a specific scale $L_i(Scale)$ and the length of the smallest parcel on the specific scale $L_i(Parcel_{min})$ are included.

$$2 * L(gap_{fixed}) + L_i(Parcel_{min}) >= L(Scale) + L(Weigh) \quad 6.9$$

$$L(gap_{fixed}) >= \frac{L_i(Scale) + L(Weigh) - L_i(Parcel_{min})}{2} = \frac{2100 + 540 - 760}{2} = 940\ mm \quad 6.10$$

With this equation the other limiting gap-setting as listed within Figure 6.14 can be retrieved. This results for the scale of 1300 mm in a critical gap of 790 mm and for the scale of 800 mm in a gap of 595 mm. These gaps are even marked within Figure 6.14 which also includes the gap of 540 from what the gap becomes below the weigh-length. Therefore, no parcel can be weighed anymore from this setting which results in 100% overflow.

6.3.3 Gap-setting in a loop-sorter

The behaviour as described for a line-sorter, forms the basis for the experiments on a loop-sorter. As retrieved from the experiment on a line-sorter, a fraction of the parcels cannot be sorted when the gap- and window-length are smaller as the functional limit. This experiment describes the effect of this overflow within a loop-sorter.

Since this experiment is involves a constant input-pressure the parcels with a too small gap may be continuously recirculating on the system. This eventually may result in blockage of the loop when the gap within the following rounds even does not match the functional requirement.

Fixed-windowing

Firstly, the fixed-windowing method is examined as listed within Figure 6.15 and Figure 6.16. These figures show that for conventional weighing and a window-setting below 2100 mm an overflow-fraction above 50% occurs. This is due to the recirculation of the parcels with a length between 760 mm and 1200 mm which require the window-setting of 2100 mm. Since it is a small probability on these parcels, as retrieved from the previous experiment, total blockage of the system does not occur. Eventually, these parcels still may be sorted, which is when the parcel from the infeed does not fit behind the recirculated parcel. This results in a larger gap-back for the recirculated parcel and can therefore be sorted.

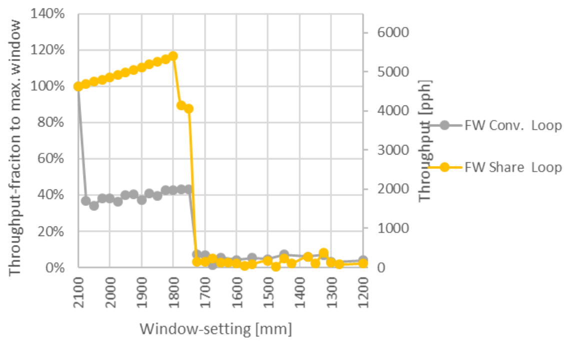


Figure 6.15:Throughput comparison for fixed-windowing

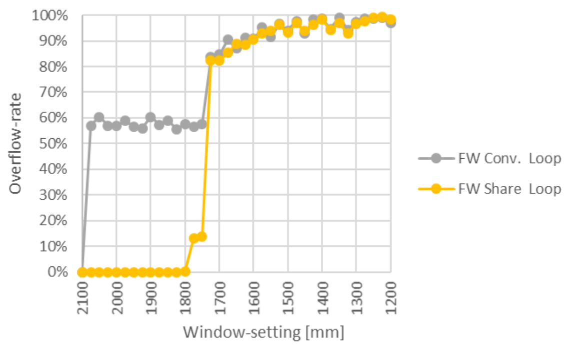


Figure 6.16: Overflow comparison for fixed-windowing

It turns out that total blockage of the system occurs when the window is set below 1740 mm. This is since for the largest parcels, the gap-back becomes smaller as the weigh-length. In addition, the gap-front of the succeeding parcel becomes even smaller as the weigh-length. Therefore, both parcels cannot be sorted and keep recirculating, which eventually results in blockage of the loop.

Lastly, the highest throughput with shared-gap weighing is reached with a window-setting of 1800 mm. This is since this is the maximum window which is required for the largest parcels on the sorter as described within Figure 5.3. Therefore, these largest parcels generally cannot be sorted resulting in a decrease in throughput.

Fixed-gapping

The fixed-gapping method shows a similar effect which may even be linked to the overflow which occurs on a line-sorter. When the gap-setting is set smaller as the minimum requirement the parcels keep recirculating. This reduces the throughput as visualized within Figure 6.17 and Figure 6.18. When the parcels from the infeed do not fit within the space which is behind a parcel from the overflow these overflow parcels may still be sorted. This describes the effect for conventional weighing, like this occurred with fixed-windowing.

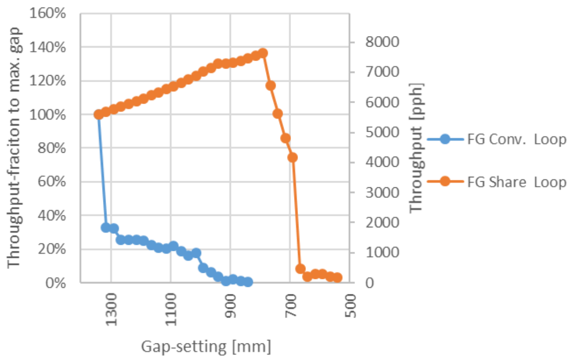


Figure 6.17: Throughput comparison for fixed-gapping

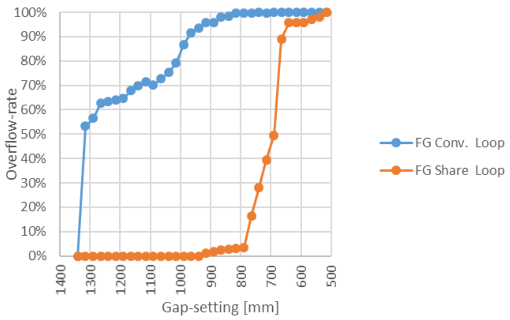


Figure 6.18: Overflow comparison for fixed-gapping

6.4 Input-pressure

The impact on the throughput within the previous experiment occurred within an ideal situation, where the maximum rate of parcels arrives at the infeed. Within operation this generally does not occur. Therefore, this last experiment concerns the impact of a varying input-pressure of parcels on the infeeds. This experiment is, as described within the experimental plan, only applied to a line-sorter. This is since the variation in input-pressure does not affect the throughput within steady-state of a loop-sorter. Within a line-sorter this may have impact since the overflow-parcels are after sorting out of the system.

