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Feasibility of Large-scale Multi-AGV based Parcel Sortation Systems

TU Delft

Feasibility of Large-scale Multi-AGV based Parcel Sortation Systems

By

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Summary

The parcel sortation industry is growing and increased pressure is observed to deliver quicker, more volume, with higher accuracy and flexibility. More smaller distribution points closer to the potential clients are build called local depots. Also new challenges due to package variety, increasing volume, higher customer expectations (e.g. parcel tracking) and automation integration lead to investigations in implementing new and more flexible systems. More flexibility is required when looking at long-term planning, as currently existing system are difficult to upgrade or expand. Therefore an alternative is investigated: using Automated Guided Vehicles (AGVs). These are small battery operated vehicles which are very flexible in terms of building lay-out and future expansions (by adding more AGVs). Therefore this research has the main research question: How to feasibly design scalable multi-AGV parcel sortation systems taking influential design parameters into account? This is done by using the following key performance indicators (KPIs): amount of charging stations, deadlocking %, empty load (no parcel on top of AGV), rated load time % (parcel on top of AGV), idle % (no job for the AGV available), peak capacity %, space utilization and waiting time % (queueing and re-routing).

To find the answer to this question a literature study has been done on conventional parcel sortation systems. As well as these aspects of parcels: dimensions and weight. The use of these AGVs are likely more feasible for smaller sortation centres for example local depots and smaller regional depots. Furthermore AGVs in general are investigated as they need to be charged to operate. The AGVs will be modelled by an A* algorithm and use grid-routing (either X or Y -movement at the same time). These kind of AGVs are controlled by a centralized Robot Control System (RCS). Meaning the AGVs send updates on their location and retrieve new locations by one controller.

With the use of a literature study several brands of AGVs are analysed and 3 groups are conducted, AGVs with a rated load of: 6 kg, 32 kg and 70 kg. Their values for maximum speed, acceleration, battery capacity and battery type (lithium-ion) are averaged and used for the model. The task allocation of a job-less AGV is done by a market- auction-based algorithm. Parameters for the model are set as well as anti-deadlocking, dispatching and routing. Several lay-outs are investigated which can be created and generated by the model itself. As this is not an optimization model generalised differences are accumulated and investigated. The workflow of the RCS is designed to select if an AGV needs to start a job of collecting, scanning and delivering a parcel or waiting near a collection point or go and charge. A test plan is used to verify the model. Also an experimental plan is used to find the influence of the design parameters. This plan consists of determining a feasible lay-out. After which a sufficient amount of drop-off points is determined used to look into the effects of adding pick-up points in the system. At last the AGV charging process is analysed to be able to functionally work during a 16 hours operation.

For the model several input characteristics are set as constants and uses the following design parameters: # AGVs, charging points, pick-up points (parcel collection) and drop-off points (parcel destinations). The output has several graphs and tables connected with the KPIs. For example the throughput of the system is calculated and the time spend by the AGVs in queues, with a parcel (rated load) or without (empty load). The first test set consists of a map of 1000 m^2 to operate at a throughput of at least 1600 $\frac{parcels}{hour}$. Here the placement of the pick-up points on all sides of the map is more efficient than on either one or two sides. Though the placement of two sides is further used as it is a more probable solution due to the use of large truck-bays and smaller vans in terms of a parcel sortation center.

A linearity is found when adding more AGVs to the system. This is in between 5-50 AGVs for the 6 and 8 pick-up points with a ratio of 44.62 $\frac{parcels}{hour}$ per additional AGV. Linearity is decreased due to more queueing and re-routing by congestions to 39.86 $\frac{parcels}{hour}$ per additional AGV for 10 and 12 pick-up points. The ratio of pick-up points and drop-off points is investigated, ratio with at least 6 pick-up points and 4 drop-off points, as to few lead to congestions/delays as well as too many drop-off lead to close proximity of the drop-off points. The charging process reduces the throughput with at least 7.54 % on a 16 hour simulation run. This is with a

ratio of 5.71 AGVs per charging point. Using a higher ratio leads to AGVs shutting down due to low battery charge states.

Another test case is analysed with a 3000 m^2 area and the demand of achieving a throughput of at least 6000 $\frac{parcels}{hour}$. This is achieved by using 170 AGVs on a width of 75 m and a length of 40 m area. A system consisting from 150 AGVs needs at least 12 pick-up points and from 170 till 200 AGVs 18 or 20 pick-up points are advisable depending on the requirements of the design. The system is (reliably) capable of a throughput of 6000 parcel per hour from 16 pick-up points. Even a small analysis is done in the use of 6 kg and 32 kg AGVs on the same working area. From which, a throughput of 1000 $\frac{parcels}{hour}$ is gained by using 15 6 kg AGVs and 25 32 kg AGVs. the throughput is lower compared to using 40 32 kg AGVs: 1400 $\frac{parcels}{hour}$. This loss in efficiency could be considered compensated by the reduction in terms of AGV purchase costs.

Recommendations for further research are suggested. With more AGVs on the map the queueing process becomes more relevant at the pick-up points and could be further evaluated. Therefore the relevancy at looking into the pick-up points process could lead to more efficiency of the system. For example queueing underneath the conveyor of the pick-up points to eliminate routing obstacles. As well as been able to place multiple parcels at the same time per pick-up point. This research has no optimization process, more potential is possible if an optimization is done with a more elaborate/complete (design) plan. This optimization could lead to more efficiency and more insights of an AGV parcel sortation system. Finally the possibilities of multiple types of AGVs on one map can be investigated, with additional task allocation schemes or a more elaborate research in the pick-up points process.

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1
Introduction

The volume of international delivered postal parcels has doubled in the period 2010-2016 [1], as displayed in Figure 1.1. The growth in the international parcel volume is driven by cross-border electronic commerce (e-commerce) growth, which is expected to meet with a higher growth rate than the overall e-commerce market. In 2016, the number of international postal parcels dispatched across the world increased by 4.5% with the volume of parcels delivered reaching a total of 112.38 million, whereas the domestic volume increased by 12.5% to a total of 8837 million units delivered. In order to cope with this growth, estimates are made by the industry, in the parcel and express sector, of a total investment of 6.3 billion USD between January 2012 and November 2017. The geographic investments is displayed in Figure 1.2.

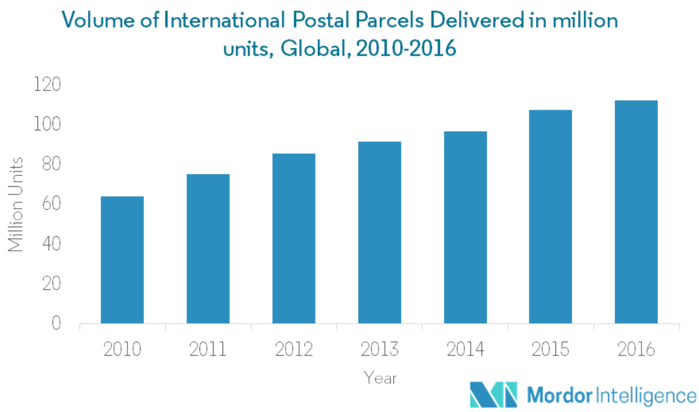


Figure 1.1: Volume of international postal parcels delivered, Global [1]

These investments have made it possible for material handling systems designs to be developed and improved in terms of efficiency and scale. Answers are sought for existing and future problems in terms of space utilization and upgrading existing factories.

1.1. Growth in post and parcel industry

The digital age has an increasing demand on parcel delivery and respected areas. This leads to many challenges in this particular area of expertise. The top 5 challenges facing post and parcel operations, discussed at the National Postal Forum in Baltimore (May 2017), are the following [31]: *Package variety*: The variety of packaging types forces postal operations to find sortation solutions with the capability to deliver everything on time. *Volume*: The increase in demand also leads to growing order volumes. *Automation integration*: Automation is an option to improve overall postal operator efficiency. *Customer expectation*: The automation is used to update customers on the location of their parcel in the logistic process. *Space utilization*: The population dynamics shift and more people move to cities, carriers must serve greater volumes in areas where business parks are

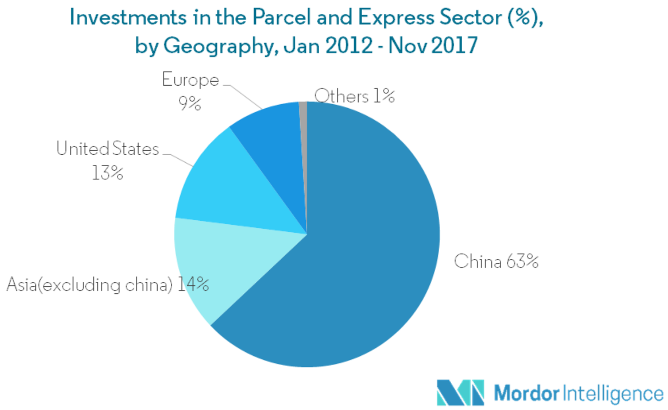


Figure 1.2: Investments in the parcel and express sector by geography with an estimated total of 6.5 billion USD [1]

limited and more expensive [32]. These challenges are further elaborated in SubSection 2.1.

1.2. Problem definition

The current solutions for parcel sortation are linear sortation systems and loop sortation systems. Linear sortation systems or Line Sorters sort in a straight line. The sortation takes products from one end and moves them along their length, diverting them to one or both sides depending on the type of unit along the way. Several solutions are: Sliding shoe sorter, Activated Roller Belt (ARB) sorter, linear belt sorter and narrow belt sorter [33]. Loop sortation systems, or circle sorters, consists typically of a series of cells linked together on a track. Several solutions are: Cross-belt sorter, bomb bay sorter and tilt tray sorter [33].

The current sortation processes need solutions for package variety. The odd or oversized items are currently handled manually or require special modifications at the sortation system. Problems are found for the sorting of a large set of different items, which would require a whole arsenal of cross-belt sorters. The peak capacity of parcel volumes is defined by seasonal shifts in demand, displayed in Figure 1.3. The sortation processes are relatively hard to up-scale. Meaning that they are designed for peak capacity and therefore have always extra chutes installed taking up more space. This and the need for redundancy in the system lead to low graded space utilization [31].

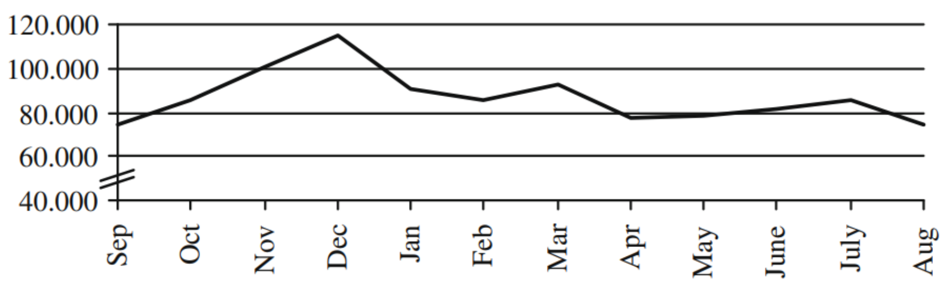


Figure 1.3: Seasonal fluctuation of average total quantity per working day in the DPWN parcel center under scrutiny [2]

The following Key Performance Indicators (KPIs) are used to evaluate the model/simulation of the Automated Guided Vehicles (AGVs).

- Amount of charging stations
- Deadlocking %
- Empty load, rated load time %
- Idle %
- Peak capacity %
- Space utilization
- Waiting time %

The KPIs are found with the use of literature, further described in section 2.5, wishes from the company VanRiet and own insights (found in response to the other KPIs). AGV charging is investigated. Preventing queues and congestion by monitoring deadlocking %. The distance and time an AGV has a parcel on top (rated load) versus the distance without a parcel (empty load). When an AGV has no job and doesn't need to charge it is idle. The capacity of the system at its peak is investigated. The space (area) versus throughput is calculated. The waiting time due to queueing and re-routing is measured.

1.3. Research question

The main research question is: How to feasibly design scalable multi-AGV parcel sortation systems taking influential design parameters into account? Sub-questions are drafted to split and structure the main research question.

- What is the configuration of conventional parcel sortation systems?
- Which characteristics of AGV systems are relevant for modelling a parcel sortation system?
- Which requirements and design parameters need to be considered for modelling a parcel sortation system?
- Which model characteristics are required to create an experiment to evaluate which design parameters are the most influential in terms of the Key Performance Indicators (KPIs)?
- Which experimental setup can be used to simulate the influence of the design parameters in a scalable multi-AGV sortation system?
- What are impacts of the influential parameters to the design of scalable sortation systems?

For these questions the meaning of the following criteria are further explained. *Feasible design*: A feasible design is defined as satisfying the required parcel handling capacities. Meaning when selecting an AGV system over a "regular" parcel sortation system it is comprehensible that this system matches or exceeds the expectations of such a system. E.g. Take a small parcel sortation system which requires a throughput of 1600 $\frac{parcels}{hour}$. If such a system requires 1000 AGVs it is an expansive operation in terms of AGVs and space utilization. This system would therefore be considered as not a feasible design.

The term *scalable systems* means that an increase of size as well as AGVs is possible. A generic method/model is provided for the designs of sortation systems with different configurations, sizes and capacities. A *multi-AGV* system is a system which operates with multiple AGVs at the same time. This is considered in the order size of one hundred or more AGVs operating in one system. As a design/model can have many design parameters a selection of it is implemented and investigated, due to limited resources in terms of time and complexity of the model. Therefore several *influential design parameters* are investigated. The proposed design parameters are considered influential (noticeably influencing the results) in the process of a parcel sortation system.

1.4. Research scope

This research takes the diversities of parcel types in terms of dimension as well as weight into consideration. This enunciates in a difference in load capacity and size of the AGVs (6 kg load capacity and 32 kg load capacity). As well as combining the smaller type AGV (6 kg) with the 32 kg AGVs on one working area. The parameters of the AGVs are found in these 2 categories and averaged over the different brands of AGVs. These AGVs work on lithium-ion batteries and a charging schematic is designed to look at the influence of AGV charging.

An AGV parcel sortation system is quite a flexible and scalable system compared to current parcel sortation solutions. This means when an system is required to grow it can be done by adding (buying) more AGVs or adding square meters to the working area. The AGVs are used on two specific site lay-outs. These are 1000 m^2 and 3000 m^2. The amount of parcel collection areas (pick-up points) and parcel destination (drop-off points) are changed. The placement of these pick-up points and drop-off points is investigated as well. The changes are: having the pick-up points at either the left side and drop-off points on the other 3 edges of the lay-out. The pick-up points of the left and right side of the lay-out with the drop-off points on the other two. And having the pick-up points of all four sides as well as the drop-off points on all four sides. After which an investigation is done into a sufficient amount of drop-off points. Using this the influence of adding pick-up points is investigated. At last the influence of charging the lithium-ion batteries and the influence on the parcel sortation process is investigated.

1.5. Structure of the report

The thesis structure is as follows, in Chapter 2 parcel sortation systems in general, with the use of literature, are presented. The challenges of parcel delivery are used to define improvement areas. Then the parcel delivery chain is recited. Examples of existing solutions in parcel sortation systems are described and a general parcel distribution center layout is given.

This is followed by Chapter 3, in which background information is given about AGVs with the use of literature. The scheduling and routing are important factors. The location identification is assumed to be known and the safety will be guaranteed by creating AGV-only zones. The management of the AGV batteries is necessary to evaluate (partially) downtime due to charging AGVs. The different types of routing in combination with AGVs is found from literature.

Chapter 4 contains the requirements for the simulation model set. These are listed as design parameters that have the potential of being influential. Then several parameters are assumed to be constants. Several existing AGVs are selected and imported as constants.

After defining these parameters, model characteristics are set in Chapter 5. Firstly the characteristics for scheduling are defined. These include scheduling and preventing deadlock. As well as collision prevention. This is for head-on, side and head-to-tail collisions. Followed by dispatching and routing characteristics. Lastly an experimental plan is made to verify the simulations.

In Chapter 6 is the system setup explained. Following the first case setup of 1000 m^2 is explained which is then scaled up to 3000 m^2 in case 2. The differences in the location of pick-up points and drop-off points setup.

With the model characteristics and experimental setup in place, experiments will be done in Chapter 7. The simulations are ran and the results are displayed in graphs and tables.

This leads to the conclusions and recommendations in Chapter 8. Followed by the References and appendices. A scientific research paper is added in Appendix A.

2
Literature study of parcel sortation systems

In this Chapter a general idea about parcel sortation systems is sketched. Firstly the top 5 challenges facing post and parcel operations is discussed, these are defining for the current problems. A Parcel delivery chain is sketched, these can consist out of different types of logistic facilities. The flow process of a transport hub is the reason for a bi-directional sortation process. Next an overview is given of existing parcel sortation systems. At last the layout of an existing parcel sortation system solution is delineated.

2.1. Challenges of parcel delivery

The digital age has an increasing demand on parcel delivery and respected areas. This leads to many challenges in the area of expertise. The top 5 challenges facing post and parcel operations, discussed at the National Postal Forum in Baltimore (May 2017), are the following [31]:

1. Package variety
2. Volume
3. Automation integration
4. Customer expectation
5. Space utilization

2.1.1. Package variety

The variety of packaging types forces postal operations to find sortation solutions with the capability to deliver everything on time. For example, sliding shoe, tilt-tray and cross-belt sorters provide fast, gentle handling of letters, soft packs, polybags, corrugated cases, cartons, totes and other odd or oversized items.

2.1.2. Volume

The increase in demand also leads to growing order volumes. Sortation solutions must offer the necessary throughput speed and scalability to deliver dependable, accurate throughput during seasonal spikes or long-term growth in volume. This can, for example, be utilised by tilt-tray and cross-belt sorters are capable of delivering the necessary capacity and speed when handling the wide-ranging product mix of post and parcel sorting environments.

2.1.3. Automation integration

Automation is an option to improve overall postal operator efficiency. This is done by streamlining processes and reducing manual labour and should decrease human error. More postal and parcel logistics processes continue to be automated, with significant investigations in drone and AGV use over the last years as companies explore adopting them as an everyday delivery solutions [34].

2.1.4. Customer expectation

The automation is used to update customers on the location of their parcel in the logistic process. This added service is more and more expected and leads to more aggressive delivery time-lines [35]. Postal operators and retailers must collaborate to enable different delivery features, such as click-and-collect, parcel lockers and delivery time visibility into logistics processes. In the race for speed and transparency, postal operators must adapt their logistics and IT processes to keep up with customer expectation.

2.1.5. Space utilization

The population dynamics shift and more people move to cities, carriers must serve greater volumes in areas with limited, more expensive real estate [32]. Instead of building out, these conditions encourage postal operations to build up and increase storage density by adopting vertical storage solutions. This can also be done with the use of AGVs, increasing floor efficiency. Implementing these sortation solutions saves valuable floor space and can save money by helping avoid the cost of expansion or new construction.

The use of AGVs in (parts of) the sortation process can lead to solutions for package variety. The odd or oversized items can be handled by AGVs. As well as doing the sorting of a large set of different items, which would have taken a large quantity of cross-belt sorters to sort. The use of AGVs in a process is relatively easily scalable. Using automated integration such as AGVs can reduce manual labour and optimise space utilization.

2.2. Parcel delivery chain

The parcel delivery chain is continuously developing. This is due to increase of demands from the growing amount of digital consumers. These consumers are creating a market which, as displayed in Figure 2.1, crosses barriers in choice, transparency and service expectations [3]. The consumers are empowered with greater choice, faster reviews and low switching costs. The retailers and deliverers are presenting more competition, easier aggregation of services and better visibility in the supply chain. The consumers are seeking lower prices, greater convenience and seamless experiences in buying, paying, receiving and returning of parcels.

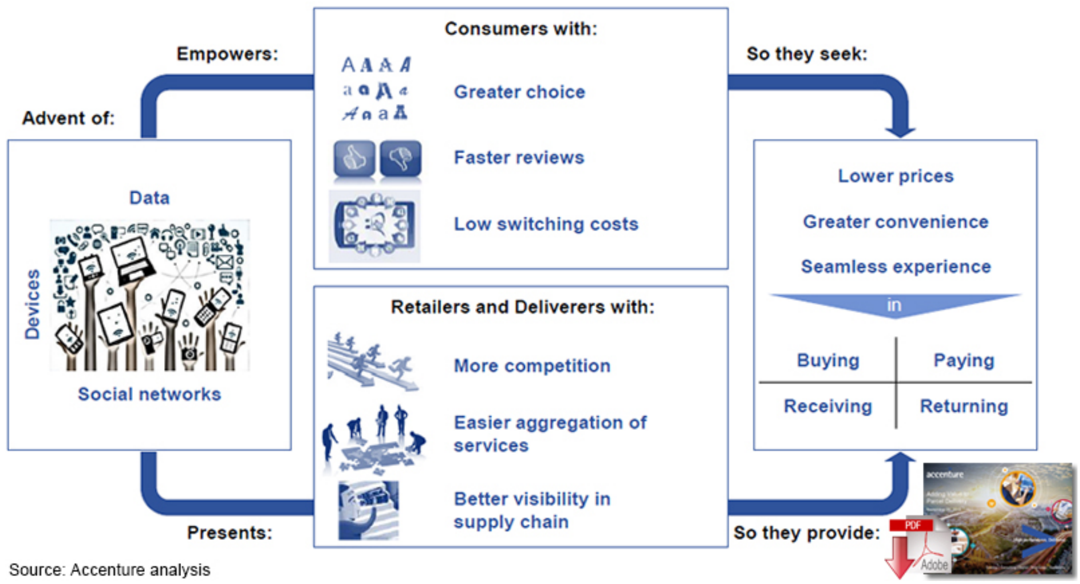


Figure 2.1: Scheme of the rise of the digital consumer [3]

2.2.1. Product specifications: different sizes of parcels

In the parcel industry are many types of package options for the smaller and less heavy object such as: Letters, soft packs, poly bags and totes [36] . Different types of solutions are used to handle the smaller packages. For bigger and or heavier objects are parcel (box) solutions available such as: Corrugated cases, cartons and other odd or oversized item boxes. For handling these parcels challenges lay in the weight and size of the casing.

Company	DHL	DPD	GLS	PostNL
Max weight [kg]	31.5	31.5	32	31.5
Max length [m]	1.2	1.75		1.75
Max width [m]	0.6			0.58
Max height [m]	0.5			0.78
Max girth (L+2W+2H) [m]	3.4	1.45		4.47

Table 2.1: Parcel specifications for postage inside EU [23] [24] [25] [26]

Company	DHL	FedEx Express	GLS	UPS
Max weight [kg]	70	68	50	70
Max length [m]	1.2	2.74	2	2.74
Max width [m]	0.8		0.8	
Max height [m]	0.50.8		0.6	
Max girth (L+2W+2H) [m]	4.4	1.45	3	1.45

Table 2.2: Parcel specifications for postage worldwide send from EU [27] [28] [29] [30]

In Table 2.1 is a list made of the dimension and weight restrictions currently handled by large courier companies. This Table is specific for the European Union (EU) as can be seen it is limiting parcels to a maximum of 32 kg. It is possible to overstep these limitations with addition of extra charge per parcel, Appendix B is an example of the extra charges by DHL [37]. As can be seen from the Figure an extra handling in the factory is necessary for smaller or extra heavy parcels. As well as overstepping the weight or size limitations of the parcel.

The maximum weight of parcels for worldwide postage is displayed in Table 2.2. A maximum of 70 kilograms per parcel is given by DHL and UPS [27] [28]. If the parcel exceeds the 70 kg limit it can be palletized and will be handled differently.

2.2.2. Hub-and-spoke model

In Figure 2.2 is a hub-and-spoke model of the parcel delivery chain from UPS displayed. UPS uses a single network, meaning it does not sort in advance if the parcel is sent to air or ground freight [4]. The chain starts with the delivery of a parcel from its origin, the sender, to a local depot (local UPS center). In the next step are the ground freight parcels sent to the closest regional depot, shipped to the destination hub, and then out to a local center. An air freight parcel is sent to a “gateway” facility at the airport (air hub), shipped to a national hub, then sent from there to another airport and out to the local center. At that point, regardless of whether it was ground or air, the parcel is loaded onto a truck and delivered to the final destination. In this last step are new types of innovations explored.

For example the use of driving AGVs for transportation to end clients by Starship [38]. As well as the use of drones by Amazon Prime air [39]. These (aerial) vehicles transport the parcels from the distribution center to the homes of the recipients. To display the complexity of a hub and spoke system an example of DHL of the USA is displayed in Figure 2.3

2.2.3. Types of parcel sortation centres

In the previous Section are several sizes of parcel sortation systems described. These are the local depot, regional depot and air hub. A local depot handles the sortation of parcels to distribute to other hubs or locally. The Flow process of such a local depot is further explained in subsection 2.2.4. In Figure 2.4 is a regional depot of DPD with a Crosssorter 1500 displayed, the size is determined with the use of the measurement tool of Google Maps. This system can sort upto 9000 parcels per hour [40]. The biggest hubs are the air hub. Here are parcels prepared to be transported by air freight. These systems can have parcel-handlings larger then 15000 parcels/hour. For example the Louisville, Kentucky UPS air hub with a size of 5200000 square feet (483096 m^2) and an air sort capacity of 416000 packages/documents per hour [41].

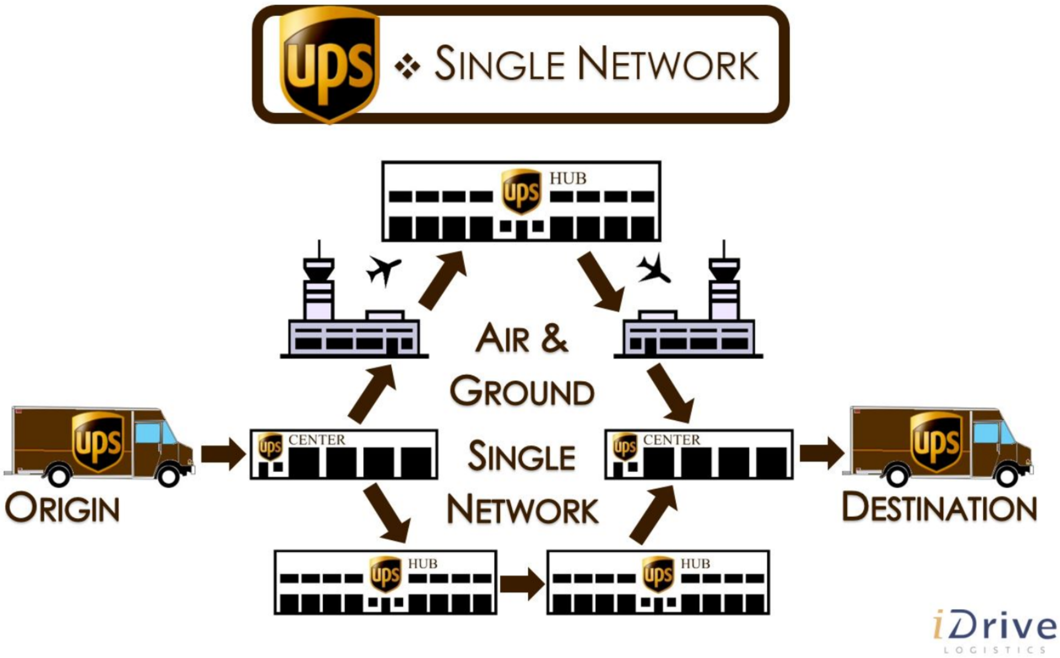


Figure 2.2: Parcel delivery chain hub-and-spoke model for UPS's single network [4]

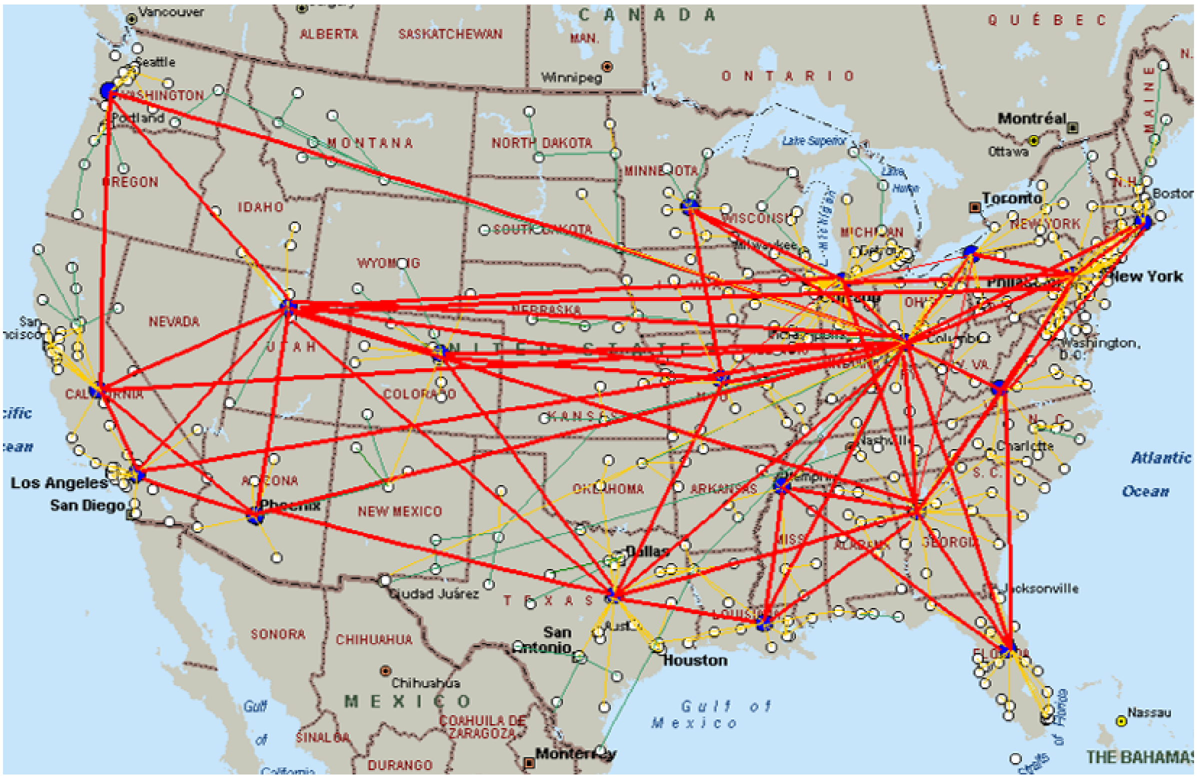


Figure 2.3: USA DHL hub-and-spoke system
Legend: Green=Aircraft Connection; Orange=Trucks to and from Stations; Red=Interhub truck moves [5]

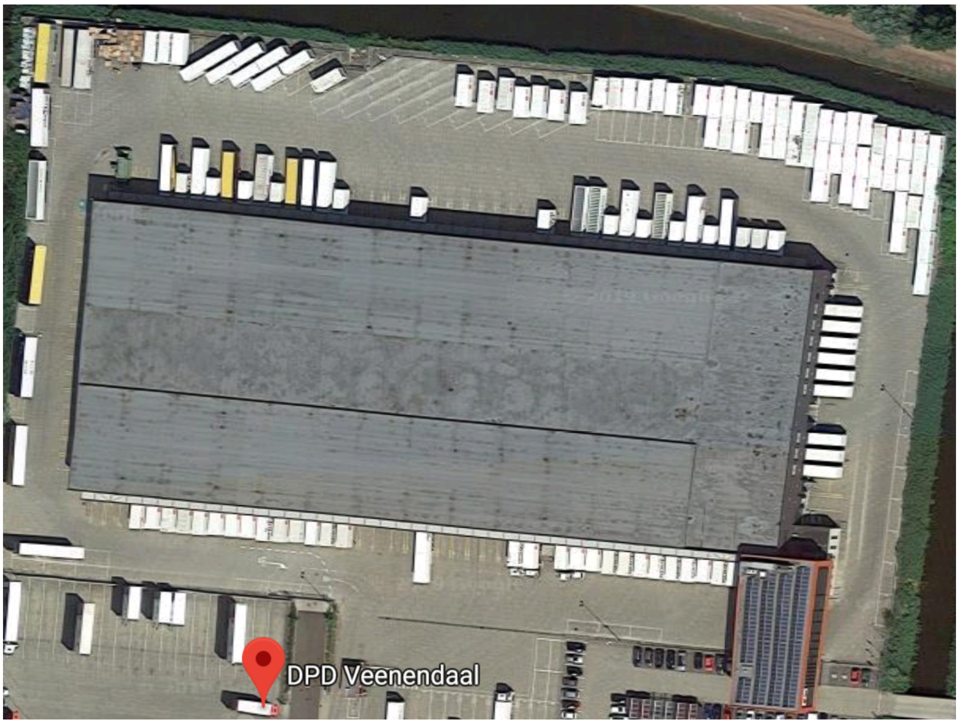


Figure 2.4: DPD Veenendaal Crossorter 1500 70x170 [m] [6]

2.2.4. Flow process of a local depot

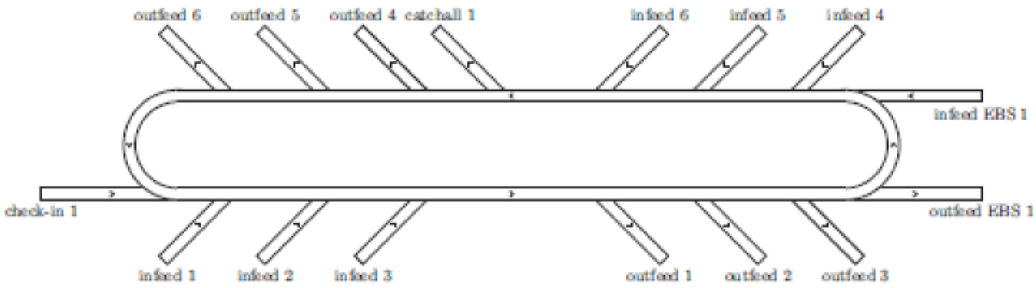
The flow process of a local depot changes during the day [42]. In the morning large inbound trucks supply incoming parcels and are emptied into the sortation system. These are sorted and transported to smaller vehicles and then the parcels are distributed locally. In the evening is the process reversed. The smaller vehicles have outbound parcels and are sorted and transported to the larger trucks which leave for freight transport. In general less trucks, which have a larger capacity, are needed then the amount of smaller vehicles. Therefore the trucks, which need special loading docks, still have the same location in the layout of the facility. This concludes that it is much easier when the sortation system is able to handle the reverse sorting process done in the evening, also called bi-directional.

2.3. Examples of existing parcel sortation systems

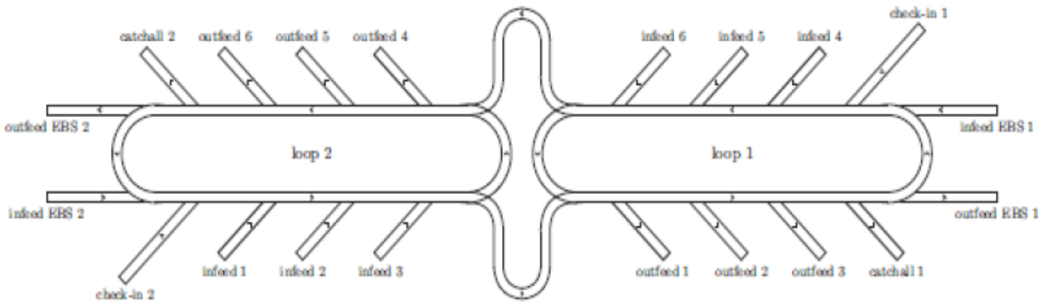
A traditional parcel sortation system has conveyor systems to transport loads of any size, shape and weight from a buffer to the right chutes. These conveyor systems have generally two types of configurations: loop sortation configuration or line configuration. The loop sortation configuration moves in a circle until the parcel is delivered in the right chute. In Figure 2.5 are the typical circular, cross-shape and U-shape layout displayed. The line configuration moves unidirectional.

Several loop sortation solutions are: Cross-belt sorter, bomb bay sorter and tilt tray sorter [43]. The cross-belt sorter comprises of a series of belts which are perpendicular to the looped track. The conveyor can discharge towards either side of the conveyor. A bomb bay sorter is a continuous sorter which has split up trays. These trays can discharge items directly below the sorter. The tilt tray sorter uses a tilting tray which makes the tray tip over to either side perpendicular to the looped track. Therefore the parcels are sorted at the moment it passes the correct chute.

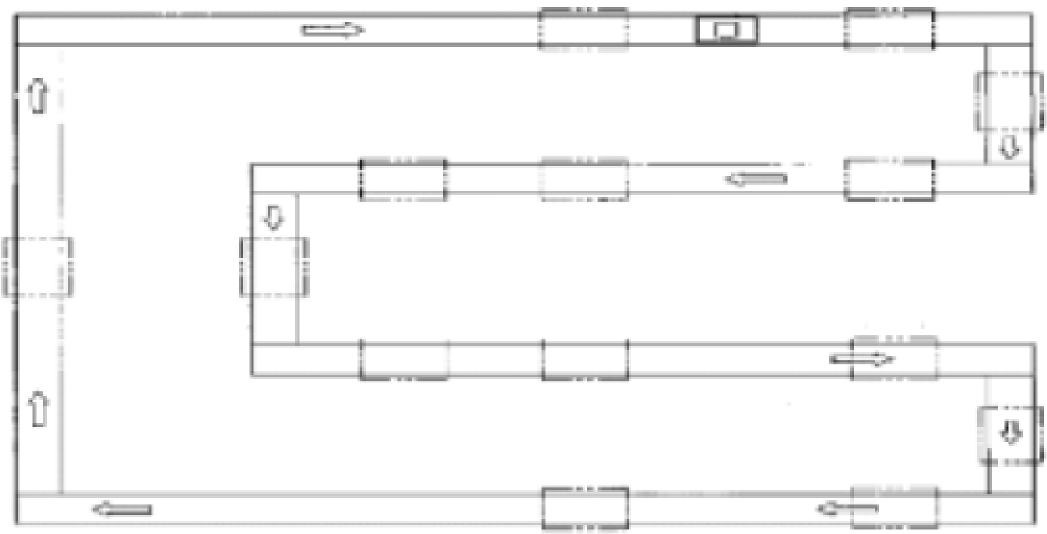
Several line sortation solutions are: Sliding shoe sorter, Activated Roller Belt (ARB) sorter, linear belt sorter and narrow belt sorter [33]. The sliding shoe sorter is composed of a bed of uniform shoes who are aligned to one side of a parcel. When a parcel reaches its assigned post sort-lane, several shoes are electronically activated to slide in the direction of the intended divert, guiding the parcel to its destination. The ARB Sorter uses angled rollers embedded in a modular plastic belt conveyor, actuated from below the conveyor, to sort any



(a) Circular [7]



(b) Cross-shape [7]



(c) U-shape [7]

Figure 2.5: Layouts of typical conveyor systems [7]

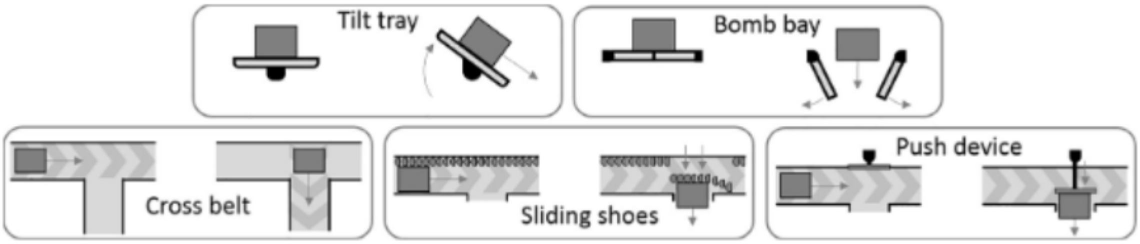


Figure 2.6: Several sorting techniques [8]

type of product. The linear belt sorter is a cross-belt sorter without the loop functionality described above. The narrow belt sorter uses wheels that pop up for a parcels at the point it needs to change direction, this can be done at 30 or 90 degrees. Several of these mechanisms are visualised in Figure 2.6.

2.4. General layout of a parcel sortation system

Every parcel sortation system is different and optimized for the clients required specifications. Though a general schematic layout of a current parcel distribution center can be sketched, such a system is displayed in Figure 2.7 [9]. This parcel distribution center has a single loading station, each tilt tray is filled (at most) only once per cycle of the conveyor system. If multiple loading stations are available, as displayed in Figure 2.8, then a tray can repeatedly be loaded per cycle provided that the tray could intermediately be emptied.

Looking at Figure 2.7 the system handles a parcel as follows: Trucks come at the inbound trailer (left-side of Figure) and unload parcels. The parcels are transported via conveyor telescope (extending in length to reach the trucks) belts and scanned at the recognition system. Then the order of packages is known including its position in the queue and the destination chute. The parcels move along the closed-loop tilt tray conveyor and is distributed to the assigned delivery van (top or bottom-side of Figure) for local distribution.

2.5. Key Performance Indicators

The KPIs are found with the use of literature, wishes from the company VanRiet and own insights (found in response to the other KPIs). A comparison will be made for a certain production area. First an area [m^2] is chosen and on this surface are several lay-out designs applied. The space utilization is a point of interest, as found in literature [31], and can be used to make a comparison with other sortation systems. To make a specific

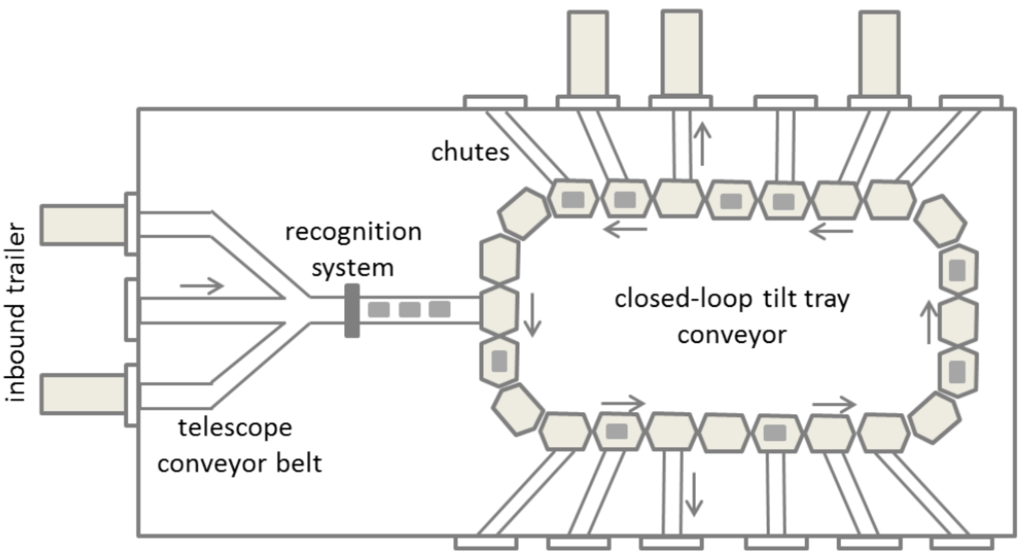


Figure 2.7: Schematic layout of a parcel distribution center [9]

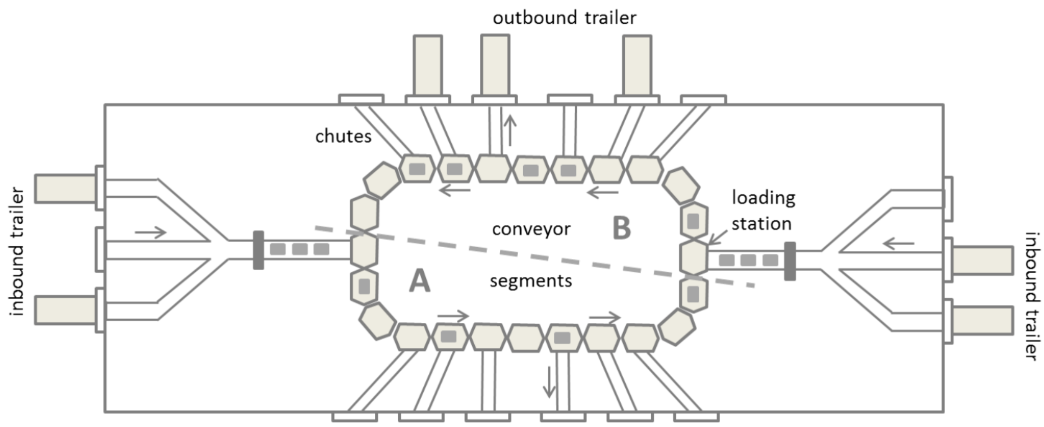


Figure 2.8: Schematic layout of a terminal with multiple loading stations [9]

throughput happen for a system, a certain amount of AGVs is required. The amount of AGVs currently operable depends on the charging state of AGVs, therefore the amount of battery charging stations is of importance. This is a wish of VanRiet. To utilize the effectiveness of task allocations, empty load travelling and rated load travelling are used, as found as a own insight. The routing and scheduling of the AGVs should be done efficiently, this can be investigated by looking at the utilisation rate of idle AGVs and AGVs which are waiting in line, as found in literature [44]. A requirement of the system will be that no total deadlocking of the system occurs, though a wish of VanRiet is looking into if a percentage of deadlocking is allowed can this benefit the overall performance of the system. Lastly an utilisation rate at peak capacity is useful to estimate the amount of time the system is close to overloading, as found in literature [2]. This means that probably extra AGVs are required, vice versa less AGVs are necessary in downtime and can go charge.