6.4.1 Fixed-window

The maximum window-setting is defined by the maximum parcel length and the related scale-length. As concluded from the previous experiment a reduction of this setting results, on a line-sorter, in a fraction of overflow. This effect may be smaller when the input-pressure is smaller as the maximum the system is able to handle.

Firstly, conventional weighing is examined as visualized within Figure 6.19 and Figure 6.20. These include the result from the previous experiment with the maximum arrival of parcels from the infeed. The rates which are examined involve the input-pressure compared to throughput which is performed by the maximum window-setting.

As retrieved from the results, it turns-out that the results have similarities with the result of a maximum arrival of parcels. The input-pressure above 1 follows the trend from the previous experiment. This is since for a large window-setting the input-pressure above one result in having continuously a buffer of parcels on the infeed. Just as with the maximum arrival, the throughput decreases and the overflow increases for a window-setting below 1300 mm. However, with a smaller input-pressure the impact of this window-setting is smaller. As a result, the throughput is higher with a smaller input-pressure since the parcels may still have the required gap when the following parcel did not arrive yet.

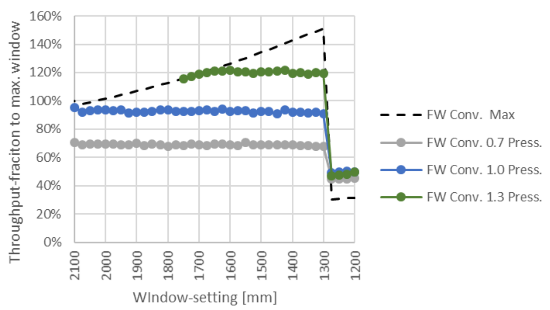


Figure 6.19 Throughput comparison with conventional weighing

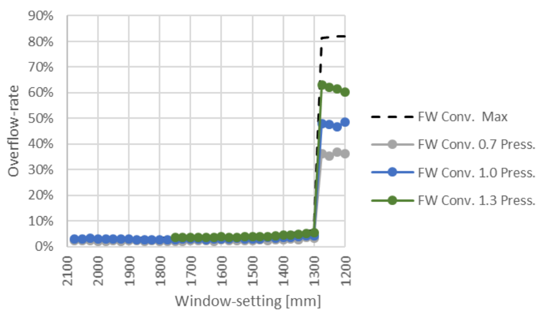


Figure 6.20: Overflow comparison with conventional weighing

Opposing to this, it turns out that with shared-gap weighing a decrease in the input-rate does not visualize a trade-off between continuous and discontinuous parcel arrival. This is since the overflow fraction slightly increases for the decreased window-length resulting in even the throughput slightly decreasing.

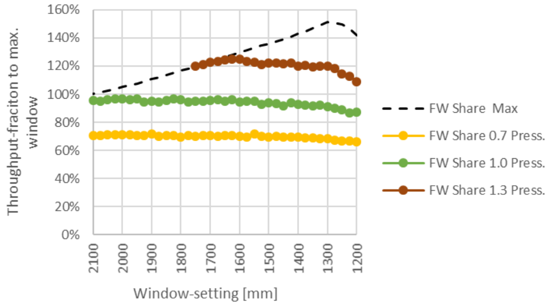


Figure 6.21: Throughput comparison with shared-gap weighing

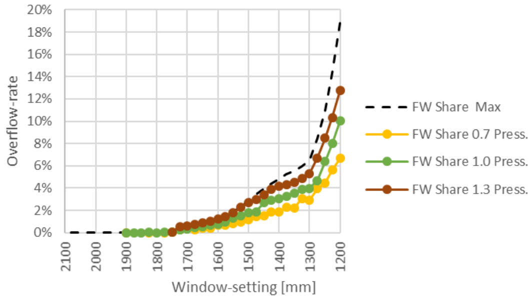


Figure 6.22: Overflow comparison with shared-gap weighing

6.4.2 Fixed-gapping

The impact of the setting for fixed-gapping shows a similar behaviour towards the input-pressure as listed within Figure 6.23 and Figure 6.24. For conventional weighing this involves, like with fixed windowing, a gap-setting of trade-off between the throughput with the maximum arrival of parcels and having a fraction of the input-pressure. This occurs at the previously described gap-setting of 650 mm where the overflow-rate for the maximum input-rate of parcels increases. Opposing to this, the overflow-rate does for a small input-pressure increase with a smaller rate. Therefore, the throughput is higher for a smaller input-pressure.

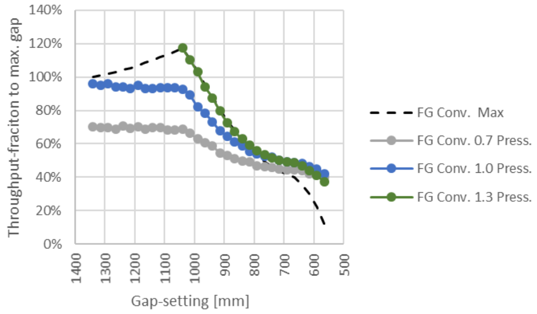


Figure 6.23: Throughput comparison with conventional weighing

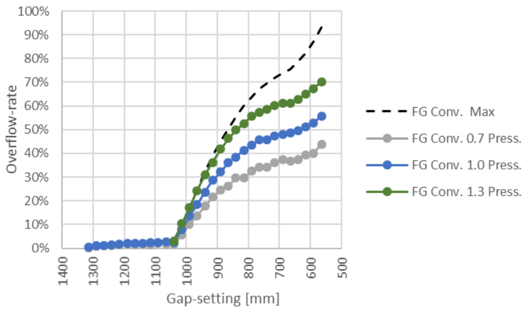


Figure 6.24: Overflow comparison with conventional weighing

The described effect even appears within shared-gap weighing. As retrieved from the analysis with a maximum arrival of parcels, a large fraction of overflow occurs at a gap-setting of 790 mm. The impact of this setting tends to be smaller with a lower input-pressure. As a result, the throughput with a lower input-pressure becomes larger as visualized within Figure 6.25.