The KPIs are divided into a two step approach. Firstly a production area in $[m^2]$ is defined and several AGV lay-outs are proposed for the area. This comprises the space utilisation percentage and the peak capacity percentage. The second step is acquiring the required throughput for this area and therefore finding the amount of AGVs necessary to reach or exceed the demanded throughput. This is limited by the charging process of the AGVs and therefore more AGVs will be required to reach the throughput. Increasing the amount of AGVs makes a dependency on the amount of waiting AGVs, the number of charge stations the change on deadlocking, the idle percentage and the empty load, rated load time.

The following KPIs are assumed to be necessary, though set to a specific value. This involves deadlocking % as the model is designed to requiring a grid-locking (total map deadlock) of zero. Therefore deadlocking is quickly dealt with by the routing algorithm for the AGVs. The KPI space utilization is used for the ratio of area of the map and the amount of AGVs though for each separate case (described in Chapter 6) is this area the same. The peak capacity % occurs when a system works at the highest throughput, this is equilibrium is found at the top till the point of adding more AGVs reduces the throughput of the total system (as queueing and traffic of AGVs reduces efficiency). At last the KPI amount of charging points is looked at only during the charging evaluation simulation runs, as this otherwise would increases the complexity of analysing the results (so the charging has no influence on the results during other simulation runs by cancelling charging or while charging is no yet activated).

2.6. Methodology simulation model

Figure 2.9 shows the methodology for a simulation study. This is used as an approach for this report. First problems with the conventional parcel sortation systems are defined. Objectives are set in terms of requirements and parameters. A conceptual model is defined and data is collected as an input dataset: a list of parcels which needs to be sorted. These are analysed and modelled into a simulation. The model is verified with an experimental plan. This is done in order to check whether the simulation model runs correctly. Validation can only be done with assumptions in terms of estimations of throughput time and amount of AGVs required. A sensitivity analysis will be done on the results. Resulting in discussions and conclusions.

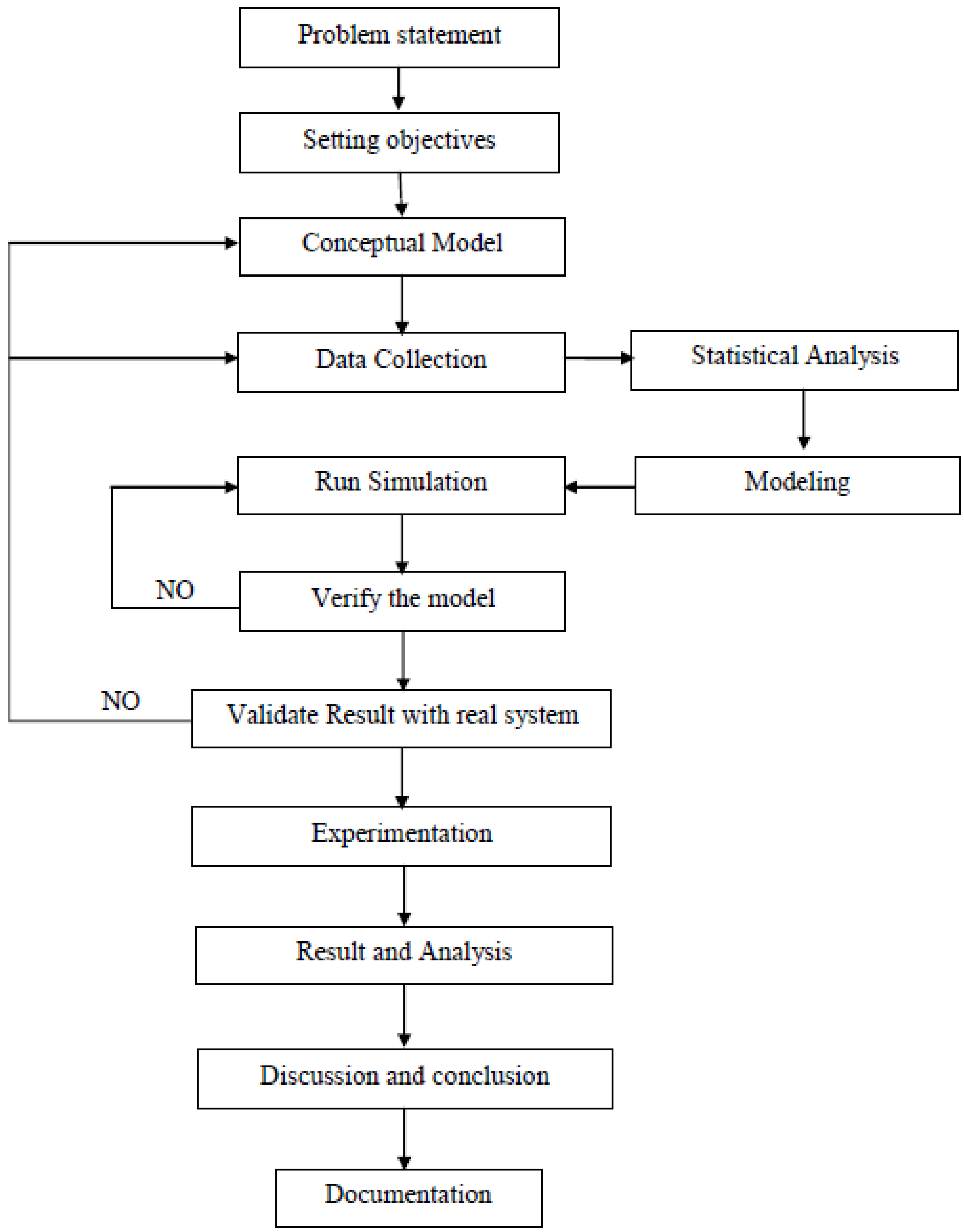


Figure 2.9: Methodology of a simulation study [10] [11]

2.7. Conclusions

Challenges in the parcel sortation industry are package variety, volume, automation integration, customer expectation and space utilization. These challenges are for example due to the increase of poly-bags as well as larger parcel ranging from small to average of 32 kg in the EU till worldwide shipments of maximum 70 kg per parcel. The interest of this report lies in the smaller parcel sortation centres for example: local depots. The currently used systems have layers of redundancy and peak capacity build into their system. As closed-loop systems are not easily altered and/or expanded the systems are quite inflexible in terms of possible future expansions.

Conventional parcel sortation system consist of inlets for large trucks and outlets (reversible as described: bi-directional) for small vans. The systems usually consist with circular, cross-shape or u-shape lay-out which have closed loop systems.

Several key performance indicators are found from literature, wishes from the company and own insights. These are: amount of charging stations, deadlocking %, empty load, rated load time %, idle %, peak capacity %, space utilization and waiting time %. These will be used for evaluation of the changes made to the model. A methodology is chosen of a simulation model for the process of creating a functioning model to simulate an AGV based parcel sortation center.

3

Literature study of AGVs

In this Chapter is background information given about AGVs. Firstly scheduling and routing is described. Followed by the different types of location identification. The safety of AGVs and its environment must be maintained. Most AGVs work on batteries and this gives additional points of interest in the routing and scheduling process. After the general introduction are several routing algorithms, used for AGV purposes, described. The allocation of tasks for a single AGV or set of AGVs can be done cooperatively to increase the overall productivity of a sorting process. Several task allocation solutions/algorithms are described. This is followed by the state-of-the-art of AGVs used for sortation systems. The difference between grid and free-ranging AGVs is elaborated. As well as the different possible sortation techniques that can be applied.

3.1. AGVs in general

An AGV is an automated guided vehicle that follows a guided path [45]. It varies in size, acceleration, speed, payload, endurance, how objects are contained on the AGV itself and distributed from the AGV. In Figure 3.1 is the development and use of AGVs in Western world and China displayed [12]. The development started with idea realization (1^{st} era), then computer and microelectronics support was implemented (2^{nd} era), it has proven as technology for application (3^{rd} era) and increase in design and efficiency is still happening now in the 4^{th} era.

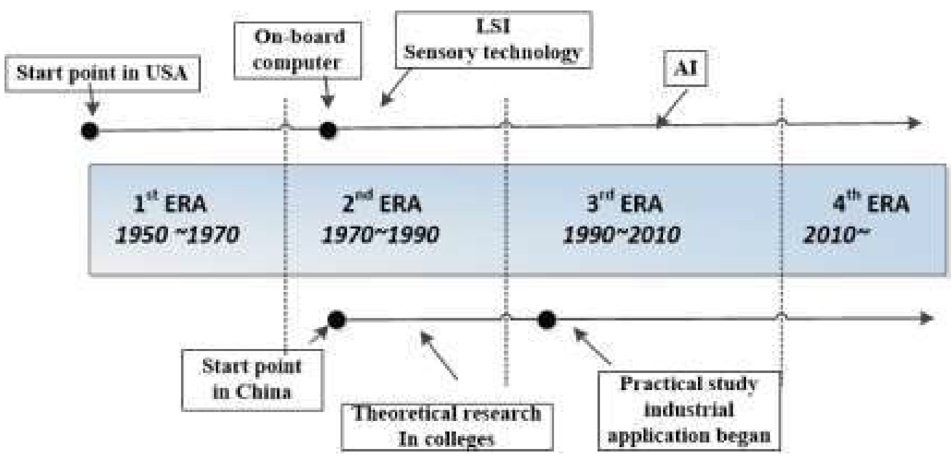


Figure 3.1: The history of AGV development in the Western world and China [12]

3.1.1. Scheduling

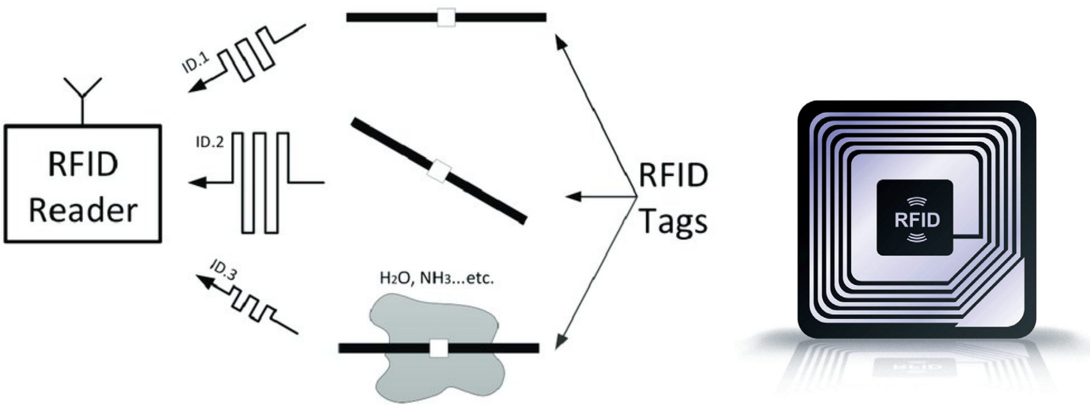
The traffic flow of AGVs in a parcel sortation system is being controlled by a Material Flow Controller (MFC) [46]. The scheduling is done in the MFC system and then send to the AGV control system. This system is also called Robot Control System (RCS) and has the task to execute the planned sequence of motions and forces in the presence of unforeseen errors [47].

3.1.2. Routing

The routing is done within the RCS part of the MFC. The routing process can be implemented with many different algorithmic solutions [45]. These vary in optimization limit, but this is not the only criteria as several other factors take in place to choose a specific type of routing. Which are computation speed, complexity in computing process, (temporarily) data storage, real-time control editing. These have to be into consideration for a new process. Various routing solutions are explained in Section 3.2.

3.1.3. Location identification

There are multiple solutions to identify the current location of an AGV. This can be done with Radio Frequency IDentification (RFID) which uses RF signals for automatic identification of objects [48]. The RFID identification process, Commercial Off-The-Shelf (COTS), is displayed in 3.2a. An object or location can be tagged by COTS RFID tags using the system displayed in Figure 3.2b. Also the use of Quick Response (QR) code labels, see example in Figure 3.3, on the ground or charging stations [49]. The use of visual or laser Simultaneous localization and mapping (Slam) navigation + inertial navigation of the AGV itself can be used [50]. In this research is is assumed that the location of the AGVs is known by location nodes.



(a) RFID process [13]

(b) Example of RFID tag [51]

Figure 3.2: COTS system of radio frequency identification (RFID) for identification and different sensing applications. [13]

Figure 3.3: QR code with link to www.tudelft.nl [14]

3.1.4. Safety

Safety of equipment and products must be maintained. This can be done by eliminating (as much as possible) objects and products in the path/workarea of AGVs. When this is done planning and routing can be used to eliminated collisions. A working area of AGVs can be limited to AGVs only, but also cases exist where the safety of possible humans must be guarded [52]. This cannot be done by planning and routing and therefore

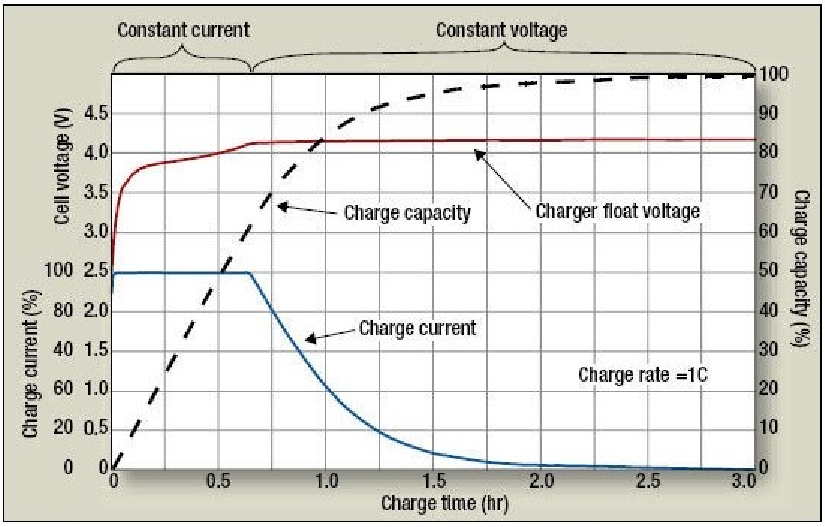


Figure 3.4: The constant-current, constant-voltage charge profile for a Lithium-ion battery depends on the charge current, cell voltage and charge capacity [15]

other solutions are found. Vision based localization is a commonly used solution, it uses environment mapping to sense presence of a human on its route. This vision guided navigation system has vulnerabilities in several areas and these must be maintained [52]. For this research it is chosen to limit these kind of extra parameters and safety will be guaranteed by creating AGV-only zones.

3.1.5. Battery management

Most AGVs are battery powered to induce an electric motor. The use of an electric motor adds the possibility for higher efficiency energy usage and is a relatively good choice to reduce noise pollution [53]. The electrical specifications about drives and discharge of batteries will not be subject of this thesis. The valuable information for this research is found in the capacity of a battery. The efficiency from the drives and internal process including the routing process [54] and loaded/unloaded distance travelled lead to the endurance of the AGV [16]. The charging time influences the amount of non-operative AGVs in the system, especially if the amount of charging stations is insufficient. The lifespan of a battery is expressed in charging cycles.

Few research is done in terms of different routing heuristics for the battery management of AGVs. The research done by Mark Ebben in his report, Logistic control in automated transportation networks, set a foundation for the research of different routing heuristics in terms of battery management of AGVs [55]. Though this research uses battery swaps instead of loading bays the routing optimisation stays the same [56]. In this report is concluded that the selection of a battery station will cause minimum delay considering both travel time and waiting time in a queue, a flowchart of this process is displayed in Figure 3.5. An AGV following this heuristic goes to a battery station from its current location (i.e. initial point or pick-up point) if the available charge is not sufficient to go to the next location and from there to the nearest battery station. It selects the battery station that will minimise total time for travelling and waiting at the battery station.

For the charging process of the Lithium-ion battery, which is the generally used type of battery in these kinds of AGVs, is displayed in the Graph in Figure 3.4. As can be seen that the charging of a Lithium-ion battery is most efficient (in terms of time consumption) from 1% - 70%.

3.2. Literature of AGV routing

In this section is a list of existing routing solutions for AGVs, described in literature, given. Generally are the routing algorithms used as a basis and extended for AGV routing purposes.

3.2.1. Dijkstra's algorithm

Dijkstra's algorithm is used to find the shortest path between nodes in a graph which may represent, for example, a factory lay-out [57]. It is generally used as a foundation for implementation after which improvements

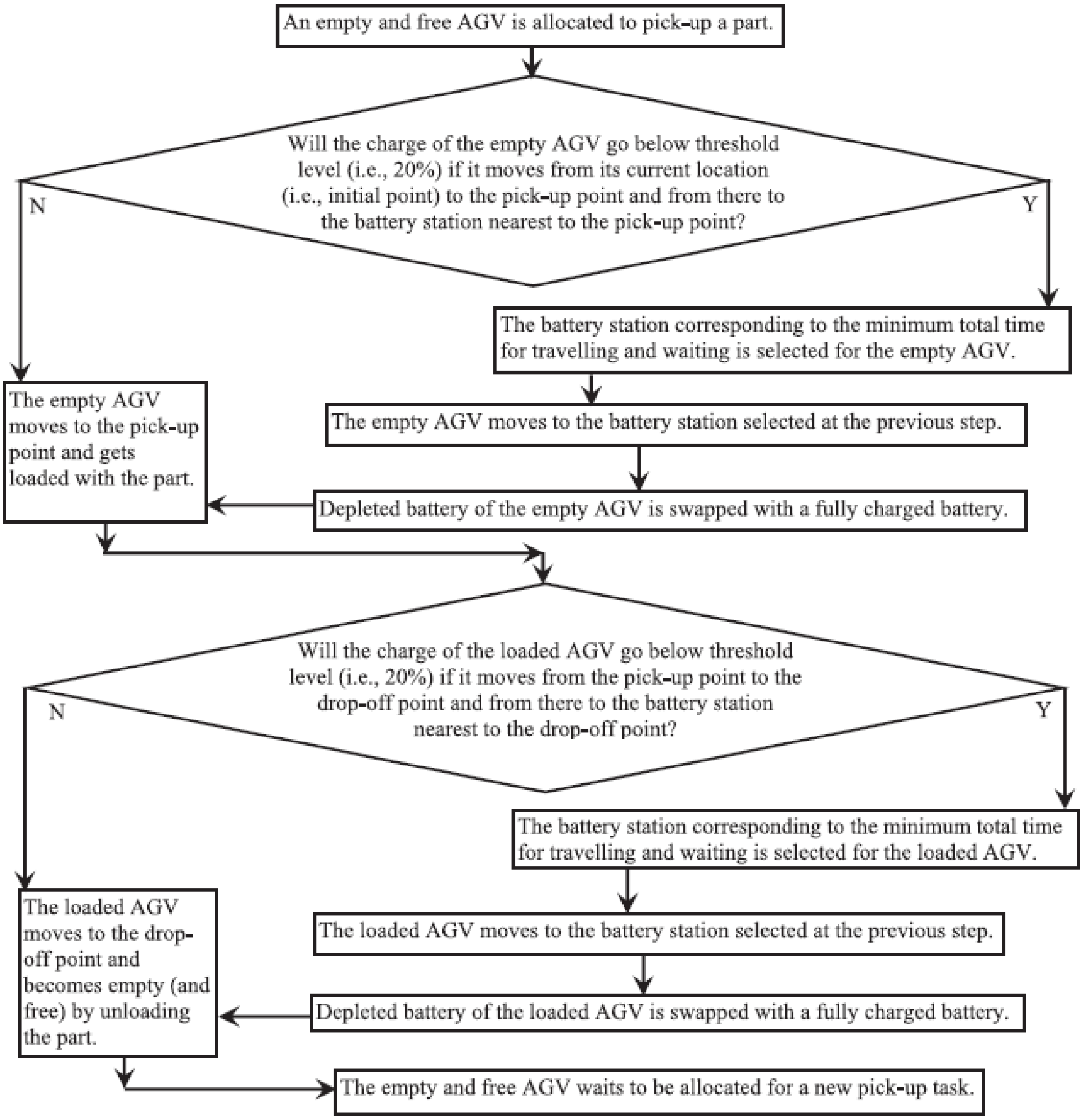


Figure 3.5: Flowchart for the heuristic of minimum delay battery station [16]

are added to the algorithm. This is due to the lower computational speed because of the algorithm's large data storage and complex computing process. This is due to the computation cycle which checks n^2 times the available actions, with n the number of nodes on the graph [58]. Though it is the basis for papers as: The Algebraic Algorithm for Path Planning Problem of AGV in Flexible Manufacturing System [57]; AGV optimal path planning based on improved ant colony algorithm [59]; Research and Design of a Path Planning Algorithm in the Intelligent Logistics Sorting System [60]; A Multi-Commodity Flow Model for Guide Path Layout Design of AGV Systems [61]; Collision-Free Route Planning for Multiple AGVs in an Automated Warehouse Based on Collision Classification [49].