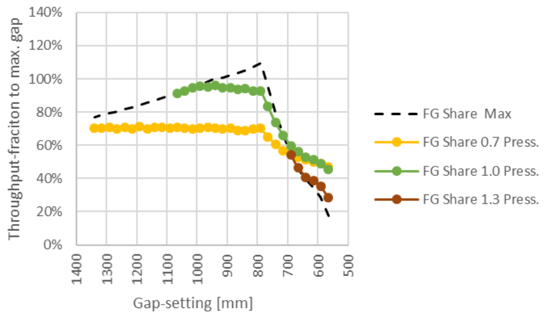


Figure 6.25: Throughput comparison with shared-gap weighing

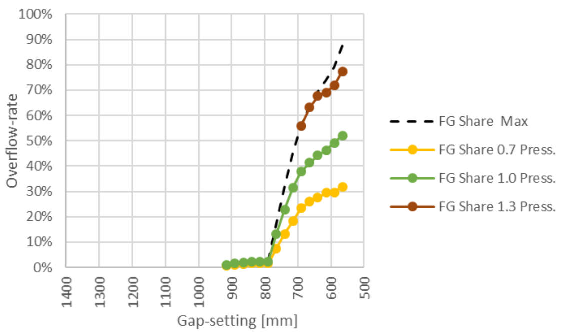


Figure 6.26: Overflow comparison with shared-gap weighing

6.5 Summary of results

In order to finalize the whole set of results these are summarized within this last section. This includes the high-lights which are retrieved from the experiments.

6.5.1 System configuration

These results for the system configuration reveal that the sort-angle has generally an impact which is smaller as 1% in systems with a checkweigher while this is around 6% without a checkweigher. As expected the impact would increase when all the parcels are the maximum parcel width. It should be noted that this impact concerns the impact for a speed of 2 m/s which describes the different gap-requirements. Besides this, the higher speed which may be used for the 20-degree sort-angle even impacts the throughput.

The experiments for the checkweigher configuration showed that these mainly reduce the throughput by around 5% for the different scale combinations. In addition, the used weigh-method and windowing method even impact the throughput of the system. This concerns for the weigh-method an impact of at least 5% while this may for fixed-gapping and fixed-windowing be between 25% and 50%.

6.5.2 Overflow

The experiments for the impact of overflow described difference throughput in a line-sorter and loop-sorter concerning the two different types of overflow. Firstly, the overflow which occurs by operational factors, such as the reliability of equipment, has a larger impact within a loop-sorter compared to a line-sorter which may be around 7% larger as the defined occurred overflow-rate.

In addition, the overflow which may occur due to a too small window- or gap-setting has a different impact on the throughput. Firstly, when the maximum arrival of parcels is concerned this highly impacts the throughput within a loop-sorter. This is since the parcels with a too small window- or gap-setting may not keep recirculating which eventually may cause blockage of the system.

Opposing to this, a reduction of the window- or gap-setting results in an increase of the throughput within a line-sorter. The described results for the reference scenario are compared with the results without overflow to compare the difference in throughput. These results are shown within Figure 6.27 and Figure 6.28 with the percentage of overflow listed below the bars.

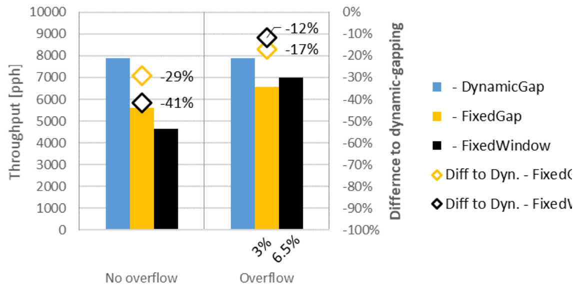


Figure 6.27: Throughput with conventional weighing

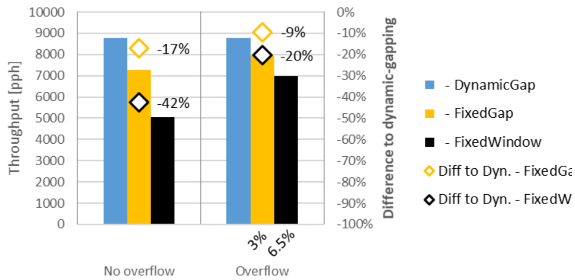


Figure 6.28: Impact with shared-gap weighing

These figures firstly include the impact without overflow for the reference scenario. This concerns an impact of the window with for shared-gap weighing an of at least 17% with fixed-gapping while this is 42% with fixed-windowing.

Moreover, the results with overflow visualize that the impact of fixed-windowing and fixed-gapping compared to dynamic-gapping reduces when overflow is permitted. It is retrieved from these results for conventional weighing that the throughput reduces compared to dynamic-gapping by 17% for fixed-gapping while this is 12% with fixed-windowing. With shared-gap weighing the throughput of fixed-windowing is equal to conventional weighing with a difference to dynamic-gapping of 20%. However, with fixed-gapping the throughput increases resulting in only a difference of around 9% compared to dynamic-gapping.

In addition to the previously described results, the impact is summarized of permitting overflow for the different windowing-methods. Therefore, the peak-throughput with overflow is compared to the case without overflow within Figure 6.29. This shows that when overflow is permitted the throughput may increase at least by 9% with fixed-gapping while this is even more then 38% for fixed-windowing.

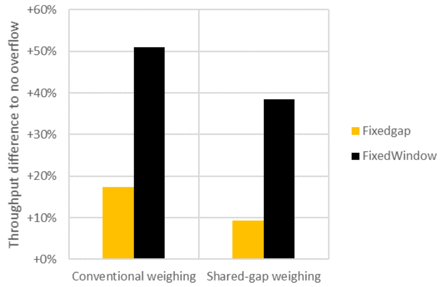


Figure 6.29: Comparison of throughput with overflow to the case without overflow for the reference scenario

6.5.3 Input-pressure

Lastly, the experiments for the input-pressure concerned the impact of a parcel arrival smaller as the maximum capabilities of the system. Therefore, when a parcel is merged onto the main-line it may occur that the following parcel is not yet present at the infeed. This effect is simulated within the experiments with the input-pressure. This concerns a rate which is the fraction of the throughput as achieved for the maximum required window- or gap-setting.

The impact of the input-pressure shows a relation to the previous experiment with overflow. Herein the throughput reduced for smaller window- or gap-setting when it reached the peak-throughput. However, it is retrieved from this experiment that a decrease in the input-pressure may still result in a higher throughput compared to the maximum input arrival. This is since a parcel with a too small gap-setting may still be sorted when the following parcel did not arrive yet.

7. Conclusion and recommendations

Within this final chapter the conclusions to the sub-research questions are discussed. First the conclusion will be presented, followed by the recommendations.