3.2.2. Travelling salesman problem

The Travelling Salesman Problem (TSP) calculates a set of points. The cost of travel in either direction between any two coordinates are given, the solution to the TSP seeks to find the shortest tour that, starting from any point, returns to the same point after visiting all other points without repetition [62]. This method can be executed and iterated, with increasing iteration-steps the solution will come closer to the optimal route. This increases computation time and a trade-off must be made which amount of iteration-steps is sufficiently close to the optimum route. This method is used and extended in these papers: Development of computer-controlled material handling model by means of fuzzy logic and genetic algorithms [63]; A Fast Algorithm on Minimum-Time Scheduling of an Autonomous Ground Vehicle Using a Travelling Salesman Framework [62].

3.2.3. A* search algorithm

The A* algorithm is a heuristic algorithm. A function is used $f(n) = g(n) + h(n)$, with g(n) is the cost of the path from current position to the starting point and h(n) is the cost of the path from current position to the endpoint [64]. Therefore the A* algorithm is a goal-directed graph traversal strategy that finds the least-cost path from a given source node to a target node [65]. The key difference between Dijkstra's algorithm and A* is that while Dijkstra's algorithm uses a priority queue to extract the node with the minimum distance from the source to visit, A* visits the node with the minimum sum of distance from the source node and the heuristic distance to the target node. This method is used in these papers: The dynamic path planning of UAV based on A* algorithm [66]; Dynamic Adjustment A* Routing Algorithm [67]; A routing algorithm for inspecting grid transmission system using suspended robot: Enhancing cost-effective and energy efficient infrastructure maintenance [68].

3.2.4. Non-dominated Sorting Genetic Algorithm-II

Non-dominated Sorting Genetic Algorithm-II (NSGA-II) is a meta-heuristic algorithm [69]. A population of candidate solutions is chosen and used for an optimization problem which then evolves towards better solutions [70]. Each candidate solution has a set of properties which can be altered and mutated. The evolution generally starts from a population of randomly generated individuals, and using iterations, changes the population in each iteration-step (called a generation). Every individual in a generation is evaluated in terms of fitness. The fitness is usually the value of the objective function in the optimization problem being solved. The more fit individuals are stochastically selected from the current population, and used for the new iteration of the algorithm.

Commonly, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached for the population. A typical genetic algorithm requires: A genetic representation of the solution domain; a fitness function to evaluate the solution domain. The genetic algorithm can find the shortest path. However, the path might not be the best path due to the random selection. This problem can be minimized by increasing the maximum generation, though this will result in increase of the computation time-costs [58]. It is used in the papers: Development of computer-controlled material handling model by means of fuzzy logic and genetic algorithms [63]; An integrated scheduling method for AGV routing in automated container terminals [71].

3.2.5. Multi-commodity flow model

The multi-commodity flow problem is a network flow problem with multiple commodities (flow demands) between different source nodes and sink nodes. It is used for Routing and Wavelength Assignments (RWA) in optical burst switching of optical network and would be approached via multi-commodity flow formulas [72]. The flow travels with the shortest distance according to the assigned transportation demand. Which starts a flow from the specified pickup node and disappears at the specified delivery node. It is used in the paper: A Multi-Commodity Flow Model for Guide Path Layout Design of AGV Systems [61].

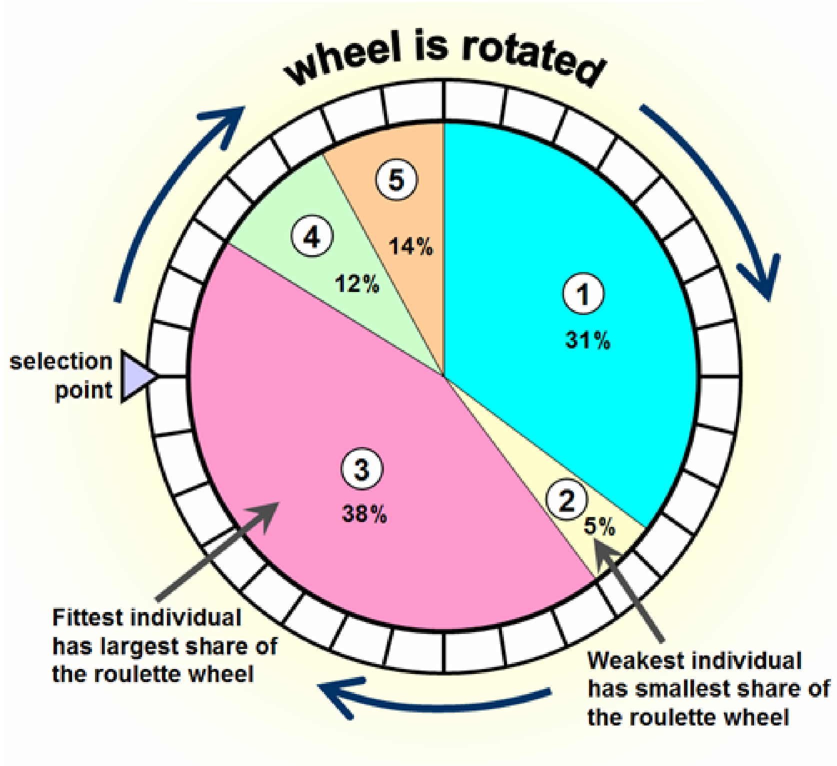


Figure 3.6: Example of a Fitness proportionate selection [17]

3.3. Literature for task allocation problems

In this Section are several task allocation techniques/algorithms described. These are used to select which parcel is to be collected next by the set of available AGVs. These task allocation techniques can consider multiple aspects of a task allocation process for example: Travelling distance for the AGV, travelling time for the AGV, First In First Out (FIFO), parcel waiting time, availability of the pickup point, amount of already assigned AGVs to this pickup point, etc. [73] [74].

3.3.1. Fitness proportionate selection

This Genetic Algorithm (GA) undergoes a process of selecting parents which mate and recombine to create off-springs for the next generation [17]. Maintaining good diversity in the population is extremely crucial for the success of a GA. This tries to prevent premature convergence, the entire population by one extremely fit solution is known, and is an undesirable condition in a GA [17]. Every individual can become a parent with a probability which is proportional to its fitness, as can be seen in Figure 3.6. The wheel is divided into n pies, where n is the number of individuals in the population. Each individual gets a portion of the circle which is proportional to its fitness value. It is clear that a fitter individual has a greater pie on the wheel and therefore a greater chance of landing in front of the fixed point when the wheel is rotated. Therefore, the probability of choosing an individual depends directly on its fitness. This fitness can be set on the aspects described in this Subsections introduction. A pro of this method is that multiple criteria can be combined. A con is that randomization could lead to reduced performance when the use of "change" is introduced into a system.

3.3.2. Hungarian Method

The Hungarian method is an algorithm which finds an optimal assignment for a given cost matrix [75]. It assigns each objective separately and is made in such a way that the overall objective function (e.g. cost, distance, profit, etc.) is maximized or minimized [76]. It works on the principle of reducing the given cost matrix to a matrix of opportunity costs. Though matrix optimization can fairly easy be done by computers, this optimization is more applicable for job-shop problems.

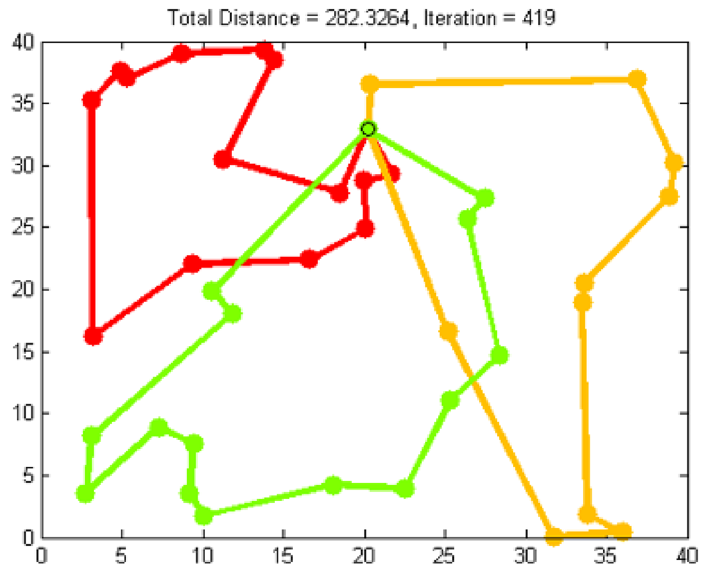


Figure 3.7: Example of a Multi travelling salesman problem [18] [19]

3.3.3. Market- auction-based

Task assignment is a continuous process of selecting a task 'j' from a set of available tasks and then assigning robots 'x_j' robots to complete the task [21]. A Market- auction-based algorithm searches for every AGV (depending on the heuristics every available AGV) the cost and the bid for an assignment of a task. The AGV with the highest bid is granted this job/task and the AGVs are used in another biding. For example, the cost can be defined as the expected number of blocks to be travelled by the $robot_i$ to the $task_j$. It is assumed that the cost to travel a single block is unity and translation is only in horizontal and vertical directions [21]. And the bid function is defined as an expectancy of $robot_i$ to opt for the $task_j$. Consider a scenario of auctions, the clients ($robot_i$) bid on a specific item ($task_j$). This Algorithm is based on grid routing and has extra heuristics available. As well its implementation includes looking at multiple available AGVs to improve the system overall and not AGV specific. It also leaves room for the implementation of extra constraints depending on the points of interest of the task allocation process.

3.3.4. Multi travelling salesman problem

Another task allocation algorithm is the multi travelling salesman problem, comparable with the travelling salesman problem as described in Section 3.2.2 [19]. Though this implementation, as the name implies, considers multiple devices at the time. In Figure 3.7 is an example given of 3 travelling salesman, optimized for the system as a whole. It can be used with a cost metric and/or distance metric. The implementation is less practical for an AGV system as it needs to connect each point once and returning to the start-location.

3.3.5. Simplex algorithm

The simplex algorithm describes the minimization of a function of n variables, which depends on the comparison of function values at the (n + 1) vertices of a general simplex, followed by the replacement of the vertex with the highest value by another point [77]. The simplex adapts itself to the local landscape, and contracts on to the final minimum. It maximizes a linear function (which could be the profit of investments) within the feasible region given by the linear constraints (which could be limitations of available resources) [20]. To solve such a simple example, one can draw its graphic representation and sweep through (pointing to the correct direction) the feasible region, see Figure 3.8, until reaching the optimal extreme point. The simplex algorithm walks along the boundary of the feasible region, moving from one vertex to a more profitable one, until reaching the optimal vertex. This algorithm gives an optimum with low computation times, though it is limited by linearity constraints.

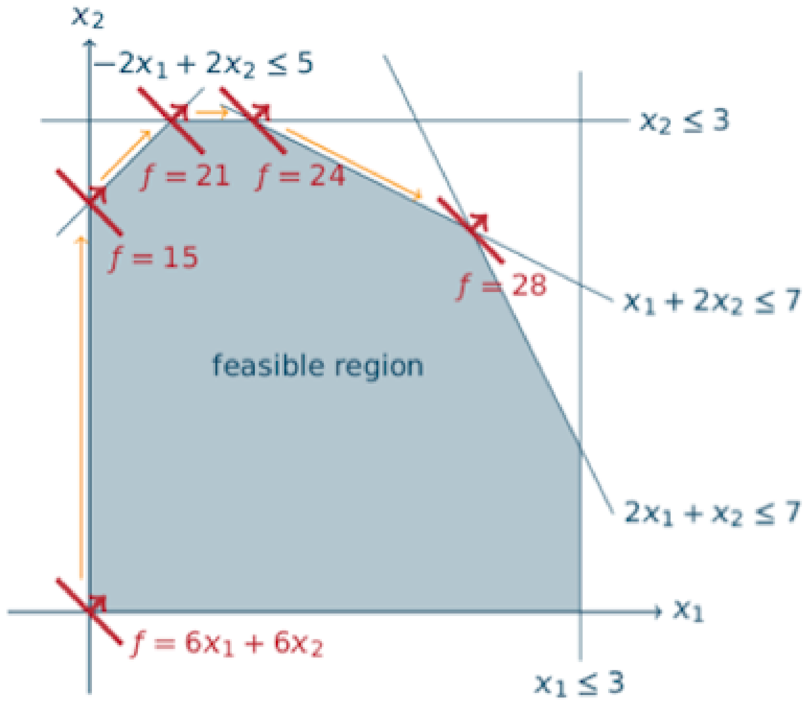


Figure 3.8: Linear programming problem - Simplex Solution [20]

3.4. State-of-the-art: using AGVs in sortation systems

In this Section will current AGV sortation systems be described, the difference between either straight x or y movement versus free-ranging will be explained. Also a research is done in combing these two types into mixed-routing. An AGV can be used as flat surface tabletop or can be equipped with distributing-techniques like the tilt tray or (cross) belt conveyor. When these techniques are used solutions are found to receive the parcels dispensed at the end location.

3.4.1. Open navigation: grid versus free-ranging

Open navigation is a navigation method with no physical guide paths [78]. Instead of using a specific road layout, anchoring point navigation is used which uses a type of orientation technique to identify a location [79]. This can, for example, be done with techniques described in subsection 3.1.3, RFID and QR code labels. These techniques can be used to make grid route-planning possible. An example of an AGV layout is displayed in Figure 3.9. On the inlet side is a parcel distributed to an AGV. From which it is moved to a Scan area where the parcel is weighed and scanned and hereby the end destination is determined. A route is made towards the destination by grid or free range routing. If an AGV has no job to execute, it can go charge or wait in the designated waiting areas.

AGVs can move in a grid in either x or y-direction, at a time. This reduces the complexity in terms of steering, routing and preventing deadlock. Another possibility is using free-range routing. This means x,y movement is possible and more flexibility is added to a system [80]. Also a location can be reached in a straight line instead of a zigzag motion, reducing the amount of distance travelled. A third option is combing these two into a mixed routing system [81]. For example grid routing is used on relatively small areas/lanes while free-ranging is used on larger areas with no/few obstacles are influencing the routing process.

The systems can be expanded by adding (several) different types of AGVs in a single area [82]. This adds extra possibilities, for example being able to handle more types and shapes of parcels as well as different load capacities. Though challenges are added when combining AGVs, because probably the AGVs will have different specifications in terms of size, maximum speed and acceleration.

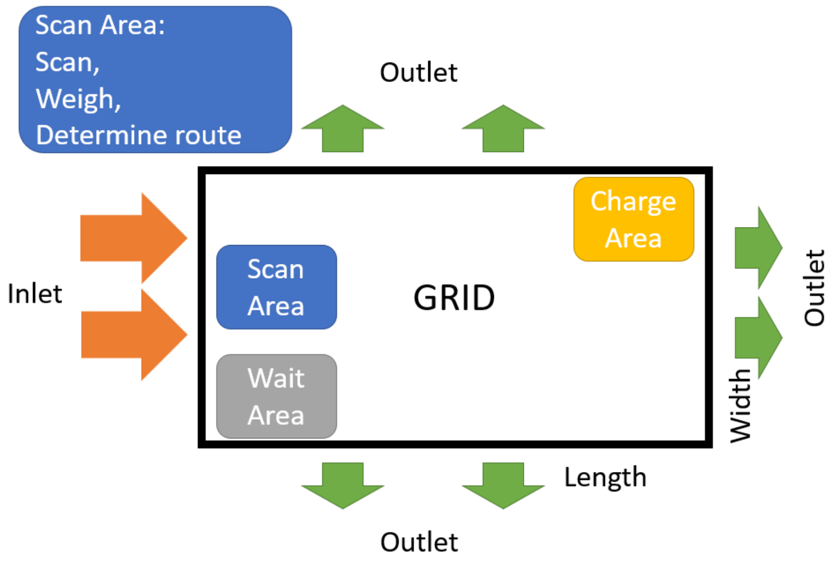


Figure 3.9: Example of an AGV layout can be used for grid or free-ranging

3.4.2. Sortation techniques when AGVs are applied

The use of AGVs in the industry has started from the 1950s, as described in Section 3.1. Though the implementation of AGVs in parcel sortation systems is relatively new. Few information/documentation is available, due to the fact that these are not made yet or have an embargo by companies on them. Therefore the following techniques are found from on-line clips and company website information which is likely to be simplified and/or redacted.

An AGV can serve as a flat surface carrier on which parcels can be placed, scanned, transferred and picked off. This pickup-function can also be added to the AGV itself. By adding a tilting top, also known as a tilt tray, or conveyor belt the parcels can be transported of the AGV. This means that the AGV receives, drives, sorts and delivers. The tilt tray can for example be used to transfer parcels to a specific opening in the ground and then it tilts the parcel into the chute beneath it, as displayed in Figure 3.10a. An alternative to this is raising the AGVs onto tabletops, making them tilt parcels into boxes which can be transported if full, see Figure 3.10b. In Figure 3.10c is a belt conveyor placed ontop of the AGV, this drops the parcels into mailbags/transport-containers. An extension of this idea is shown in Figure 3.10d, in which a double cross belt conveyor is used. It can be used to handle one large or two separate parcels.

3.5. Conclusions

In this chapter are AGVs and its uses for parcel sortation systems evaluated. Parcel sortation systems use a material flow controller to monitor its process. In addition a lower layer of the AGVs, which shall communicate with the MFC, is added to control the AGVs: a robot control system. This system routes the AGVs, as each AGV updates their location to the RCS. The AGV uses to find its location by location identification e.g. RFID or QR code. The AGVs are separated from human workers for safety. The AGVs operate generally with a Lithium-ion battery a approximation of these will be used for this report.

AGVs which are bought from another company are supplied with a routing program. As the actually used algorithm is not known a routing algorithm from literature is used. The following algorithms are described and a section will be made in Section 4.3: Dijkstra's algorithm, Travelling salesman problem, A* search algorithm, Non-dominated Sorting Genetic Algorithm-II and the Multi-commodity flow model. The task allocation by the MFC can be done by the following algorithms and a section will be made in Section 4.4: Fitness proportionate selection, Hungarian Method, Market- auction-based, Multi travelling salesman problem and the simplex algorithm.

Current available AGVs use grid navigation, as the AGVs move in either x or y direction at the same time. Therefore movement is quite straight, the change of direction is done by rotating on its axis on top of a location identification marker. Several existing solutions are charted and an example of a generalised AGV lay-out is

(a) 1.3 km^2 sortation transit, chutes beneath every opening in the ground and tilt tray AGVs [83]

(b) Tompkins Robotics: t-Sort sortation on a tabletop design with tilt tray AGVs [84]

(c) Geek+ S20-warehouse AGV, belt conveyor AGVs [85]

(d) GreyOrange Flexo, crossbelt conveyor AGVs [86]

Figure 3.10: AGV sortation system selection with different sorting solutions

given. This provides the inlet of parcels. These are transported on top of AGVs. The parcels are scanned and their destinations (outlets) are determined by the MFC. When no job is available for an AGV the process is as follows. Either charging the Lithium-ion battery or waiting at a predetermined area.

4

Requirements and assumptions

In this Chapter are potential parameters evaluated. These will not be out-and-out, though are used to narrow the research scope for practical reasons as complexity and time-limitations. Other parameters will be assumed to be a constant. This is done to limit the amount of possible combinations in the modelling process, as well as reducing computation time. Then the design parameters are described which can be varied and then monitored by the KPIs.

4.1. Assumed constants

In this Section are several parameters described which are assumed to have a specific value, constants. These are set to limit the variations for the simulation process. The constants are separated into the groups: AGV, scanning, routing and scheduling.

4.1.1. AGV constants

Several companies sell various AGVs, the maximum payloads ranges between 5 kg and 3000 kg (AGVs for container terminals even upto 70000 kg [87]) [88]. For the process of sorting parcels is the use of a large AGV, which is capable of handling a payload of 3000 kg, over-design. The larger delivery companies (DHL, FedEx, GLS, UPS) have a non-palletised weight limitation of 70 kg per parcel [89], as stated in subsection 2.2.1. In Appendix B is a Table given with the AGV specifications. This Table is (non-ideally) empty in various areas, especially in the areas: Rated load acceleration, endurance and charging time. Due to this and the lack of a large dataset, estimations need to be made.

With the use of the AGV specifications from Appendix C [50] [88] [90] [91] [92] [93], is an average per selection group made to predict the AGV specifications, if a certain payload is required. No concrete linear or non-linear relations are found between the specifications of an AGV. This is because an AGV can be designed with any kind of specification. For example a speed of 5 m/s is requested (ignoring the probability of launching the parcels), this would require a more expensive motor and therefore the AGV price rises. The scope of this research excludes designing specifications for AGVs. Therefore an analyses is done for a selection group of AGVs, sorted by payload.

These AGV payloads are set around the 6 kg (small parcel), 32 kg max weight EU [94] and 70 kg [89], as displayed in Appendix B. All AGVs can rotate around its own axis and therefore can be used with the same kind of routing in a grid layout. The distribution will be modelled as a time process to reduce complexity. Several AGVs are selected and their specifications are set as constants. Though keeping in mind that choosing which AGV to use is indeed a design parameter.

The amount of noise generated by AGVs is a valuable parameter but no specifics are distributed. The drive-system of the AGVs are electrically powered and noise pollution is assumed to be within limits. It is not required for the feasibility process of using AGVs for sortation purposes. Therefore noise generation is out of scope for this research.

4.1.2. Scanning constants

In Europe are the boundaries in terms of legal for trade established by the European Community (EC) [95]. Legal for trade is applicable for commercial applications where products are sold by weight, therefore a legal requirement is set that weighing equipment must be verified. At the location of the scanner is an EC weighing instrument situated, to match the barcode identification with the weight of the parcel. Generally this is an Automatic Weighing Instrument (AWI), which does not require the intervention of an operator during the weighing process to adjust the quantity of material being weighed [95].