7.1 Conclusion

This research involved the analysis of the performance of parcel sorting systems. The motivation of this research is that the impact of configuration on the performance is currently unknown. This is represented by the following research question:

> ***What is the sensitivity on the performance of parcel sorting systems including a checkweigher, subjected to stochastic input characteristics?***

To answer this research question a simulation model has been developed which is applied to experiments. It is retrieved from these experiments that the performance, represented by the throughput, is, next to the system speed, mainly dependent on the checkweigher configuration, with the used windowing-method and window-setting. With this stated, the sensitivity is summarized as following:

- A larger sort-angle may result in a larger required gap to sort the parcels, which reduces the throughput. This concerns, for a speed of 2 m/s with a 30-degree sorter compared to a 20-degree sorter, a throughput-reduction of 1% in a system with a checkweigher. In addition, this impact is 6% in a system without a checkweigher.
- The configuration of the checkweigher, concerning the scale-lengths, generally impacts the throughput by 5% compared to the optimal checkweigher configuration. In addition, it can be concluded that the checkweigher generally limits the throughput instead of the shoe-sorter.
- The largest impact is caused by the, commonly used, fixed-windowing and fixed-gapping methods, which define the gap based on a merge setting for all the parcels. This reduces the throughput, compared to dynamic-gapping for in the reference scenario, with at least 17% for fixed-windowing while this is around 40% with fixed-windowing.
- The above-mentioned impact may be reduced, within a line-sorter, when it is permitted to have a fraction of the parcels to become overflow. However, the throughput may be still smaller compared to dynamic-gapping which concerns a difference of at least 12% with fixed-windowing while this concerns at least 9% with fixed-gapping.

These conclusions are based on the answers to sub-questions. Therefore, the conclusion is enriched by answering the sub-questions, as done below:

1. *What factors within a parcel sorting system configuration limit the performance?*

Firstly, the speed of the system is described by the shoe-sorter which is the maximum for a sort-angle of 20-degrees. This sort-angle sets limits towards the required gap behind the parcel, related to the parcel width. In addition, the checkweigher requires a gap which is based on the used scale-lengths, the parcel length, the weigh-length and the weigh-method.

In addition, different methods are available to set the gap which is used between the parcels. This may be exactly the minimum requirement, as achieved with dynamic-gapping. However, also a fixed setting may be defined for the whole range of parcel concerning fixed-gapping or with a fixed head-to-head distance which is called fixed-windowing. These, so called, windowing-methods reduce the throughput since the gap is generally larger as the minimum requirement.

2. *What KPIs may be used to predict the performance of a parcel sorting system?*

It is found that the generally defined requirement towards the system concerns the capacity related to an average handled parcel length. Therefore, the performance of a system is represented by the throughput which occurs within the steady-state. This performance may be directly compared when the average parcel length does not differ. Within the applied experiments this scenario is tested and therefore only the throughput is regarded as performance indicator. When the average parcel length would vary, the indicator of utilization should be included.

3. *What is the impact of system configurations on the performance of a parcel sorting system?*

This is answered by discussing briefly discussing the main factors which characterise the configuration which concern the sort-angle, checkweigher configuration and the windowing method.

Sort-angle
Within the high-speed sorting systems, for speeds up to 3.2 m/s, only the sort-angle of 20 degrees can be applied. With a speed of 2 m/s even a sort-angle of 30 degrees could be applied which further decreases the throughput since it generally requires a larger gap. The impact of the sort-angle is related to the parcel width. Therefore, in one experiment the impact is examined for the handling only the maximum parcel width. The results show that, compared to a 20-degree sorter, a reduction occurs for a 30-degree sorter of at maximum 2.5% in a system with a checkweigher, while this is 17% in a system with only a sorter.

Checkweigher configuration
The impact of the checkweigher configuration is examined for a variety of scale-combinations. Moreover the two methods of weighing, conventional weighing and shared-gap weighing are examined using experiments. From the experiments it can be concluded that the optimal scale-combination involves two scales which are almost the same length. In addition, it is retrieved from the experiments that the difference between a one-scaled, or a two-scaled checkweigher may involve a difference of 25% on throughput. Besides this, it appears that when conventional weighing is used, it reduces the throughput by at least 5% compared to shared-gap weighing.

Windowing-method
Generally, the gap-setting at the merge, which is based on the system configuration, influences the throughput of the system. The maximum throughput is achieved with dynamic-gapping which is based on the specific parcel dimensions. It turns out that compared to dynamic-gapping, for conventional weighing, fixed-windowing reduces the throughput between 25% and 50% while this is for fixed-gapping reduced by around 40%.

4. *What is the impact of unsorted parcels on the performance of a parcel sorting system?*

The previous experiments described the maximum capabilities of the system configuration. However, within operation a fraction of the parcels may not be sorted which is called overflow. Within a line-sorter a fraction of overflow is directly related to a reduction in throughput, while this differs for a loop-sorter. Due to recirculation in a loop-sorter the main-line may not be fully utilized, which reduces the throughput. It is concluded that the impact of overflow in a loop sorter may be around 7% larger as the defined overflow-rate.

In addition, overflow may occur due to a too small window- or gap-setting. For the summarized peak-throughputs an overflow 6.5 % with fixed-windowing occurs while this is 3% with fixed-gapping. The described effect differs on a loop-sorter since the overflow-parcels may temporary or totally block the loop. This is because these parcels, which do not match the gap-setting, may continuously recirculate.

5. *What is the impact of stochastic parcel arrival on the performance of a parcel sorting system?*

The described effects involved a system which is applied to the maximum arrival of parcels. Within operation this generally does not occur while the pressure on the infeed highly varies. This may impact the previously described effect with a decreased window- and gap-setting. It is retrieved from the experiments that when the input-pressure decreases the throughput may be higher compared to the maximum input arrival. This is due to the fact that a parcel with a too small gap-setting may still be sorted when the following parcel did not arrive yet.

7.2 Recommendations

During this research assumption were made on the actual system which includes the defined scope. Resulting of this scope some factors are excluded from this research which may still be of interest for further research. In addition, the experiments lead to new insights for the system which may be used as a start for further research. The recommendations are divided into recommendations for academic research and practical recommendations for VanRiet.

7.2.1 Recommendations for academic research

The recommendations for academic research include:

Impact of different characteristics

The impact of variations on the parcel lengths and widths is included within this research. However, the impact of different length- and width-distributions, with for example a different mean, is not examined. These are recommended to include within further academic research.

Impact of the window-setting within multiple checkweigher configurations

Within this research insight is given on the impact of the window-setting for a reference scenario. However, due to the limited available research time, the impact for some experiments within this research is only applied to the reference scenario. Therefore, the configurations which are not examined in this research may be included within further academic research.