The scanner setup is an expensive part of a parcel sortation system [96]. This is due to the demand for higher throughput which requires quicker scan speed and processing time. Also the angle of the scanner is a factor for the selection of a system. The options are a three-dimensional (3D) scanner, which can scan 5 sides of a parcel, which is more complex versus a two-dimensional (2D) or even one-dimensional (1D) scanner [97]. The 1D/2D scanner has the requirement that the barcode needs to be on the view-side of the scanner. Doing this for every parcel (generally) adds another process-step to the system. The scanning process is assumed to be out of scope for this research and is assumed to be fully functional when a parcel is picked up, given it's destination/end-location to the AGV.

For the simulation is assumed that the scan speed and process time of the scanner is sufficient. Also the communication between the scanner and sorter is out of scope. The angle of scanning is necessary to investigate in a further point of the design process and will therefore not be included in this research. The scanner will be placed at the loading bay, at which a parcel is scanned and gets an end-destination. Following a route can be calculated to reach this end-destination.

4.1.3. Routing constants

When an AGV is purchased from a company a RCS is included, which contains the routing process. Therefore the purchase of an AGV defines the routing-type. Nevertheless the experimental model must have a routing algorithm to properly work. A presumption will be done to select a routing algorithm. This is done based upon AGV-video's or hopefully information of the companies themselves. To narrow the scope of this model the AGVs will move in a grid instead of free-ranging. Therefore either x or y-movement at a time is possible. This decision is made due to the nature of the currently (feasible) available AGVs and modelling complexity. Also the amount of failing AGVs can influence the scheduling as it limits the possible routes. Though it is possible to have failing AGVs in the system, it considered for the AGV company to solve this problem. It is assumed that the and therefore is out of scope

4.1.4. Scheduling constants

The scheduling contains several KPIs, as well as collision %. To reduce damage done to the AGVs and parcels the collision % must be contained at zero. The current available AGVs are supplied with a centralised control unit, which plans the tasks for the RCS [90]. Therefore it is chosen to use such a centralised control unit for the model.

4.2. Design parameters

Many things in a system can influence a system and therefore a design. Though to narrow the scope of this research not every aspect of designing a sortation facility are investigated in this report. The design parameters are found by literature, experience from the integrator or gained insights during the creation of the mode and described in the following subsections. The design parameters are changed and therefore used to find if they are influential in the sortation process. The influence of changing the design parameters can be based upon the KPIs. The design parameters are separated into the groups: building/layout and scheduling.

- Amount of charging stations
- Deadlocking %
- Empty load, rated load time %
- Idle %
- Peak capacity %
- Space utilization
- Waiting time %

4.2.1. Building and layout design parameters

The layout of the building is estimated to be influential. The assumption is done to look at an AGV-only zone and therefore the length, width and height of this zone is relevant. The amount and location of inlet and outlet places for parcels determine the routes of the AGVs. The location of the charge station will influence the routing and potential sites of traffic jams. Also the location of the waiting areas while an AGV is idle is of importance, perhaps close to a new job-location, but not limiting the movement space of currently running AGVs. This is put in short in Table 4.1.

Amount of AGVs
Amount of charging points
Drop-off point locations
Amount of drop-off points
Pick-up point locations
Amount of pick-up points

Table 4.1: Design parameters

4.2.2. Scheduling design parameters

The computation/process time of a model is depending on several factors. The program itself, size of the simulation, the amount of AGVs (which need to be routed) and therefore the amount of changing values. The amount of jobs to be handled is a design parameter, as well as its distribution interval.

4.3. Selection of the AGV routing algorithm with the use of MCA

Several routing techniques are described in Section 3.2. These are compared with the use of a Multi Criteria Analysis (MCA) [98] to select the preferable algorithm for this research. As the routing of AGVs is included in the purchase of an AGV the routing should be sufficient for the model to work (for analysis of this report), but not necessarily optimized for designing an AGV as it is not the scope of this report. The following criteria are determined for the routing algorithm. The applicability on a grid routing based lay-out (see Subsection 3.4.1), as movement is done either in ”x” or ”y” direction at the same time. The simplicity of the algorithm to implement it in the model, this due to time limitations for this part of the report. The capability of the algorithm in terms of to work on a large system with (estimated) at least 300 AGVs and in correspondence the computation time. The ability for the routing algorithm to alter routes and not be limited by fixed paths from 1 point to another.

In Table 4.2 is the MCA displayed. In which the routing algorithms are rated from 1 to 5, rated separately meaning 1 not applicable to 5 very applicable. The criteria are weighted with 40% applicability for grid routing as this is a large requirement. The ability to reroute and calculate different paths is rated at 30%. The less complex the routing algorithm is, leads to reduced time for the implementation, 15%. Computation time and support of large systems/many AGVs is rated at 15%.

The Dijkstra Algorithm is applicable and not complex to implement, though the computation time rockets in larger systems. The travelling salesman problem requires to start and end on the same node, this is not very applicable for AGVs in grid routing. The Non-dominated Sorting Genetic Algorithm-II is very complex to integrate and requires many iterations while ”x” or ”y” movement is quite straight forward. The multi-commodity flow model has fixed ratings for each path and is less flexible to create different routes. The A* search algorithm scores the highest as it takes the benefits of the Dijkstra’s algorithm with a better computation time for large systems and it searches for a route in the general direction of the required destination which is known.

Criteria	Applicable for grid routing	Capable of large systems	Simplicity	Not limited to fixed paths	Sum of weighted scores
Weight	**0.40**	**0.15**	**0.15**	**0.30**	
Dijkstra's Algorithm	4	2	5	3	3.55
Travelling salesman problem	2	5	4	3	3.05
A* search algorithm	5	4	4	3	4.10
Non-dominated Sorting Genetic Algorithm-II	2	5	2	5	3.35
Multi-commodity flow model	3	4	3	2	2.85

Table 4.2: MCA routing algorithm

4.3.1. Additional information on A* algorithm

The A* routing algorithm finds the shortest route from the start location to the determined destination. A function is used $f(n) = g(n) + h(n)$, with g(n) is the cost of the path from current position to the starting point and h(n) is the cost of the path from current position to the endpoint [64]. Therefore the A* algorithm is a goal-directed graph traversal strategy that finds the least-cost path from a given source node to a target node [65]. This also takes into account route specific limitations in terms of impassable directions (sides on which the AGV cannot leave the current location node). For each node a cost to travel towards this node is calculated. This is equal for each direction (as either X or Y-movement is possible), though a turn has an additional cost. Therefore making less turns is profitable. The algorithm calculates multiple routes and the route which has the least cost is chosen and send to the AGV. If an AGV is re-routed due to deadlock prevention or collision prevention the A* algorithm can recalculate the remaining route.

If no route is found an random waiting time between 0.01 and 0.1 seconds is executed. After which a recalculation is done. This process is repeated until a route is found or 3 simulation seconds have passed. After this time a route is planned to a neighbouring node of the destination, after reaching this location the RCS will calculate the last few steps to route to the intended destination.

4.4. Selection of the AGV task allocation with the use of MCA

Several task allocation techniques are described in Section 3.3. These are in this Section compared in a MCA. The task allocation can influence the distance an AGV needs to travel to collect a new parcel. As well as the waiting time of a parcel to be collected. For example if only the travel distance is taken into account a possibility appears that parcel pick-up stations are completely ignored due their positioning. This is taken into consideration if a task allocation algorithm is capable of handling multiple aspects simultaneously. In a system with multiple AGVs waiting for a job the selection of which AGV collects which parcel (job) can reduce overall travel distance/time. This is considered in the criteria applicable for multiple AGVs system. The simplicity of integrating this algorithm in the model is taken into account as well. As this is report aims for a model which could be further expanded/improved the possibility to add more aspects to improve the task allocation is added to the MCA.

In Table 4.3 is the MCA displayed. Again the algorithms are stated from 1 to 5, separately and from 1 not applicable to 5 very applicable. The criteria are weighted with 40% for multi AGV/multi job selection, as this is considered to be a critical element in a multi AGV system which does work with one single centralized RCS. To handle multiple aspects simultaneously is rated at 30%, as some algorithms first optimize 1 aspect after which it optimizes the next. Simplicity of integrating the algorithm in the model is situated at 15%. The possibility to expand/improve the model even further is taken into account at 15% for growth in (possible) optimization of the model (out of scope, due essential to keep in mind).

The fitness proportionate selection algorithm is certainly scalable and takes all aspects into account. Though due to the element of randomization of this algorithm less optimal decisions are still possible. The Hungarian Method can only be used to optimize 2 aspects and is matrix based, which would require to put other elements of the model into matrices as well. The Multi travelling salesman problem has the same limitations as the travelling salesman problem described above as it requires to start and end on the same node, though applicable in selecting multiple jobs for multiple AGVs. The Simplex algorithm can be used for multiple aspects, though it is limited to linearity constraints which could be a problem to reduce the criteria to linear problems which increases the complexity and makes it less appealing for the multiple AGV problem. The Market- auction-based task allocation is applicable for multiple job selections for multiple AGVs. It has room for growth, as adding more aspects is easily done. It is also already used in an AGV application as further explained in Section 4.4.1.

Criteria	Applicable for multiple AGVs system	Capable of handling multiple aspects simultaneously	Simplicity	Possibility to add more aspects	Sum of weighted scores
Weight	**0.40**	**0.30**	**0.15**	**0.15**	
Fitness proportionate selection	3	5	3	5	3.90
Hungarian Method	4	3	2	2	3.10
Market- auction-based	4	5	4	5	4.45
Multi travelling salesman problem	2	5	5	1	3.20
Simplex algorithm	3	4	3	5	3.60

Table 4.3: MCA task allocation

$$C_{ij} = |\ \mathrm{Robot[i].pos}_i - \mathrm{Task[j].pos}_j\ |;$$
$$0 <= i < n; 0 <= j < m$$

Figure 4.1: Formulas for market- auction-based algorithm $Cost_{Method}$ ($Robot_i$,$Task_j$) [21]

$$bid_{ij} = \begin{cases} \frac{1}{e^{|x_i - x_j| + |y_i - y_j|}} & x_i \mathrel{!=} x_j \text{ AND } y_i \mathrel{!=} y_j \\ \frac{1}{e^{|x_i - x_j|}} + \frac{1}{e^{|y_i - y_j|}} & x_i = x_j \text{ OR } y_i = y_j \\ 2 & x_i = x_j \text{ AND } y_i = y_j \end{cases}$$

Figure 4.2: Formulas for market- auction-based algorithm Bid_{Method} (Robot[i].pos_i,Task[j].pos_j) [21]

4.4.1. Additional information on market- auction-based algorithm

Dispatching rules are generally divided into two types of operation decisions: workstation-initiated and vehicle-initiated, depending on whether the system has idle vehicles (vehicle-initiated) or queued transportation requests (workcenter-initiated) [99] [100].

> *"The vehicle-initiated dispatching determines the load to be assigned to a vehicle when the vehicle is ready for the next task, whereas the workcenter-initiated dispatching determines the vehicle to be selected when loads initiate transportation requests*" [101].

When an AGV has been assigned the job of collecting a parcel, the following procedures are instigated. As described in section 4.4, a market- auction-based algorithm is used. The algorithm selects the most suitable available AGV to collect a parcel, this is done in term of distance and waiting time. This method is obtained from the paper Priority Based Multi Robot Task Assignment [21].

> **Cost:** Cost method is defined as the expected number of blocks to be travelled by the $robot_i$ to the $task_j$. It is assumed that the cost to travel a single block is unity and translation is only in horizontal and vertical directions [21].

As can be seen in Figure 4.1.

> **Bid:** The bid function is defined as an expectancy of $robot_i$ to opt for the $task_j$, see Figure 4.2. Consider a scenario of auctions, the clients ($robot_i$) bid on a specific item ($task_j$). If a $robot_i$ bid on a $task_j$, it does not guarantee that the $task_j$ is to be assigned to the $robot_i$. However, it provides an opportunity for the $robot_i$ to complete the $task_j$ [21].

4.5. Conclusions

In this Chapter are requirements and design parameters described which are considered to be useful for modelling parcel sortation system. Firstly existing AGVs are combined in three categories (6 kg, 32 kg and 70 kg) and its specifications averaged per category. The Routing process of the AGVs is controlled in a centralised manner by the robot control system. The scanning process of a parcel sortation system is described and set a constant time for each parcel the same.

The following design parameters are described: amount of AGVs, amount of charging points, drop-of point locations,amount of drop-of points, pick-up point locations and amount of pick-up points. The A* routing algorithm is selected with the use of MCA. For the task allocation process a marker-auction based algorithm is selection with the use of MCA.

5
Model characteristics

A model is made for evaluating the design parameters compared to the KPIs. To determine the value of a new system a prognoses of Life Cycle Cost (LCC) can be made [102]. Building a new system has several primary costs. It requires investment (acquisition cost), upkeep (maintenance cost) and energy consumption costs combined with facility space cost and personnel cost (operating cost).

5.1. Function based versus object based

The model can be made with the use of two programming paradigms, Object-Oriented Programming (OOP) and Functional Programming (FP) [103]. FP programs are constructed using functions and by avoiding changing the state. Computation is done by changing the environment, rewriting the function rather than changing the variables. OOP is built around "objects" these object may contain data, in the form of fields often referred to as attributes, and code, in the form of procedures often referred to as methods [104]. These objects are created by the programmer to represent something with the help of its attributes and methods. What kind of variables and functions an object should contain is defined in a class, which works like a blueprint for the object. For this model OOP is chosen for the reason that adding more components after setting up a general model is possible. For example the charging part of the AGVs can be an addition after the AGVs are programmed, making it more flexible to extend the model in later stages. As well as the program provided by the company VanRiet is Object-Oriented based.

5.2. Centralized control

The currently available AGVs (as can be found in Appendix C), which are using grid routing techniques, have a single centralized RCS. This means that the AGVs do have the ability to collect, drive and distribute parcels but do not have an own operating system to interact with the routing-path of other AGVs. Meaning the AGVs updates and communicates the location and the RCS does the routing for each AGV.

5.3. Model input

The model uses the following model characteristics and design parameters, as can be found in Figure 5.1. The model characteristics which are further described in this chapter. The design parameters: Amount of AGVs, charging points, drop-off points and pick-up points. Following the model will provide the space utilization, throughput $\frac{parcels}{hour}$, average rated load %, average rated load waiting time %, average empty load time %, average empty load waiting time %, average idle %, average service time parcels and average service time parcels.

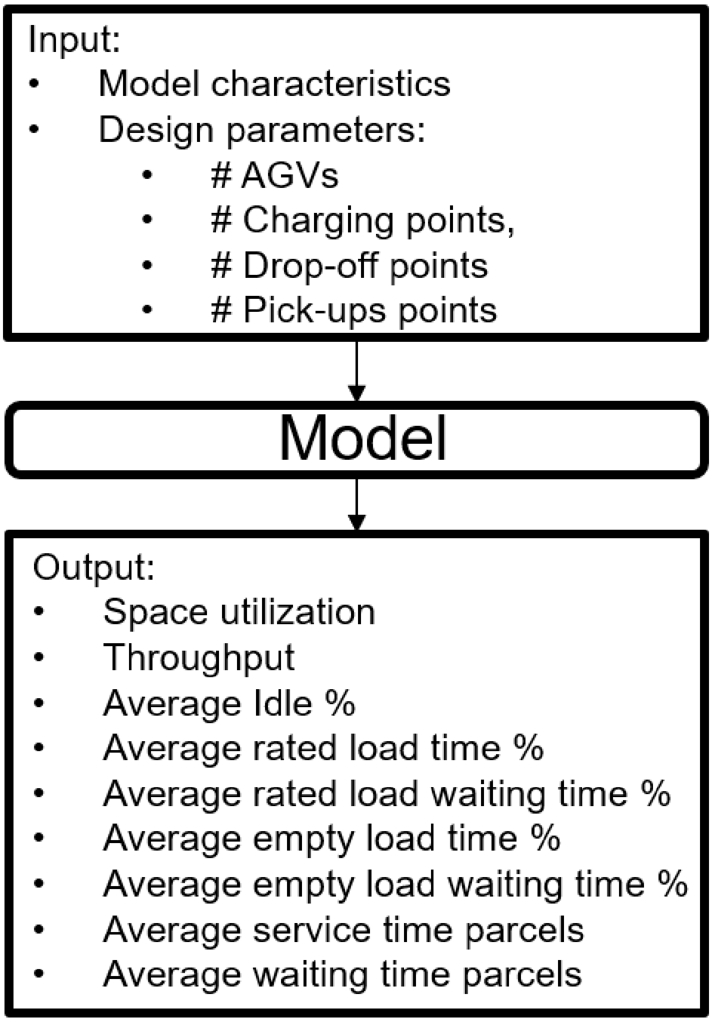


Figure 5.1: Model input and output

5.4. Model elements

The model is divided into several elements [105]. These are the AGVs (RCS), Parcel, Pick-up point, Drop-off point, Charging points and Waiting points. First the elements are described, then several constraints are given.

5.4.1. Modelling the AGVs

The AGVs have the specifications as described in subsection 4.1.1. The RCS is a centralized control unit which collects the updated data from the AGVs. These updates can be: Location, parcel collected, parcel delivered (job executed) and the battery status. The AGVs also update the empty load (no parcel on-top of the AGV) distance as the rated load (parcel on AGV) distance. These two are also update while the AGV is waiting, for instance in a queue or due to routing on cross-roads. The idle time (the AGV has no job) is updated. At last the charging time (AGV is connected to charging point) is updated. The dispatch of a parcel is estimated at 0.8 seconds (by the use of available AGV movies) [83] [84] [85] [86].

5.4.2. Modelling the parcels

Each parcel has a specific dimension (length, width, height) which, as can be seen in Table 2.1, could be limiting which AGVs can handle such a parcel. The model is simplified to set the dimensions of the whole parcel to the largest values of these three. The weight of a parcel influences which AGVs can handle a parcel. This model will use a parcel distribution set, which is confidential, with a distribution is parcel size and weight. No correlation is known and therefore a correlation of 85% is estimated. Hereby a short disclaimer: It is noted here that indeed the model will be somewhat an optimization of this distribution but the parcel distribution set is still used as it is likely to be more adequate to a real parcel sortation center. The model also registers the time the parcel is waiting to be collected from the pick-up point (as described in the next subsection) and the time it is on-top of an AGV, further described as service time.

5.4.3. Modelling the pick-up points

A Pick-up point is the location where a parcel is collected and placed on top of an AGV. This can either be done manually or mechanically for example by a robotic arm [106]. As for this model the simplification of this process will be as follows. Parcels are generated with a time interval of between 3 and 5 seconds, these are moved on a series of short conveyors with 1-D sensors. The parcel is added to the available parcels-list used for by the MFC. The sensors at the distributing side of the conveyor-line detect a parcel and can distribute when the AGV is ready underneath the conveyor, this is estimated at 1 second.

5.4.4. Modelling the drop-off points

The drop-off of a parcel is done by the AGV as described in subsection 3.4.2. This is for the model simplified by placing a (already available in the software program) small conveyor on top of the AGV. This conveyor does, like the tilting top examples, only distribute at one side of the AGV and therefore the distribution side of the AGV is still important in the RCS. The drop-off points will count the amount of passing parcels after-which the parcel information is put into the database and are deleted from the Scene as they otherwise consume computation power.

5.4.5. Modelling the charging points

The charge state of AGVs are modelled with discharging at a rate of 1 % is equal to $\frac{8\,[hours]\cdot 3600\,[seconds]}{100\,[\%]} = 288\,[\frac{seconds}{\%}]$. When an AGV is required to charge (explained in more detail in section 5.7) it will drive to the closest charging point. At which it rotates with the charging connection points towards the charger [91]. The charging is implemented at a charge rate of $\frac{1.5\,[hours]\cdot 3600\,[seconds]}{100\,[\%]} = 54\,[\frac{seconds}{\%}]$. The assumption is made that each AGV will charge 10% before leaving, if not forced to leave due to other circumstances, as otherwise AGVs will make many trips to the charging points reducing efficiency.

5.4.6. Modelling the waiting points

When an AGV has no reason for charging and no job available it will go to a waiting point, at which it remains till a job is available or charging is required. These waiting points are placed in close proximity of pick-up points where a job should come available.

5.4.7. Modelling constraints

Several constraints are determined for the model. A maximum of 1 parcel per AGV, as (most of) the currently available AGVs. A maximum of 1 AGV per node to prevent collisions. Parcel need to be dispatched before a new parcel is made available, FIFO per pick-up point. AGVs may not leave the designated area (e.g. drive off the map), as it is an AGV-only zone. AGVs are modelled to operate without any breakdowns. The amount of nodes is larger then amount of AGVs. As well as the amount of waiting point is equal or larger then the amount of AGVs. No negative values for the elements described above can be entered as values for the model.

5.5. Model output

After a simulation run is concluded the relevant data of the AGVs and parcels are exported to an Excel-file. This file is further analysed with the use of Matlab. The data is then put into tables and graphs. Examples of the data received from the model and converted into figures, per run, are displayed in Appendix D. For each run the throughput per hour is exactly calculated (amount of parcels delivered in that hour). As well as commonly used in the parcel industry is the average mean of parcels [107]. In Figure Appendix D.A are is the average mean displayed with intervals of 2,5,10,60 minutes. After 3.2 hours (3 hours 12 minutes) is the charging scheme activated which as can be seen leads to an reduction in the average throughput.