Merge-algorithm analysis

The currently used merge-algorithm is left out-of-scope within this research. However, it is known that this currently impacts the parcel-throughput while the exact impact is unknown. The results from this research may be used to analyse the impact of different merge configurations concerning the number- and distance between the infeed. Lastly, this algorithm may be optimized to reduce the lost parcel-throughput within this section.

Impact of batch-arrival

The process within a parcel-hub bears a varying arrival of trucks which is not examined within this research. Generally, the trucks deliver the parcels in batches towards the system. The impact of this batch-arrival, including the number of infeed, may be included within further research.

Infeed- and outfeed-scheduling

An outfeed generally has a capacity which is smaller than the capacity of the main-line. Therefore, it may occur that a parcel cannot be sorted when too many parcels need to be sorted towards a specific outfeed. This reduces the parcel-throughput of the system which may be prevented by assigning a truck to two outfeeds. Within further academic research an improved scheduling method may be examined to reduce this effect.

Peak throughput reduction
It is noted that the peak-throughput only arises at specific times in operation. The parcels are directly fed into the system, the arrival of a large number of trucks directly results in a peak for the required capacity. It may be examined in further academic research what options are available to reduce the pressure on the system, while the parcels still arrive on time at their destination. This may include improvements in the optimization of the supply-chain or for example the impact of a temporary storage within the system.

7.2.2 Practical recommendations for VanRiet

In addition to the recommendations for further academic research, it is recommended to implement the following improvements within the operation at VanRiet:

Implement the checkweigher in the capacity prediction
Resulting from this research is noticed that the checkweigher is often the limiting factor within the system. However, commonly the focus is on the limits of the sorter to determine the system capacity and define the window-setting. A combination of the sorter and checkweigher configuration should be used to predict the system capacity as initiated within this research using a simulation model.

Windowing-method
The current method to merge the parcels with fixed-gapping or fixed-windowing reduces the system capacity. When dynamic-gapping is implemented the capacity increases. In addition, it may be considered to implement the suggested gap-setting below the maximum requirements to increase the parcel-throughput.

Detailed input characteristics
It is noticed within this research that the description of the parcel characteristics by the parcel handler may include only average and maximum values. To be able to predict the capabilities of the system the parcel characteristics should be defined in detail. Therefore, this information may be requested by VanRiet from the parcel handler. Whenever this information is not available, a distribution may be created which involves the described averages as is initiated within this research.

Operational performance
The currently used indicator of the parcel-throughput, may not provide full insight in the operational performance of the system. Therefore, the utilization should be implemented as an additional indicator as this includes the effect of variating average parcel lengths. Since an operational system may bear variation in the arrival of parcels, the update interval, of the performance should be clearly defined. In addition, the pressure on the infeed may be included within the monitoring, to obtain insight if the system is limited by the performance or either a lack of input of parcels.

Validate slippage
Currently it is unknown in what matter slippage of parcels occurs and what factors have an impact on this slippage. Therefore, within the current prediction of the capacity some standards are used which may need to be reviewed. This slippage is expected to be related to the parcel characteristics including the probability it occurs. When a clearer insight is gained on these effects, this may be implemented within the developed model to improve the prediction of the system capacity.

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Appendix

A. Scientific paper

Performance analysis of parcel sorting system configurations

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Abstract— **Within this research the impact of system configurations is examined for a parcel sorting system. Currently, the impact of the configurations on the performance is currently unknown while no performance analysis exists which includes the whole system configuration with the expected parcel characteristics. Therefore, this research firstly involves a system analysis with the functional limitations. Hereupon, a simulation model has been developed obtain insight in the impact of the system configuration on the performance.**

I. Introduction

Within recent years, the parcel transport industry has experienced an increase in the volume of handled parcels due to the rapid growth in e-commerce (Clausen et al. 2015). The commonly known parcel handlers, such as DHL, DPD, UPS and TNT, collect the parcels from the sender and deliver these via one- or several parcel-hubs to the destination. Within these parcel-hubs the transport and sorting is often performed by an automated parcel sorting system (Bonini and Jain 2000).

These systems are characterized by having multiple loading areas which are connected to a main-line conveyor. This is followed by the identification of the parcel which concerns scanning, measuring, weighing and eventually the sorting to the correct truck.

Due to the described increase in parcel volumes the parcel handlers bear a higher pressure on their handling process (Fikse 2011). Conventionally, the method to enhance the capacity of the systems involved the improving of the system speed. Therefore, the interest has moved towards a higher utilization of the system (Intelligrated and Naylor 2013) which is related to the used configuration.

Within an ideal system the parcels would be placed, on the main-line without any gaps between the parcels. However, to perform the described functions a gap is required which is based on the parcel characteristics and the system configuration. Whenever the gap between the parcels does not match the required gap, the parcel may not be sorted correctly, called overflow.

The current method to define a system configuration includes a prediction of the system performance which is generally based on individually the sorter- and checkweigher configuration. In addition, different, so called, windowing-methods are available to specify the gap at what the parcels are merged. However, as retrieved from literature, the impact on the performance of the system configuration, including the different windowing-methods, is currently unknown.

Therefore, this research is initiated, with the objective to retrieve insight in the impact of system configuration on the performance.

II. Method

The method to match a system design to the specification is generally a highly iterative process with different design steps (Veld 2002). Within this research, the definition of a system configuration towards the specifications with the functional limitations is examined which is defined by Veeke (Veeke 2003) as function design.

Within this research, firstly a system analysis is performed for the functional limitations. This is used as input for a simulation model which has been developed within Simio. Hereupon experiments are performed which obtain insight in the impact of the system configuration on the performance.

III. System analysis

Within this system analysis the functional limitations, concerning the minimum required gap, are listed with their dependencies. The parcels which do not match this requirement, as listed within Figure 1, may become overflow. The method how these parcels are handled depends on the layout which is firstly described.

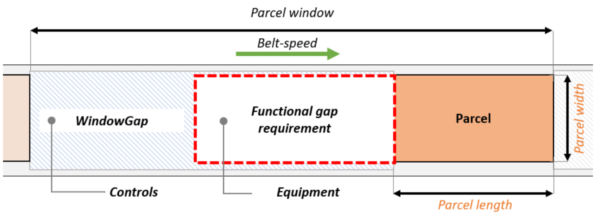

Figure 1: Specification of the gap on the main-line by the functional limitation and the windowing-method

Layout
Within a line-sorter the overflow-parcels are handled manually. Opposing to this, the parcels may recirculate within a loop-sorter which decreases the throughput of the system.