For each AGV is the time spend in the system split in the categories, see Figure 5.2: average empty load time (without parcel), average empty load waiting time (queueing and traffic), average rated load time (with parcel), average rated load waiting time (queueing and traffic), average idle time (waiting for a job on a waiting

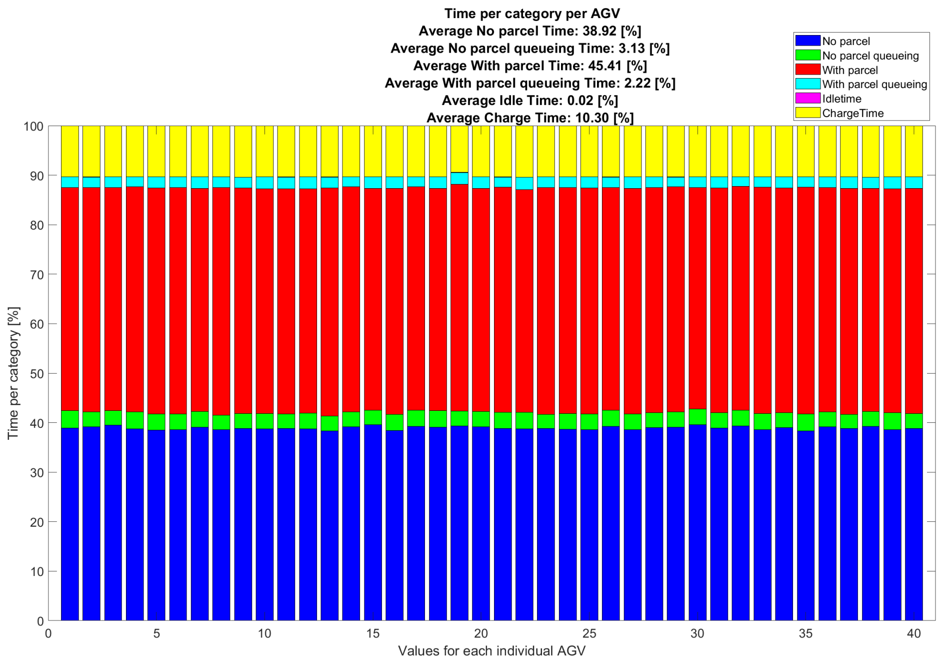


Figure 5.2: Example of 16 hour run, 40 AGVs difference is all waiting times

point) and charge time (standing on a charging point and charging).

In Figure Appendix D.B is the time to service a parcel from pick-up to the scanner and eventually the drop-off point displayed. The average time is calculated. Also several peaks can be seen, probably, from an AGV that was re-routed. In Figure Appendix D.C is the waiting time from the moment a parcel is created till the moment it is distributed onto an AGV for every parcel displayed. The average waiting time increases as more pick-up points are placed on the map with the same amount of AGVs.

In Figure Appendix D.D is the progress of the AGV charge state displayed. The values from the AGVs are combined into the AGV with the lowest charge (minimal-chargestate), the average of all AGVs and the currently highest charge (maximal-chargestate). These values are the same till the point the charging scheme is activated (3 hours 12 minutes).

5.6. Scheduling the AGVs

The RCS reserves an area for an AGV. This is called a node, as displayed in Figure 5.3, the complete surface is divided into nodes and in-total called a grid. The AGV drives on-top off the QR code where identification of its position is done and rotation is allowed. When an AGV moves forward the RCS checks if this node is not occupied and claims the node for this AGV. Therefore the AGV currently blocks 2 nodes until it leaves the previous node.

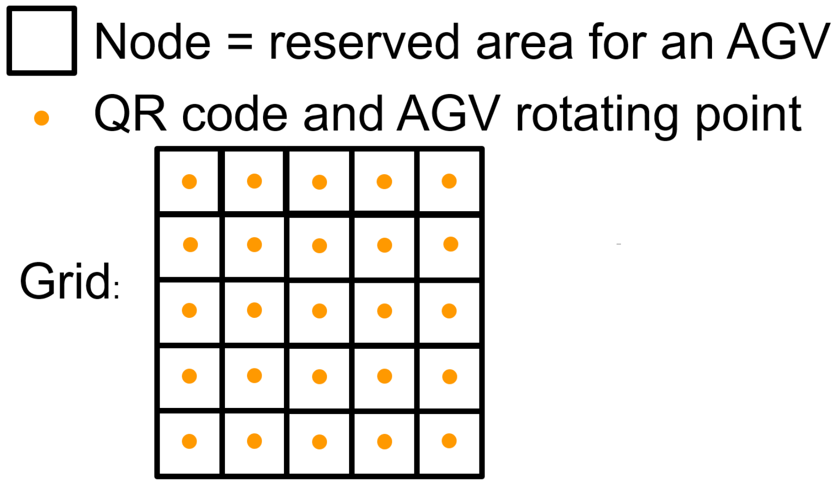


Figure 5.3: Representation of a grid

5.6.1. Collision prevention

AGVs are routed by the RCS, as such it should be able to prevent head-on collision, cross collision, node occupancy collision [49]. Head-on collisions (two AGVs near each other while coming in from opposite directions) are prevented by node allocation. One AGV is rerouted to its new shortest path and the other AGV shall resume its path when the node has been cleared. Cross collision, when an AGV hits another on the side, is prevented by node allocation. It is assumed that the model works and therefore node occupancy collision is taken care of as well. When 2 AGVs face the same direction no prevention is required, as it is most likely they are queueing to reach the same destination.

5.6.2. Deadlock prevention

Deadlock or even gridlock is not desirable in the model [108]. When at least 3 AGVs (in corners) or 4 AGVs (in a circle) are deadlocked a single AGV is rerouted, see Figure 5.4. This is done as well as for larger deadlocks is the following systematic approach. If an AGV is put to a hold due to an already claimed node, the RCS notes that this AGV is waiting for that node as well as the specific AGV and added to the possible-deadlock list. When the AGV reaches that node the AGV is removed from the possible-deadlock list. This list can contain a series of AGVs if a loop is made of AGVs referencing to each other a deadlock is made and an AGV is rerouted to prevent total deadlock.

5.7. Charging scheme for AGV battery process

As described in Section 3.1.5 are the batteries of the commonly used AGVs Lithium-ion batteries. This information is used to create a charging scheme as can be found in Table 5.1. The first 30% is slow charging and therefore no AGV will go and charge, though after the operations have finished the AGVs should be charged to 100% for maximum efficiency. For every run is assumed that the AGVs start with a 100% charge-state, this charging should be done in downtime and is for this research out of scope. The percentages given in the first column combined with the second column are just estimations as no research is found for these kinds of AGVs. For this research is the influence of charging in scope, though the optimization of such a charging scheme not. Therefore recommendations will be placed but, as long as this scheme is sufficient to run simulations (of 16 hours) without AGVs shutting down (due to lack of charge) the scheme is considered acceptable.

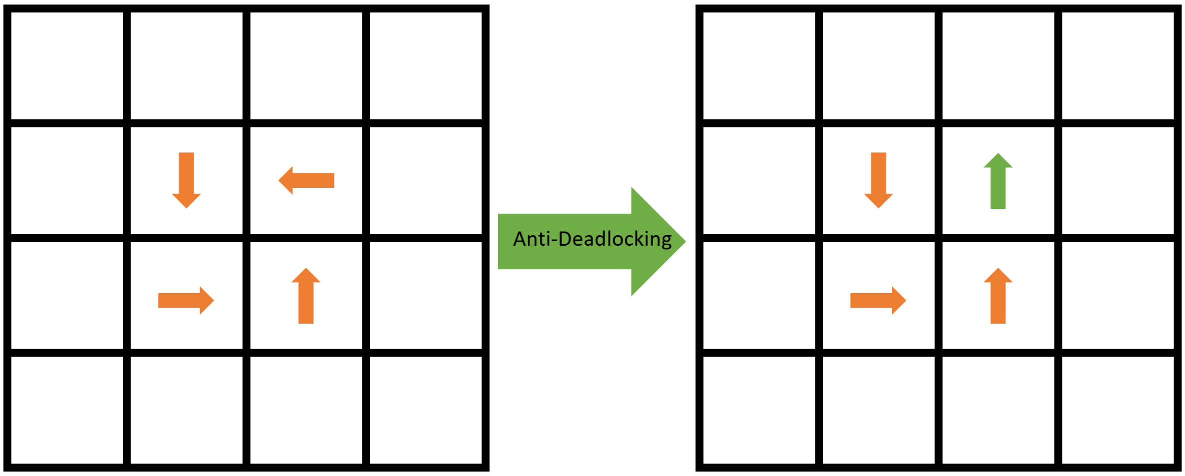


Figure 5.4: Example of anti-deadlocking

% Charge capacity	Only go charge if # of charge points are available	Rules
5 or less (Bare Minimum)	Always	No available: Kick AGV with highest charge, if all <15% kick highest charge
5-15 (Assign No Job)	Always	No available: Kick AGV with highest charge, if all <15% go to waiting point
15-25	>Truncate(0.20 * Total #)	Charge till at least 25%
25-40	>Truncate(0.40 * Total #)	
40-55	>Truncate(0.60 * Total #)	
55-60	>Truncate(0.75 * Total #)	
60-100 (not during operation)	Never	After operation (out of scope)

Table 5.1: Proposed charge scheme

When an AGV goes to charge it drives to the closest charging station, rotates in the correct position to connect with the charging connectors [84], and charges for 10% (see also 5.4.5) limited to 70%. AGVs which are running low on charge capacity will not be assigned new jobs. As well AGVs which are running on bare minimum charge capacity will go and charge neglecting eventual parcels on top of the AGV. The bare minimum percentage is added for an extra layer of protection to prevent stranded AGVs on the grid. When an AGV reaches bare minimum charge state, it triggers the RCS to find an available charging station. When no available charging station is found, the RCS kicks a currently charging AGV with the highest charge state.

5.8. Workflow robot control system

The RCS uses the following workflow for each AGV, as displayed in Figure 5.5. If an AGV is operational it is applicable for receiving a job. If a parcel is available, the charge state is sufficient, the AGV can handle the weight and size of the parcel and the AGV is the closest to the parcel the job (depending on task assignment) is assigned to this AGV. Unless the charge state drops below bare minimum charge state (as described in subsection 5.7) it drives and completes the job set for it.

The AGV drives to the pick-up point. The parcel is loaded onto the AGV, time passes. The AGV finds the closest scanner and scale combination from which the RCS receives the end-destination. The AGV is send to the drop-off point onto which it unloads the parcel, time passes. The AGV is set available for another job. If no (applicable) parcel-job is available the AGV will either go charge as described in Section 5.7, or drive towards a waiting point. This point will, according to the layout generator 6.3 be placed at strategic points. The AGV awaits a new job or will leave the waiting point (as time passes and the charge state decreases) to the charging point (not likely but a possibility).

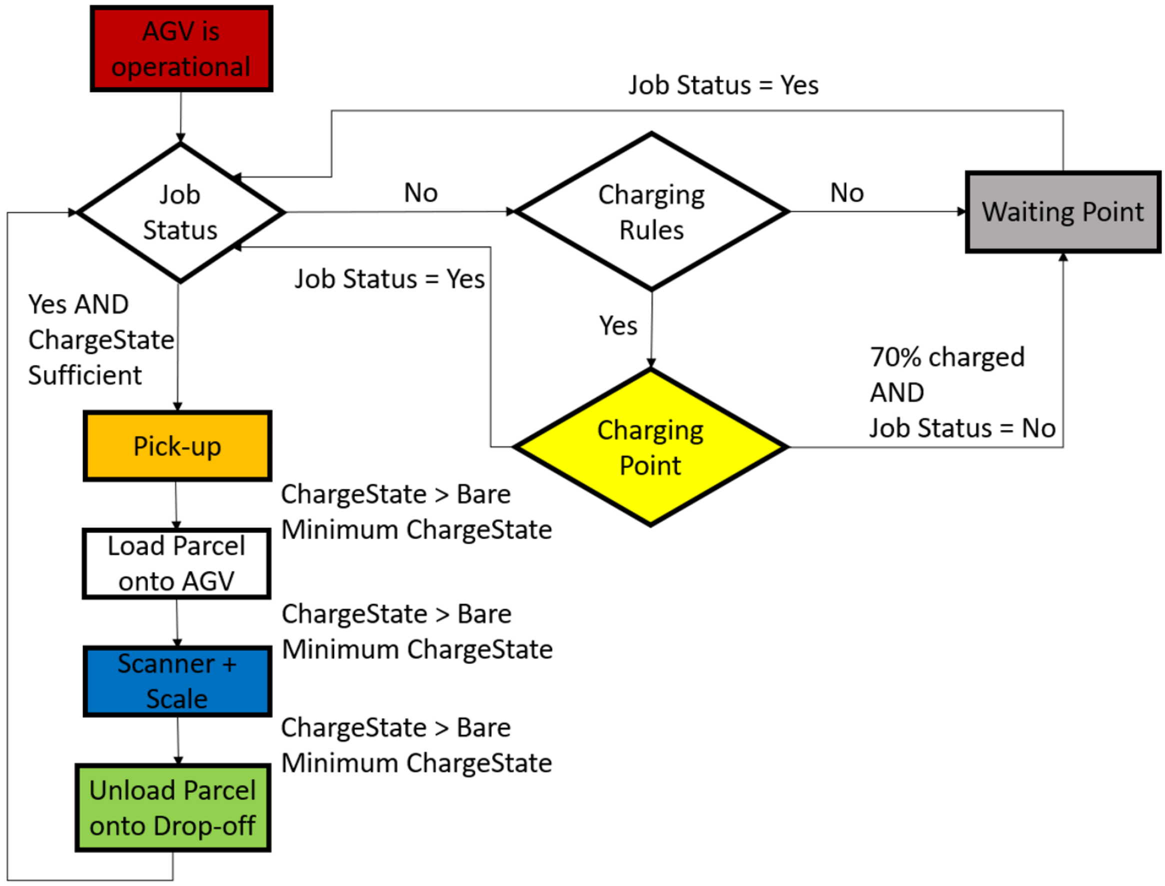


Figure 5.5: Workflow Robot Control System

5.9. Class diagram of the simulation model

A class diagram is made for the different classes used for the model. In Figure Appendix E.A are the different classes described with their attributes and operations, as can be found in subsection 5.4. As expected the RCS contains the largest part of the system. In Figure Appendix E.B are the additions specified for the sub-classes of the general Node. On a node is the accessible exit-direction visible and changeable.

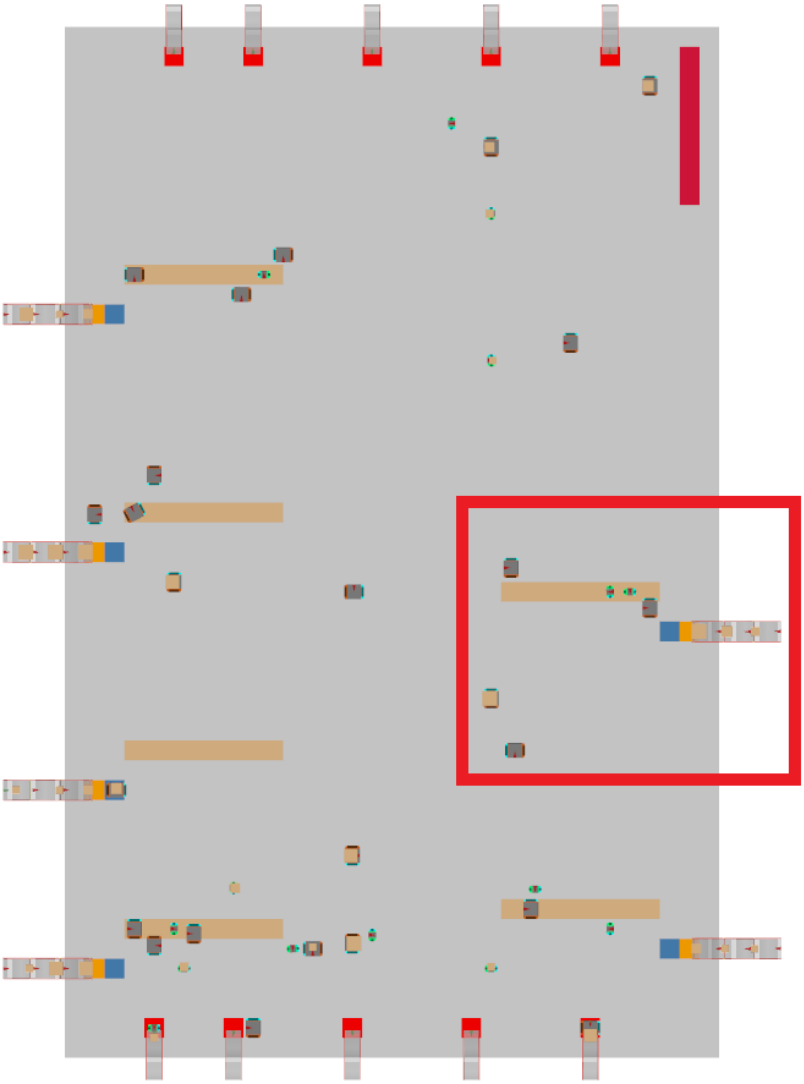
5.10. Multiple types of AGVs

The use of multiple AGV types on the same working area is considered. Two types of AGVs are used on the same area: 6 kg and 32 kg AGVs. The required claiming area of the larger AGV, for placement and rotation, leads to reduced amount of nodes on the map which could influence the routing possibilities, see Figure 5.6a. Also the 6 kg AGVs are unable to carry parcel heavier parcels exceeding the 6 kg payload as well as parcel dimensions larger then the estimated 0.4 m. This means the smaller AGV will have to wait on the waiting points till a larger AGV retrieves the (excessive) parcels in front of the suitable smaller parcel, see Figure 5.6b. Also the larger 32 kg AGVs will prefer these larger/heavier parcels to limit the queueing time of the 6 kg AGVs. The use of this combinations of AGVs could lead to reduced costs and quicker service-times for the smaller parcels.

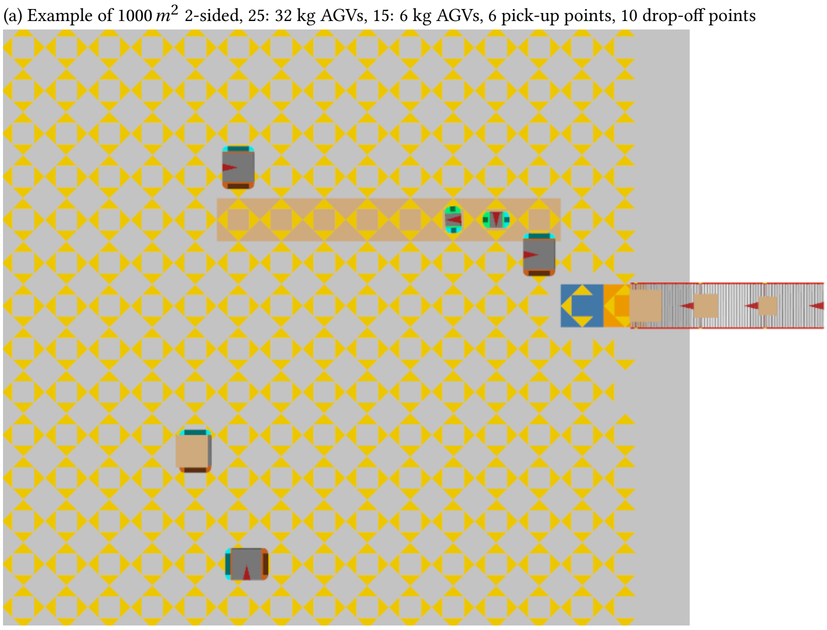
5.11. Conclusions

This Chapter explains model characteristics which are required to create an experiment to evaluate which design parameters are the most influential in terms of the Key Performance Indicators. The model uses an object based script in C#. It has a centralized controller which is referenced to as a robot control system. The model has several elements: AGVs, parcels, pick-up points (parcel retrieval points), drop-off points (parcel destinations), charging points (AGV charging), waiting points (parking places for AGVs without job) and modelling constraints.

The model has several graphs and values in terms of KPIs as output. This results in average time spend by all AGVs, without a parcel, queueing, with a parcel on top of the AGV, queueing with parcel, idle time without a job and charging time while standing on a charging point. The AGVs are scheduled with collision and deadlock prevention. A workflow and class diagram for the simulation is described.



(a) Example of 1000 m^2 2-sided, 25: 32 kg AGVs, 15: 6 kg AGVs, 6 pick-up points, 10 drop-off points



(b) Zoom-in with waiting 6 kg AGVs, pick-up points and waiting points

Figure 5.6: Example of a lay-out made by the lay-out generator

6
Experimental setup

In this chapter is the system setup explained. This is done with explanations of several model details. Followed by the lay-out generator which creates a map with a given amount of pick-up and drop-off points, AGVs, as well as the AGVs vs charging points ratio. After which the experimental plan is elaborated. First the experiments needed to select a feasible lay-out are explained. The feasible amount of drop-off points in ratio with the amount of pick-up points is required to select a normative amount of drop-off points. Thereafter the influence of chancing the amount of pick-up points and its influence on the throughput will be examined. Leading to the feasible amount of AGVs per charging point ratio. A test plan is used for verification. Also a sensitivity analysis is done. The two different cases are used for analysing scalability. A short investigation into using multiple types of AGVs on one map is discussed.

6.1. System setup

For the first tests is a small area selected to test several lay-outs as well as the influence of the amount of charging points, drop-off points and pick-up points. The lay-out of case 1 is chosen at 1000 m^2. The length is set at 40 m as the width therefore 25 m. The aim of this area is getting at least 1600 $\frac{parcels}{hour}$. After which a lay-out is chosen and used for another system setup.

Case 2 tries to match a known parcel center with publicly known parameters in size and throughput: DHL Express Austria [109]. These parameters are used as a benchmark to compare it with the use of AGVs on this specific area. The parcel center has an area of 9000 m^2 and inside an HC sorter is used which has a throughput of 6000 packages per hour [109]. In Figure 6.1 is the amount of outlets (estimation of 90) found, counting doors at the truck loading docks at the facility, with the use of Google Maps [22]. This area is used and lay-outs will be generated as described in Section 6.3.

For the parcel dimensions and weights is a realistic dataset (confidential) used. The specifics are included in Appendix F as they will be redacted from the publicly accessible report (after 2 years). The weight or length of parcels can limit the amount of applicable AGVs. This means less AGVs can pickup these parcels and waiting times can be increased.

Figure 6.1: DHL Express Austria Google Maps [22]

6.2. Model details

The model consist of AGVs, the RCS controls the routing of these AGVs. The AGVs, the representation is displayed in Figure 6.2, are driving around and update their locations to the RCS. The AGVs drive on nodes and in Figure 6.3 are the different functions of the nodes visualised. On the left is the pick-up point given. It generates parcels with different sizes and weights as described in 6.1. The left arrow is disabled and therefore the AGV can not pass in that direction (out of the map). The parcels are transported towards the right and if a sensor is blocked the system knows the parcel is ready for dispatch. The sensors on the left are added for queueing and can be multiplied to create more available parcels in the queue. The second is the standard node placed if no special node is required. The third is the scanner, which has a scanning time. This scanner can only be accessed from the pick-up point. An AGV standing on the scanner point can not exit backwards on the right side onto the pick-up point eliminating unexpected routing problems. By doing this the routing algorithm will not prefer to pass onto the scanning point if not necessary by the AGV. The fourth node is a waiting point strategically placed near the pick-up points. The fifth node is the charging point, the AGV can wait here while the battery charge is added over time, it is only accessible on one side due to the charging operation on most AGVs is one-directional. The node on the right is the drop-of point. It conveys the received parcels, it counts the passed parcels and estimates the parcel per hour (pph). As well as deletes the parcels at the end of the conveyor to reduce computation power.

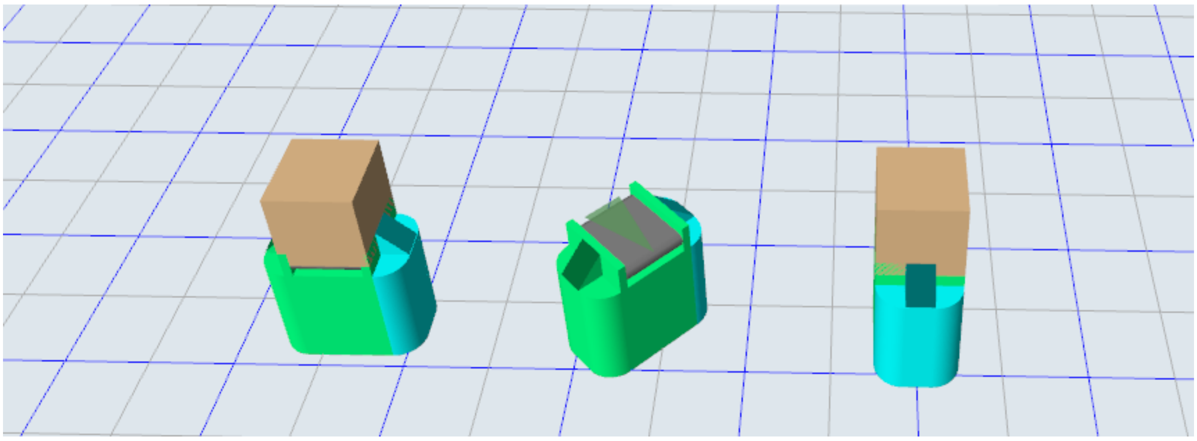


Figure 6.2: AGV representation, 6 kg AGV with parcel at maximal dimensions on top

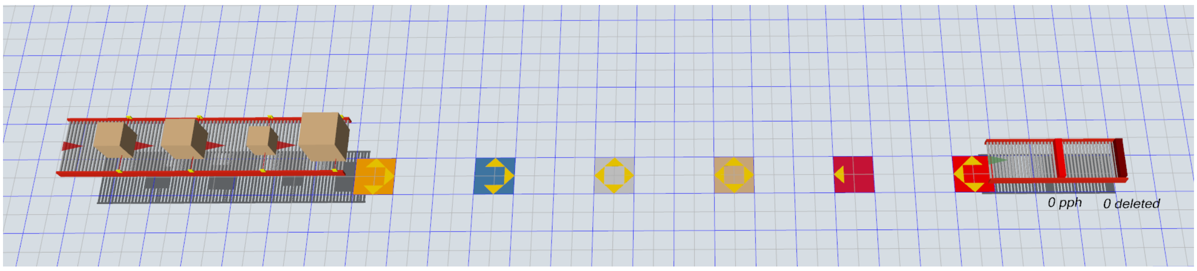
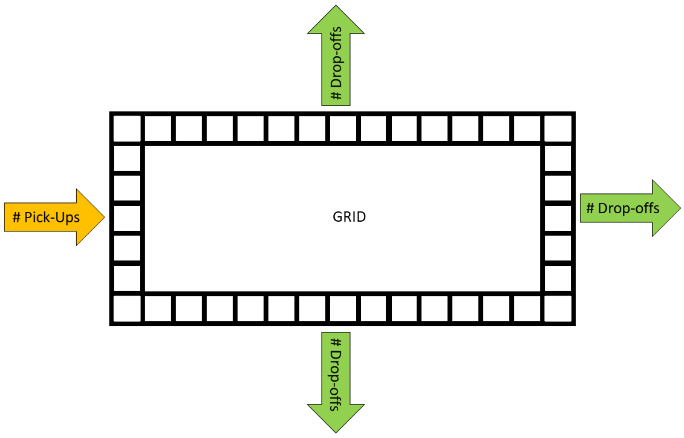


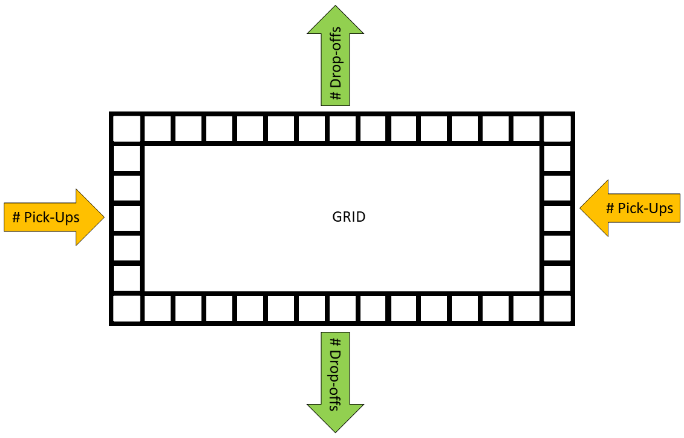
Figure 6.3: Node representation, Left to Right: Pick-up point, node, scanner point, waiting point, charging point, drop-off point

6.3. Lay-out generator

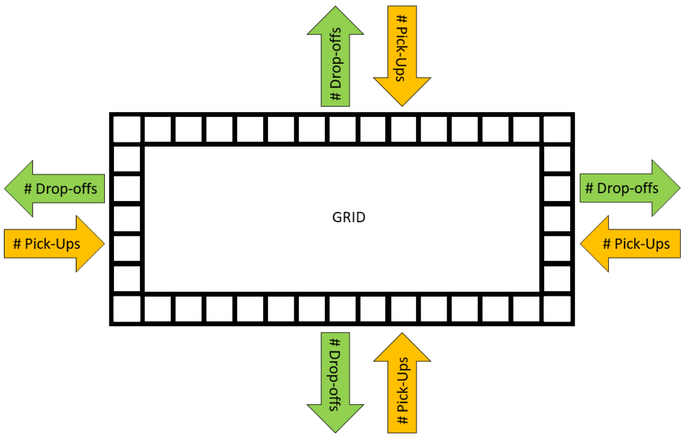
To test the influence of the locations of pick-up points and drop-off points on the map several locations need to be considered. As this report is no optimization, merely looking into the influence of the changes the exact location of each point is not required. Therefore three different lay-outs are proposed in Figure 6.4. These lay-outs differ in the location of the pick-up points on either 1 side (6.4a), 2 sides (6.4b) and 4 sides (6.4c) and the drop-off points respectively 3, 2 and 4 sides. These lay-outs are generated by the lay-out generator, in which the amount of pick-up points and drop-off points can be varied but are the equivalent amount when comparing the schemes. An example of such a lay-out can be seen in Figure 6.6.



(a) Pick-up Scheme 1: one-sided



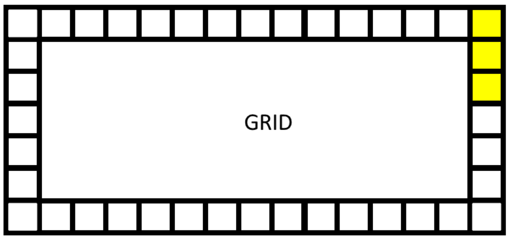
(b) Pick-up Scheme 2: two-sided



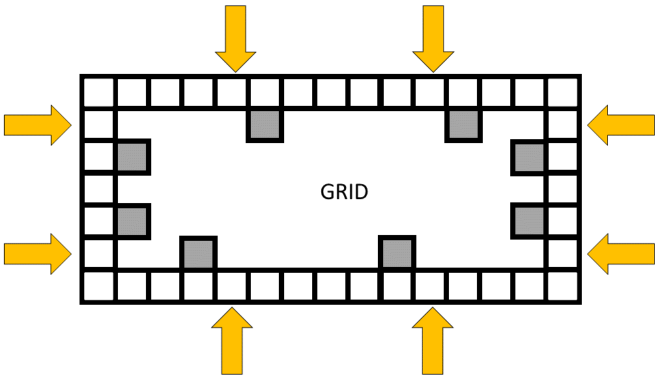
(c) Pick-up scheme 3: four-sided

Figure 6.4: Pick-up lay-outs with variables: # Pick-up Points, # Drop-off Points

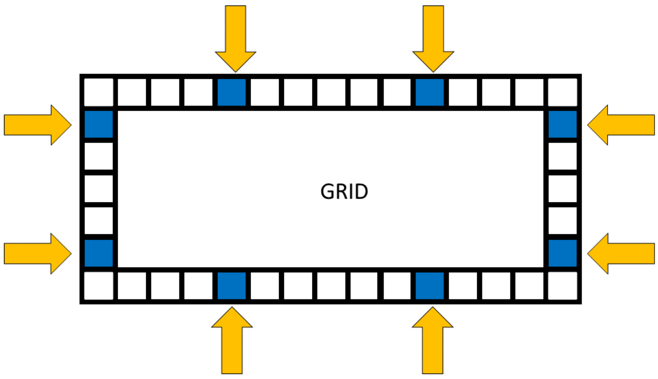
The placement of the charging points is set on the top right corner of the lay-out, see Figure 6.5a, this is done as the expected influence of the location is low as well as practicalities. The charging points need power access points and it is therefore not very practical to not place it near an edge. On optimization of a real system a smart location is of course required for the charging points but considered out of scope for this model. The waiting points are set close to the pick-up points, see Figure 6.5b, as it most likely a new job is available soon. The scanning and possible weighing of the parcels is done near the pick-up points, Figure 6.5c.



(a) Charging point locations: Variable # charging points



(b) Waiting point locations: # charging points equal to # AGVs

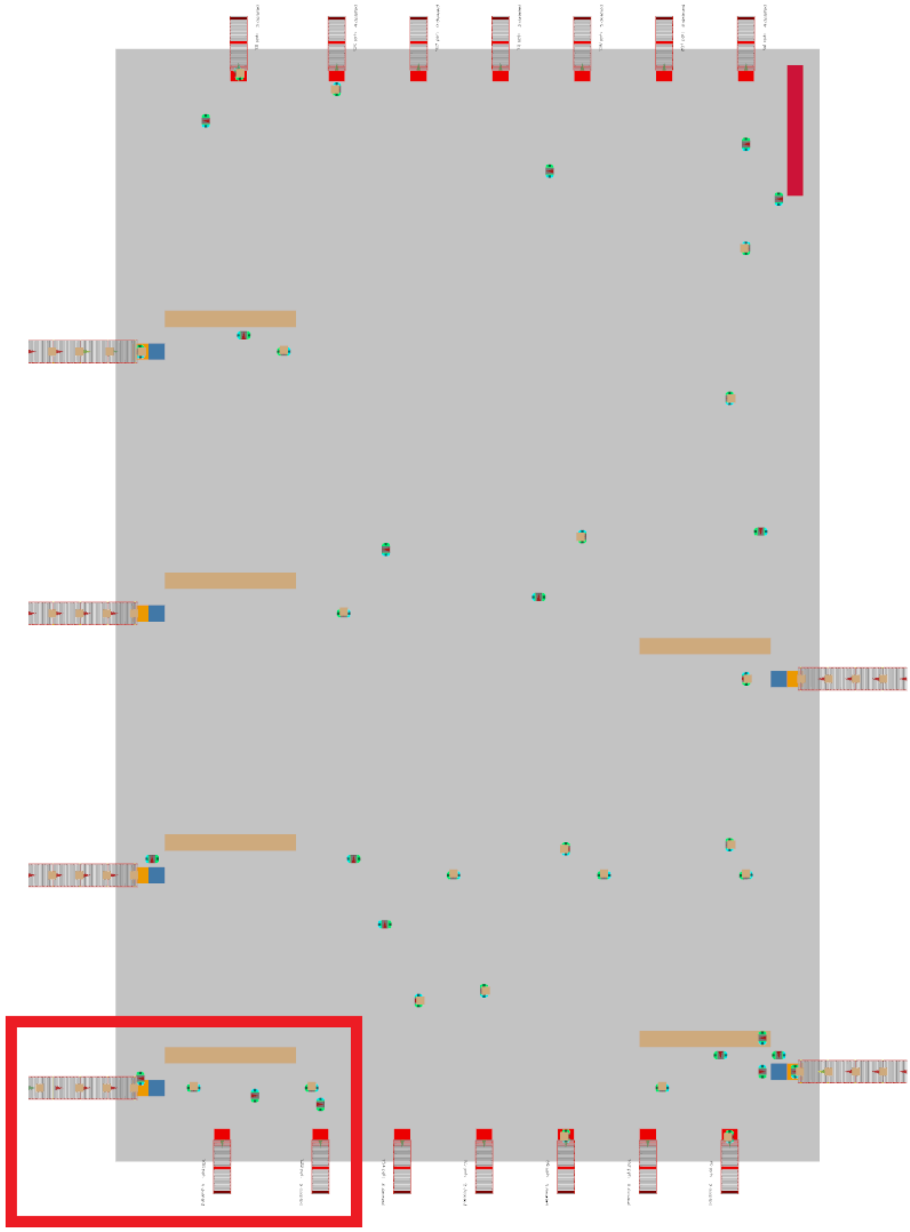


(c) Scanner/scale point locations: # scanning points equal to # pick-up points

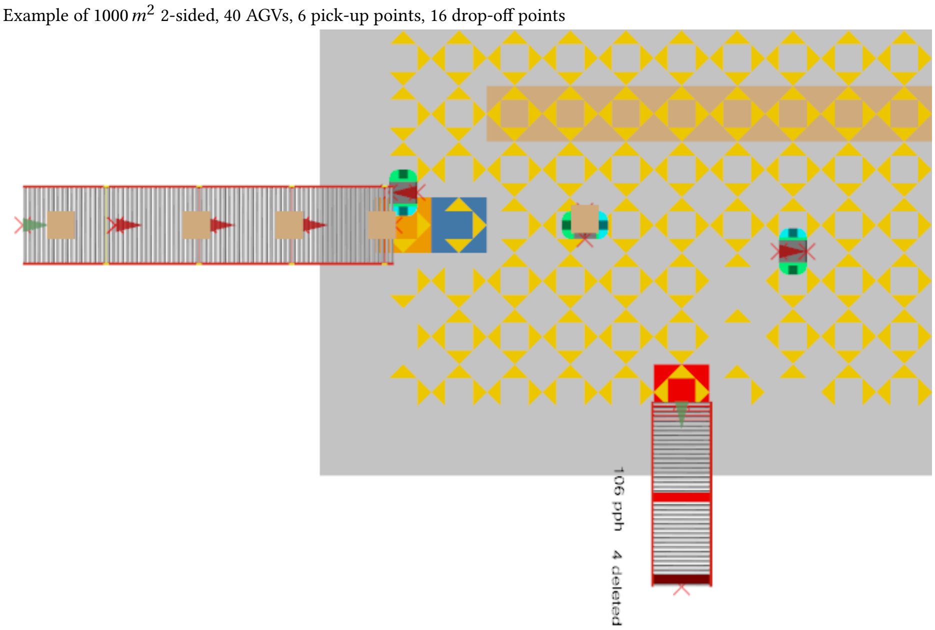
Figure 6.5: Lay-outs with locations of the charging points, waiting points and scanner/scale points

6.4. Verification: test plan

A test plan is made for verification of the model. The verification is separated in the following categories: AGV, Multi-AGV, Pick-up point, mapbuilder as well as for verification of the KPIs. In Table 6.1 are the verification steps noted and the boxes are ticked if they are verified.



(a) Example of 1000 m^2 2-sided, 40 AGVs, 6 pick-up points, 16 drop-off points



(b) Zoom-in with AGVs, pick-up points, waiting points, and drop-off points

Figure 6.6: Example of a lay-out made by the lay-out generator

Number	Category	Description	Expected Result	Obtained Result	Verified?
1	AGV	Set AGV Unload-Time to 10 seconds	Every time a parcel is distributed from the AGV	Every time a parcel is distributed from the AGV	Ok
2	AGV	Set AGV speed 20 m/s	Delivery time reduced, throughput increased	Delivery-Time reduced, throughput increased, Computation speed reduced more calculations required due to more moves/hour	Ok
3	AGV (KPI)	Set Charge Time 100x less	Charging is less influential for model	Less influence due to charging	Ok
4	Multi-AGV	Set 2 types of AGVs	Different parcel-reward scheme activates	Different parcel-reward scheme activates	Ok
5	Multi-AGV	Set 3 types of AGVs	Different parcel-reward scheme activates	Different parcel-reward scheme activates	Ok
6	Pick-up point	Set Throughput time 10 seconds	Every time a parcel is distributed from the pick-up point	Everytime a parcel is distributed from the pick-up point	Ok
7	Pick-up point (KPI)	Set parcel generation interval 50-99 seconds	Lots of waiting AGVs	Lots of waiting AGVs, waiting time increases	Ok
8	MapBuilder	Try every Scheme	Generation of lay-outs	Generation of lay-outs	Ok
9	MapBuilder	Increase Nodesize	Less nodes on same area	Less nodes on same area	Ok
10	MapBuilder	Increase amount of charging points versus AGVs rate	More charging points, more charging AGVs (see charging scheme)	More charging points, more charging AGVs, higher end charge after 16 hours	Ok
11	Empty load distance (KPI)	Set FiFo for job selection AGVs	AGV don't take into account distance and (could) travel further	Empty load distance increased	Ok

Table 6.1: Test plan for verification

6.5. Experimental plan

An experimental plan is made for the model to determine which options are suitable solutions. Firstly a feasible lay-out is determined. The three different lay-outs, described in section 6.3, are tested. After selecting a lay-out the influence of changing the ratio pick-up points and drop-off points is investigated. From these tests will come a suitable amount of drop-off points. After which this certain amount of drop-off points is used in the configuration to determine the influence of changing the amount of pick-up points. At last the influence of the ratio of charging points is investigated. This is done by adding more charging points with a fixed amount of AGVs. Investigated is the ability of the system to run for 16 hours. Also a comparison is made with AGVs with 1000 % charge state meaning no charging is necessary.

6.5.1. Feasible lay-out

The influence of the placement/locations of the pick-up points and drop-off points are evaluated. The difference in the amount of AGVs required to have at least (Case 1) 1600 $[\frac{parcels}{hour}]$, as well as the different averaged time the AGVs spend on parcel collecting, delivering and queueing. After this a comparison will be made with an equal amount of 40 AGVs to compare the differences in performance.

6.5.2. Feasible amount of drop-off points in ratio with the amount of pick-up points

The influence of the amount of pick-up points are evaluated. A single pick-up point could generate with a distribution of 3-5 seconds respectively 1200 $[\frac{parcels}{hour}]$ or 900 $[\frac{parcels}{hour}]$ or 720 $[\frac{parcels}{hour}]$. A simulation with a single pick-up point is done with sufficient AGVs to always have AGVs waiting at the pick-up point leads to 640 $[\frac{parcels}{hour}]$. This is due to the distribution time of parcels onto the AGV as well as the time required for the AGV to move into position on the pick-up location node. The required amount of pick-up points to operate with an amount of AGVs as well as the ratio between pick-up points and drop-off points is evaluated.

6.5.3. Feasible amount of pick-up points

After a sufficient amount of drop-off points is selected a range of pick-up points is investigated. With an increasing amount of AGVs the linearity of adding AGVs and the throughput is analysed. This is done with the use of the Matlab linear regression tool as well as the correlation coefficients [110].

6.5.4. Feasible amount of AGV charging points

The influence of the charging process is looked at with the use of the model. A run with the same lay-out (except varying the amount of charge points) and the same amount of AGVs is analysed. After which the ratio AGVs versus charging points is analysed through altering the ratio. It is noted here that the design of the charging scheme has influence on this, though this analysis will provide insight in the influence of charging AGVs as a whole.

6.6. Sensitivity analysis

A Sensitivity Analysis (SA) is done on the model [111]. This is used to analyse how different values of a set of independent variables affect a specific dependent variable under certain specific conditions [112]. The following analyses are considered to look at the influence of charging, the location and amount of pick-up points and drop-off points and adding AGVs. Most model runs are done for 3 hours as after 3 hours and 12 minutes (40 % charge at a discharge rate of 288 $[\frac{seconds}{\%}]$) the AGV charge scheme is activated. The start-up state of the model is quite short due to the close locations of the AGV to the pick-up points as well as the quick parcel generation times. Therefore it is assumed that the steady state is quickly achieved. The charging process is evaluated at simulation runs of 16 hours, which is equal to 2 full battery discharges (see Appendix C for average values for AGV battery's).

6.7. Case 1: $1000\,m^2$

A system with a $1000\,m^2$ lay-out is chosen. The length is set at $40\,m$ as the width therefore $25\,m$. The aim of this area is getting at least 1600 $\frac{parcels}{hour}$. Various design parameters are investigated. These lead by the differences in terms of lay-out, the ratio between pick-up points and drop-off points and the influence on pick-up points with a sufficient amount of drop-off points. As well as the charging of AGVs. An analysis looks at the influence of a varying 2,4,6,8,10,12 pick-up points and 2,4,6,8,10,12,14,16 drop-off points.

6.8. Case 2: 3000 m^2

The scalability of an AGV parcel sortation center is evaluated by the use of a 3 times larger system: 3000 m^2. The length is set at 40 m as the width therefore 75 m. The system should be capable of a throughput of 6000 packages per hour as described in section 6.1. An analysis looks at the influence of a varying 10,12,14,16,18,20 pick-up points and 10,15,20,25,30 drop-off points.