Scanner
The system may include a scanner which scans up-to six-sides of the parcel for the barcode. This requires a gap between the parcels to read the barcode on the front- or the back-side of the parcel.

Checkweigher
The weighing may be performed by one or two conveyors, so called scales, which monitor the parcel weigh. A two-scaled configuration may function as three separate scales since the two scales may be combined to perform weighing. In order to have a correct weighing, a parcel needs to be individually on the scale for the weigh-time. Therefore, the gap which is required for a parcel is dependent on the parcel length. In addition, two methods are generally used to perform weighing. From these conventional weighing is mainly dependent on the gap behind a parcel while shared-gap weighing requires smaller gaps since it is based on the gap-back and gap-front of the parcel.

Shoe-sorter
Eventually, the sorting is commonly performed by a shoe-sorter (Jodin and ten Hompel 2012b) which slightly guides the parcel to correct outfeed by a number of shoes. These shoes follow a guidance in a specified angle. In order to prevent that parcels collide a gap is required behind the parcel based on the sort-angle and the parcel-width.

Windowing-method
Currently, the parcels are commonly merged onto the main-line with a gap based on the maximum required gap for the range of parcel dimensions. Therefore, the parcels are placed behind each other with a fixed head-to-head distance, which is called fixed-windowing, or an equal gap which is called fixed-gapping. In addition, the parcel may be merged with the minimum gap for the specific length and width which is called dynamic-gapping. Furthermore, the settings for fixed-windowing and fixed-gapping may be defined below the maximum requirements, resulting in a fraction of the parcels what becomes overflow.

IV. Model

Within this research the described problem is examined by usage of a developed discrete-event simulation model. This model, has the ability to retrieve the performance of different system configurations subjected to a specified parcel length and width distribution.

Performance indicators
The requirements towards the system generally involve the capacity and the overflow-rate. Therefore, the performance of the performed experiments is represented by the throughput, in handled parcels within steady-state, including the overflow-rate.

Reference scenario
Prior to the experiments, an analysis is performed on installed system configurations. It is retrieved from this analysis, that a 20-degree shoe-sorter is generally installed with a system speed of 2.7 m/s and a checkweigher with two scales of 800 mm and 1300 mm. Therefore, this scenario is used as reference within the performed experiments.

Input characteristics
In addition to the reference scenario the variability on the parcel lengths and widths is included within the experiments. This is represented by two lognormal distributions which are based on monitoring data from an operational system.

Window-requirements
The window which the parcel requires, is related to the parcel characteristics. Therefore, this is listed for the reference scenario within Figure 2. This figure shows the required window for conventional weighing with the dependencies towards the parcel characteristics.

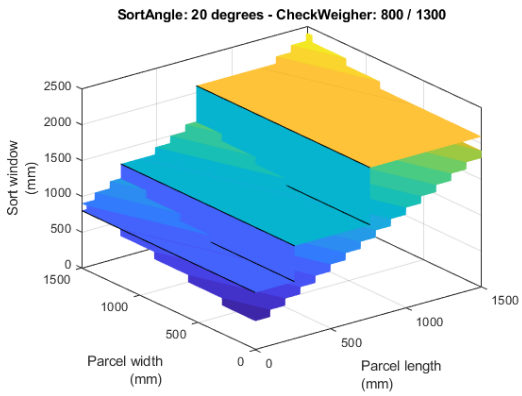

Figure 2: Window requirements with a checkweigher

Assumptions
A model is a representation of the real-word situation. Therefore, the system has been simplified to examine the experiments. This involves the excluding of operational effects as slippage of parcels, full outfeeds and the algorithm to prioritize the parcels from different infeeds. As a result, the model simulates the system with one infeed and one outfeed which represents whole infeed and outfeed section as visualized within Figure 3.

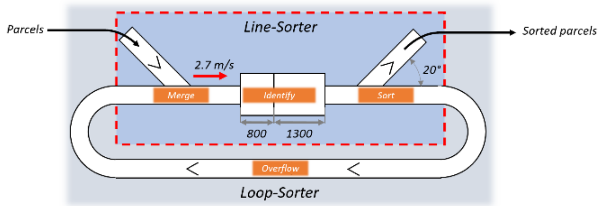

Figure 3: Representation of the reference scenario

Validation

The impact of these assumptions has been validated towards the peak throughput of the operational system. This shows that the throughput on the main-line differed with 16%. However, within operation a higher rate of overflow occurred which reduced the throughput on the outfeed by 35% compared to the model.

In addition, the variability on the parcel length and width may is represented by separate distributions This may exclude relations between the lengths and widths which is examined. It is retrieved from this validation that usage of the distributions had a maximum impact 1.5% compared to the input of the actual parcel characteristics.

V. Results

A variety of experiments are performed on the created model to analyse the impact of the system configuration. Prior to these experiments the behaviour of the model is analysed which resulted in the default setting for the experiments. This concerns ten replications and run-length of three hours to represent the steady-state behaviour. The results are categorized in the sort-angle, checkweigher configuration and the windowing-method.

Sort-angle

The impact of the sort-angle is analysed by comparing the throughput of a 20-degree, with a 30-degree shoe-sorter. A shoe-sorter of 30-degrees specifies the smallest maximum speed of 2 m/s and therefore these are compared with this speed. The results for the comparison of the sort-angle are listed within Table 1, which show that the sort-angle does have only a small impact in the reference system with the checkweigher.

	Sort-angle		
Configuration	*20° [pph]*	*30° [pph]*	*Difference*
Sort	8469	8016	-5,4%
Sort and weigh	7034	6991	-0,6%

Table 1: Throughput difference for different sort-angles

In addition, the maximum impact of the sort-angle is analysed. This concerns the case when all the parcels concern the maximum parcel width. The impact of this revealed a difference of 17% in a system with only a sorter, while this concerns at maximum 2.5%in as system with a checkweigher. This result shows that the checkweigher generally limits the throughput of the system.

Checkweigher configuration

The impact of the checkweigher on the performance of the system is analysed by comparing the throughput for different configurations. In addition, even the impact of the shared-gap weighing compared to conventional weighing is analysed. It is retrieved from the experiments that the throughput of the checkweigher configuration is related to the ratio of smallest scale-length towards the total-scale length as listed within Figure 4.

These results show that the throughput is the highest when the scale lengths have almost a similar length. In addition to this, the results show that most of the configurations only differ up-to 5% compared to the optimal configuration. In addition, experiments for the used weighing methods showed that the using conventional weighing reduces the throughput by at least 5% compared to shared-gap weighing. While this difference is larger for non-optimal configurations.

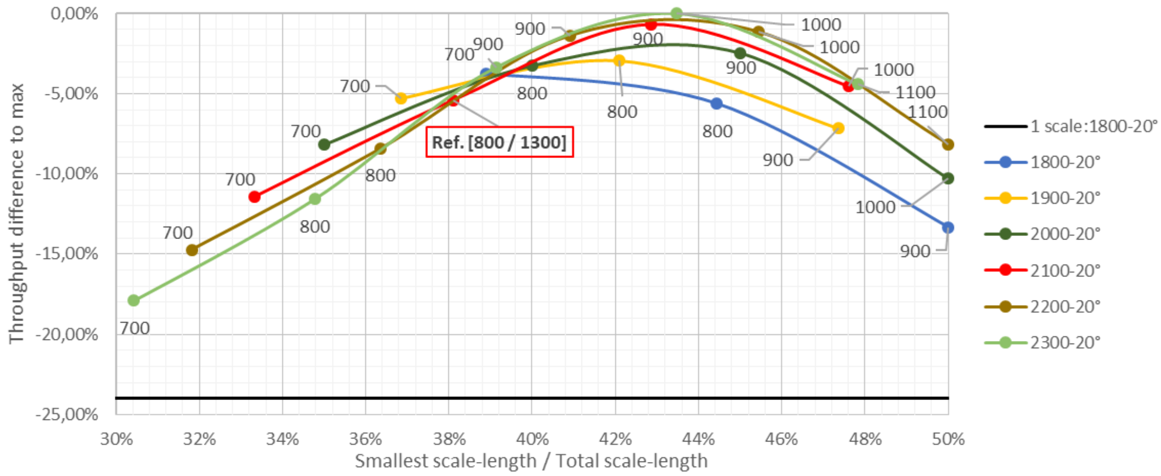

Figure 4: Impact of the checkweigher configuration

Windowing-method

The previous experiments concerned dynamic windowing which describes the maximum capabilities of the system. However, when fixed-windowing or fixed-gapping are used the throughput reduces. The impact of these windowing methods, with- and without overflow, is examined for the reference scenario. The results of this analysis are listed within Figure 5 and Figure 6.

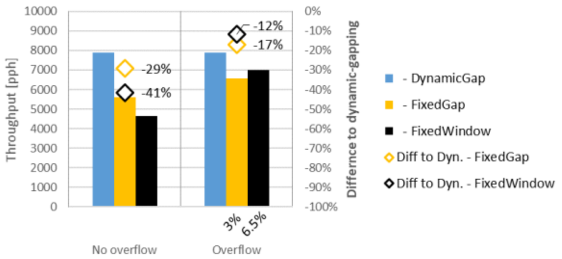

Figure 5: Impact of the windowing-method with conventional weighing

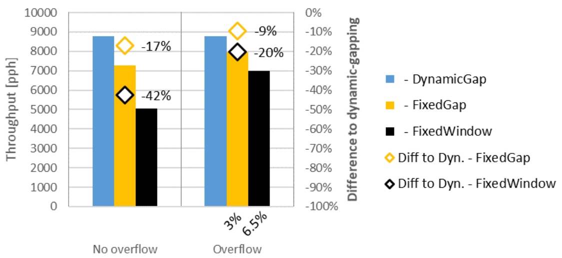

Figure 6: Impact of the windowing method with shared-gap weighing

These results, show that the windowing-methods may highly impact the throughput. This concerns a reduction compared to dynamic-gapping of 40% with fixed-windowing, while this effect is at least 17% for fixed-gapping. However, these effects may be smaller when overflow is permitted which concerns for the maximum throughput an overflow-rate of 6.5% for fixed-windowing and 3% for fixed-gapping. The difference compared to dynamic gapping may be reduced to 9% while this is at least 12% with fixed-windowing. It has to be noted that these described effects may only occur within a line-sorter system. Opposing to this, within a loop-sorter, the parcels with a too small gap may keep recirculating which eventually may cause blockage of the loop.

Besides the comparison towards dynamic gapping, the impact of the window setting for fixed-windowing and fixed-gapping is listed within Figure 7. This shows that when overflow is permitted the throughput may increase by at least 9% for fixed-gapping while this is even over 38% for fixed-windowing.

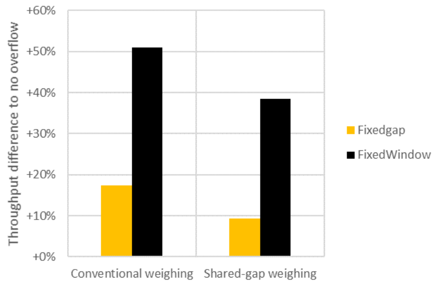

Figure 7: Comparison of the impact of permitting overflow

VI. Discussion

Within this paper the impact of parcel sorting system configurations is investigated by performing experiments on a developed discrete-event simulation model. The performance which is analysed within this research matches the specification which is generally described towards a system. Therefore, the performance of the configurations is represented by the throughput within the steady-state with the related overflow-rate.

Results of the performed experiments, revealed insight in the impact of system configurations on the performance. This concerns that the appliance of the checkweigher mainly limits the throughput instead of the shoe-sorter. In addition, this research quantified the impact of the configuration which showed that the currently used windowing-method with fixed-gapping or fixed-windowing highly impact the throughput.

VII. References

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B. Reference definition

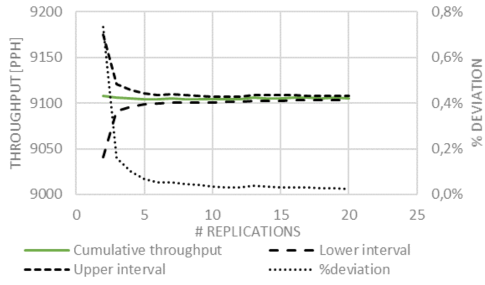
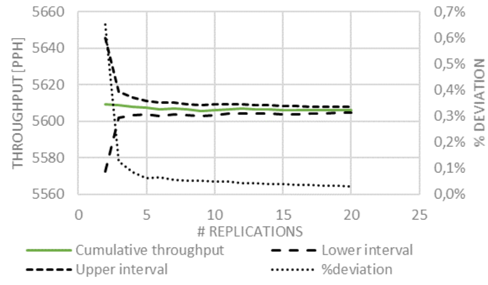
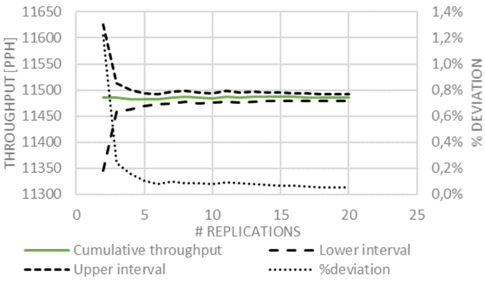
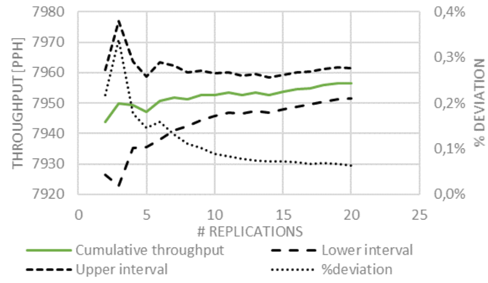
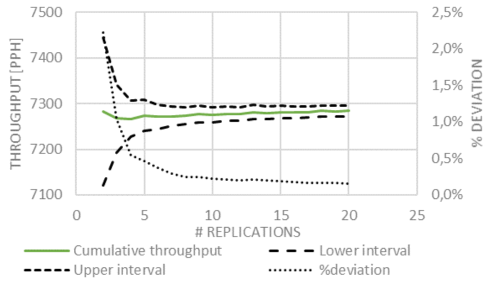
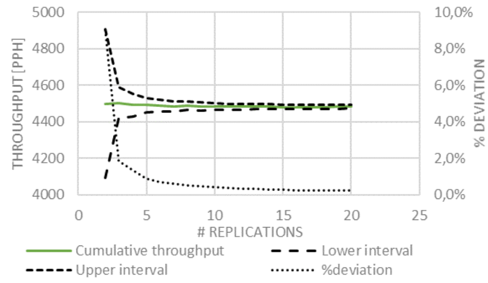
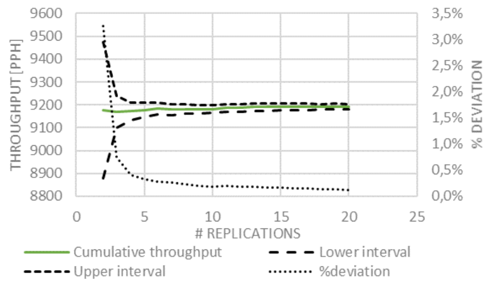
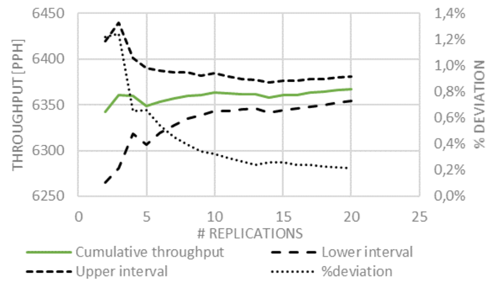
System characteristics

Location	Sort-angle	System-speed	Overflow	Weigh-Lengths	Scanning
#1	?	2.7	Loop	?	?
#2	25	2.6	Line	700/1100	?
#3	25	2.1	Loop	900/1300	5-sided
#4	25	2.7	Line	1600	6-sided
#5	20	2.7	Loop	900/1200	5-sided
#6	20	2.8	Loop	800/1300	5-sided
#7	?	2.7	Loop	800/1300	?
#8	?	2.7	Loop	?	5-sided
#9	20	2.7	Loop	800/1300	5-sided
#10	25	2	Line	1600	3-sided
#11	20	2.7	Loop	900/1300	5-sided
#12	20	2.7	Loop	?	?

Parcel Characteristics

Location	L_Min	L_Avg	L_Max	W_Min	W_Avg	W_Max
#1	150	600	1200	100		800
#2	200	500	1200	100		800
#3	150	651	1175	100		600/1000
#4	150	600	1200	100		750
#5	150	600	1200	100		750
#6	150	600	1200	100		750
#7	150	600	1200	100		800
#8	150	600	1200	100		800
#9	150	600	1200	100		750
#10	150	450	1200	100		700
#11	100	450	1200	100	350	800
#12	150	600	1200	100		800

C. Number of replications

		Sorter	Sorter+Checkweigher
No overflow	Figed gap		
	Dynamic gap		
20% overflow	Figed gap		
	Dynamic gap		

D. VDI design methodology

The design procedure, as described by the VDI (Jänsch and Birkhofer 2006), starts with the *Specification* where the customer requirements are defined, including the (sub-) functions which needs to be performed by the system. Throughout the design process is referred to these specifications to note if the design still matches the specification. The second phase of system design is the *Conceptual Design* in what solutions for individual problems are created, whereafter these are combined to functional structures. The principle solution is commonly a draft of the layout with the main transport lines and the rough positions of infeeds and outfeeds. The third phase is the *Embodiment Design* in what the modules are further defined. Examples of the specifications are the conveyor length and width. The last phase is the *Detailed Design* which includes the creation of the required documentation for the production, assembly, maintenance and the user.

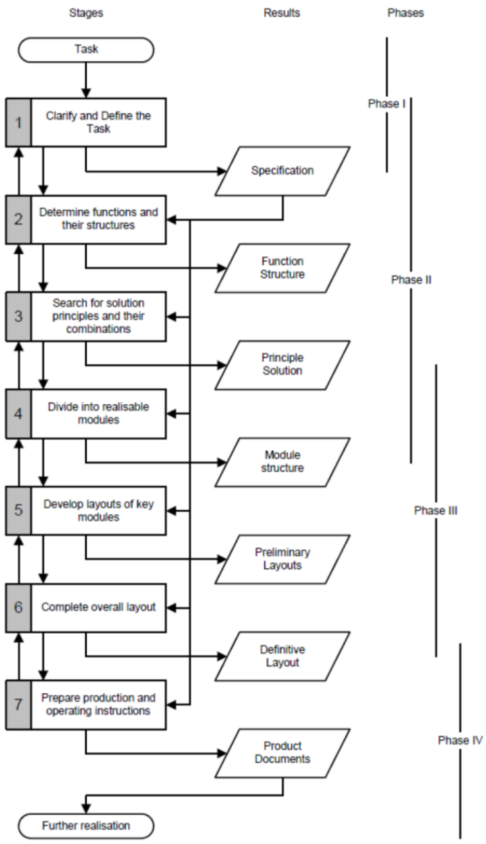


Figure D.1: VDI - design approach