6.9. Multiple types of AGVs (6 kg and 32 kg)

Two types of AGVs are used on the same area: 6 kg and 32 kg AGVs. The use of the 6 kg and 32 kg AGVs on 1 grid implies that the nodesize is increased to the estimated size of $0.8m$ to being able to fit and rotate each AGV on a specific claimed area of $0.8 \cdot 0.8 = 0.64m^2$. This means to less nodes on the same area as if only 6 kg AGVs are used. The parcel weight can limit the collection of the parcel itself to 32 kg AGVs. As well as the dimensions of the parcel could limit the collection of the parcel to only 32 kg AGVs. As smaller 6 kg AGVs are not allowed to collect the oversized/heavy parcels they wait in front of the pick-up points till a 32 kg AGV(s) collects the parcel(s) in front of the 6 kg parcel.

6.10. Conclusions

In this chapter are 3 different lay-outs explained. Theses are generated by the lay-out generator which uses the same amount of pick-up points and drop-off points but a change from location of these points. The first lay-out (one-sided) has only pick-up points on the left side and drop-off points on the other three sides. The second lay-out (two-sided) has pick-up points on the left and right side and drop-off points on the other top and down side. The third lay-out (four-sided) has pick-up points and drop-off points on all sides.

A test plan for verification is described as well as the sensitivity analysis. Two cases are instigated an area of 1000 m^2 and 3000 m^2. An experimental plan is made which firstly looks at the influence of the placement of pick-up points with the use of the lay-out generator. After which a selection of experiments is done to determine an efficient amount of drop-off points. With the proper amount of drop-off points the difference due to the changing amount of pick-up points is investigated. Furthermore the charging process of AGVs investigated to be able to run all AGVs for a simulation of 16 hours.

7

Experiments and results

In this Chapter are the experiments and its results explained. First the model input are summed up. After which the model outputs are described as well as the several graphs and table results. The system setup is further explained which are used for the tests cases with a total area of 1000 m^2 and 3000 m^2. Afterwards several model details are presented. The cases and their results are explained with help of graphs and tables.

7.1. Case 1: 1000 m^2

In this section are several test conducted at the hand of an sensitivity analysis (see also section 6.6).

7.1.1. Feasible lay-out: Amount of AGVs to achieve > 1600 parcel/hour per lay-out

First several tests are done in the placement of the pick-up points and drop-off points. A run is tested with 6 pick-up points, 16 drop-off points and at least a throughput of 1600 parcels per hour. The difference in several values are put into Table 7.1 and the difference in waiting times are displayed in Figure 7.1. Noticeable is the average delivery/service time of the parcels by the AGVs is roughly the same for the 2-sided and 4-sided lay-out. The distance required for the AGVs to travel empty to collect a new parcel is reduced. This can also be seen in Figure 7.1 as the rated load time increases and empty load time decreases. Though both waiting times increases as probably more queueing is done during the run. The data is displayed in Table 7.1. The highest: average throughput, average rated load time highlighted in green. As well as the best/lowest values: average service time per parcel, average waiting time per parcel and average distance travelled per AGV, highlighted in green.

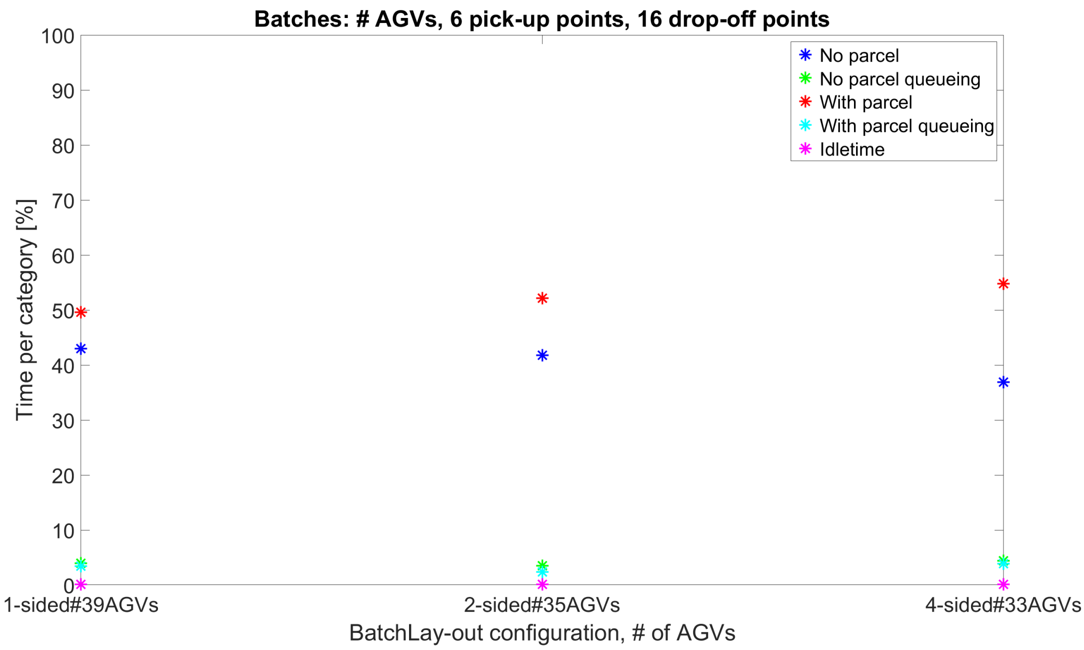


Figure 7.1: > 1600 parcel/hour per lay-out

Scheme	**1-sided**	**2-sided**	**4-sided**
# AGVs	39	35	33
Average throughput [parcels/hour]	1613	1629	1621
Average rated load distance [%]	55.99	58.92	64.72
Average service time per parcel [s]	45.82	42.26	42.92
Average waiting time per parcel [s]	48.00	47.74	47.97
Average distance travelled per AGV [km]	7.33	7.56	6.88
Total distance travelled [km]	285.87	264.6	227.04

Table 7.1: # AGVs with at least 1600 parcel/hour

Differences due to lay-outs differences with 40 AGVs

As the 1600 $\frac{parcels}{hour}$ barrier is crossed with at least 39 AGVs, another test run is done with the use of 40 AGVs to display the differences in the lay-out choices. In Figure 7.2 are 3 simulations displayed. These three different simulations are set out on the x-axis, either 1-sided, 2 sided or 4-sided. For each run the time spend by the collection of AGVs is averaged. The amount of time the AGVs spend driving around without a parcel is displayed in **dark-blue**. In the color **green** is the time without a parcel and in queues or re-routing time displayed. This includes queueing and waiting at the pick-up points which is quite likely to happen. In **magenta** is the time spend with a parcel on-top of the AGVs displayed. The aim of the task allocation algorithm is increasing the efficiency and therefore the higher values for the magenta. The routing algorithm works to reduce queueing, though it is inevitable when few drop-off points are available (**Cyan**). When no job is available the AGVs spend time on the waiting points and are therefore idle (**Pink**). Not displayed here but the time spend by the AGV on the charging point will be displayed for 16 hours simulations (**Yellow**). Mind here that all AGVs start with 100 % charge state and after 3 hours and 12 minutes charging is possible, see also section 5.7. Concluding in Figure 7.2 can be seen that the reduced distance between delivering a parcel and collecting a new parcel is slightly increasing the rated load efficiency but also increasing queueing.

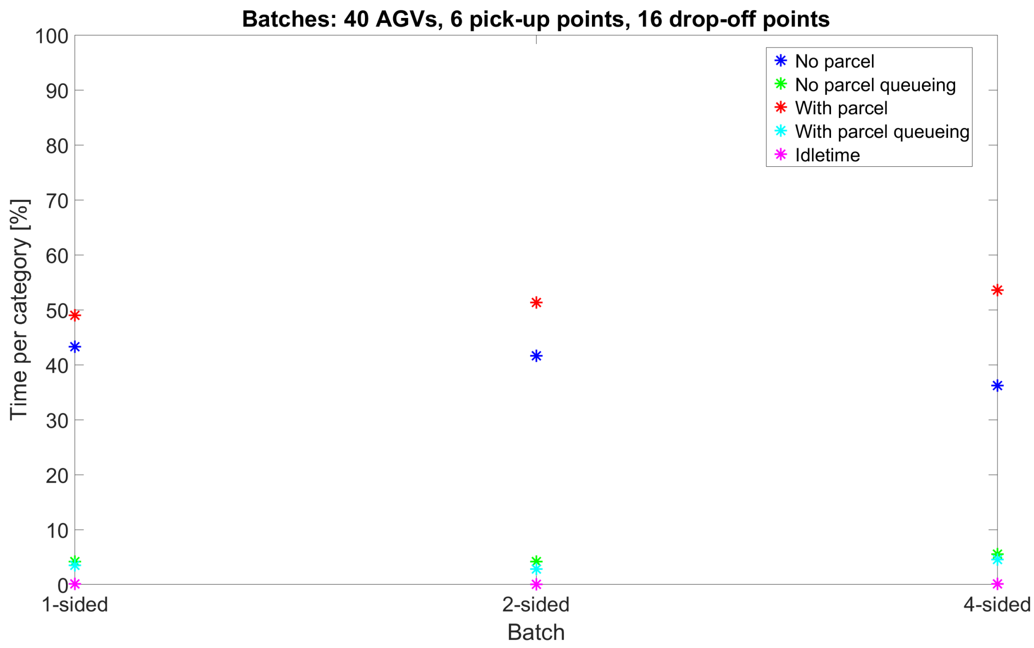


Figure 7.2: Time per category for 40 AGVs per lay-out

In Table 7.2 are the values highlighted which are considered the best of the three options, as explained above. A large gap between 1-sided and the other two is found. Therefore now is looked at the differences between 2-sided and 4-sided. The four-sided lay-out scheme is slightly more efficient due to less distance between pick-up points and drop-off points. Though the implementation in a real factory might limit this option. This is due to the build of these kind of buildings with on the one side, loading/unloading -bays of larger trucks and loading/unloading smaller delivery vans. As well as the implementation of the loading positions of the pick-up points might be more challenging to do it on all four-sides. Therefore the 2-sided scheme is further used in these experiments, but it is duly noted that increased efficiency could be made with optimizing lay-outs.

Findings: A 2-sided or even 4-sided lay-out significantly increases efficiency compared to a 1-sided lay-out. The throughput of a 40 AGVs system increase with a 9.32 % 2-sided and a 4-sided lay-out with 12.52 % due to less distance to travel for the AGVs to collect a new parcel after dispatching a parcel.

Scheme	1-sided	2-sided	4-sided
# AGVs	40	40	40
Average throughput [parcels/hour]	1663	1834	1901
Average rated load distance [%]	55.5	58.5	64.3
Average service time per parcel [s]	46.6	41.8	40.2
Average waiting time per parcel [s]	45.4	42.5	44.1
Average distance travelled per AGV [km]	7.32	7.50	6.74
Average distance travelled per job-cycle [m]	176.08	163.44	141.83

Table 7.2: Outputs difference due to different lay-out schemes

7.1.2. Feasible amount of drop-off points: differences due to ratio of drop-off points and pick-up points

The amount of drop-off points is varied in a set of 40 AGVs and 2,4,6,8,10,12,14,16 drop-off points and 2,4,6,8,10 pick-up points. These are displayed in Figure 7.3. Subplot 1 displays that the 2 pick-up points are insufficient to sustain the amount of AGVs, a lot of idle time (KPI), though a trend of more drop-off points, more rated rated distance is still seen. in Subplot 2 the waiting time as well as the empty load time is quite noticeable from 2 till 10 drop-off points. While looking at all Subplots, 2 drop-off points give a lot of waiting time due to queueing at the drop-off point.

When increasing the amount of drop-off points the distance between two points decrease. Therefore more re-routing/queueing could be happening, especially with the quickly retrieved parcels due to the 8 and 10 pick-up points. The ratio 12 drop-off points or more with 4 pick-up points till 10 pick-up points and 16 drop-off points are (roughly) sufficient to have no delays due to these parameters. In Figure 7.4 is the throughput given in a bar plot as the throughput varies quite a lot per simulation run. Again especially the 6,8,10 pick-up points thrive with 4 till 10 drop-off points.

Findings: Using two drop-off points are inefficient due to queueing at the drop-off points. This also occurs with 4 pick-up points and less then 11 drop-off points. With additional drop-off points comes less spacing between the drop-off locations, this leads to more queueing and re-routing. Though for 6 pick-up points a total of between 4 and 16 drop-off points is efficient for this parcel sortation center.

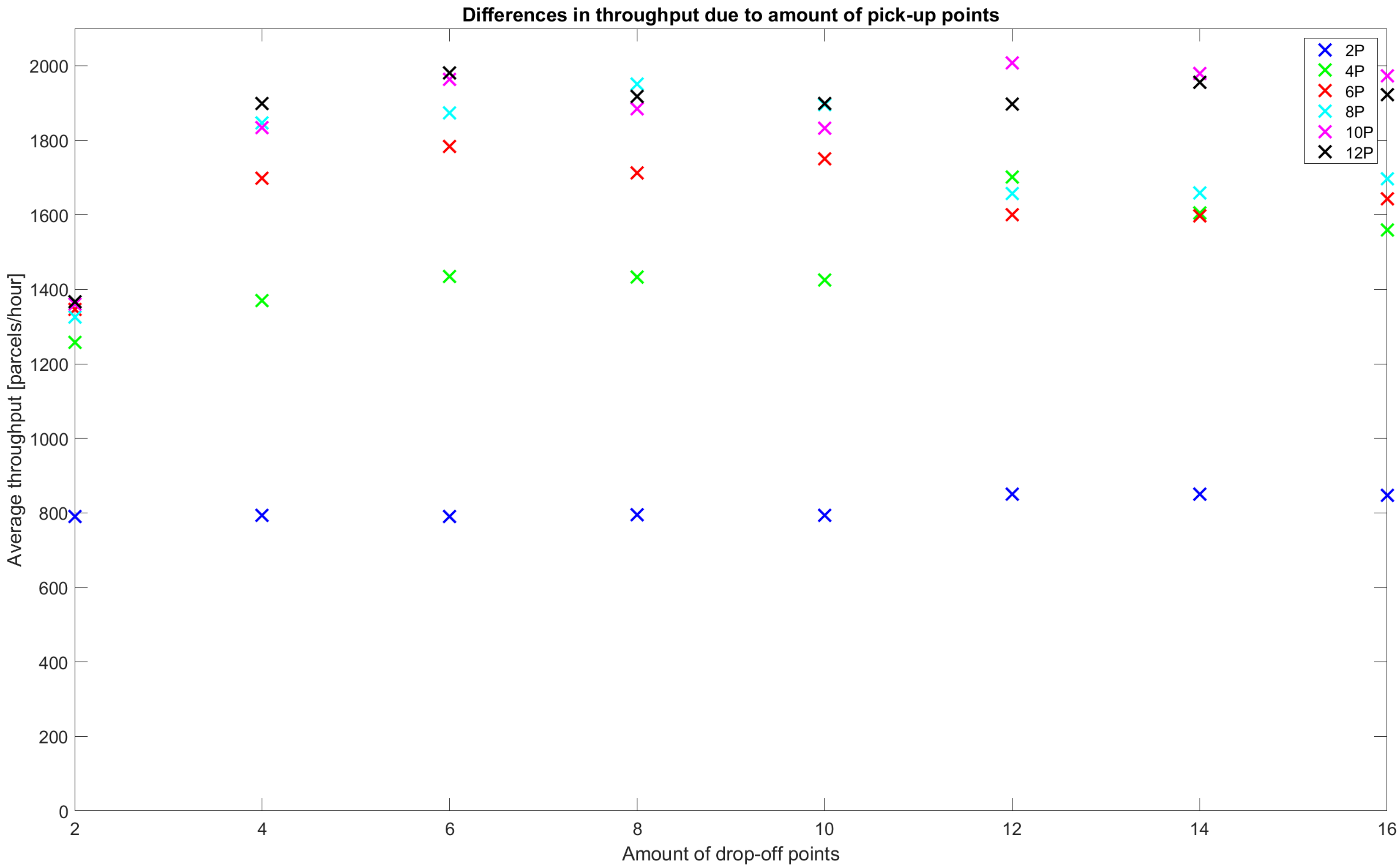


Figure 7.3: Differences due to different # of drop-off points

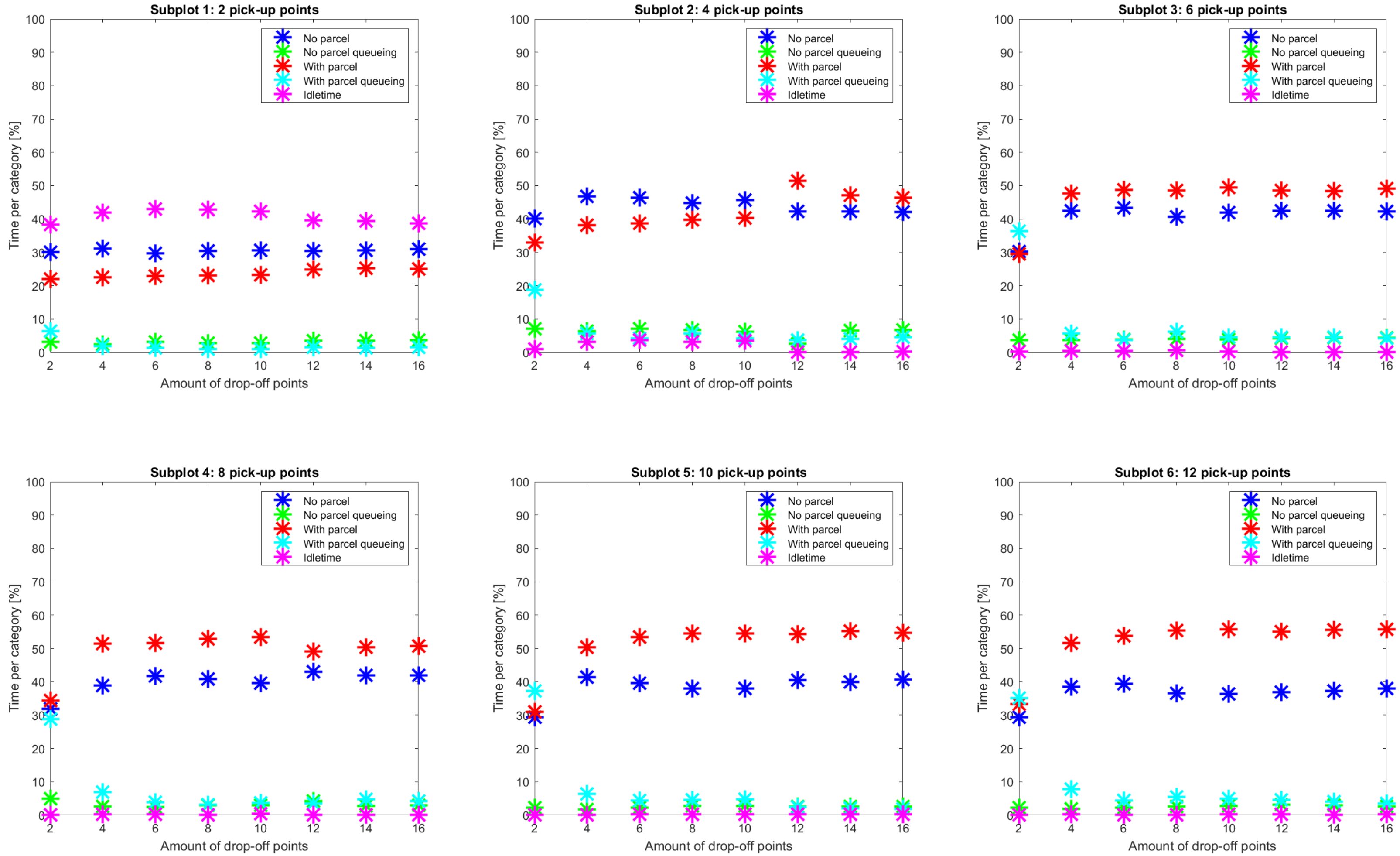


Figure 7.4: Differences in throughput due to different # of drop-off points

7.1.3. Feasible amount of pick-up points: influence on throughput due to amount of pick-up points

In Figure 7.5 is the influence of the increasing amount of AGVs from 5-80 with steps of 5 AGVs displayed. This is in combination with the amount of: 2,4,6,8,10 and 12 pick-up points. As can be seen in Subplot 1 onwards from the amount of 30 AGVs the 2 pick-up points do not provide enough parcels to stipulate the request of AGVs, to much idle time. The figure displays an increase of rated load time when more pick-up points are available. It also shows the increasing queueing with more AGVs on the map. In Subplot 2 is from 55 AGVs to much idle time. In subplot 3 the idle time increases from 60 AGVs as well as a reduction in rated load time is visible. In Subplot 4, due to queueing, the waiting time (no parcel as well as with parcel) leads to reduction in efficiency from 60 AGVs. In Subplot 5, due to queueing, from 75 AGVs efficiency is reducing. In Subplot 6 an increase in queueing is noted. Though 10 as well as 12 pick-up points are still the best options.

In Figure 7.6 are the linearity estimations with corresponding coefficient of determination given in the legend (R^2). The following formula is used to find linearity: Linear model $p_1 \cdot x + p_2$ and the coefficients (with 95% confidence bounds) are given in the list below. For each set of pick-up points is linearity given. It is concluded that the data set 12 pick-up points is completely linear with 99.021 % certainty. The 10P and 12P have an average increased throughput of 43.02 $\frac{parcels}{hour}$ per AGV. As the overall average is 42.44 $\frac{parcels}{hour}$ per AGV.

Findings: To have a functioning system of 55 AGVs 8 pick-up points or more are required. Increasing from 50 AGVs 10 or even 12 pick-up points is advisable on such a relatively small area. An average of 42.44 parcel per hour per AGV is possible.

- 2 Pick-up points: p_1 = 39.62 (36.17, 43.07) & p_2 = 37.7 (-19.48, 94.88)
- 4 Pick-up points: p_1 = 40.59 (38.64, 42.55) & p_2 = 97.87 (37.25, 158.5)
- 6 Pick-up points: p_1 = 42.83 (41.28, 44.39) & p_2 = 98.24 (45.51, 151)
- 8 Pick-up points: p_1 = 45.55 (43.7, 47.41) & p_2 = 73.91 (16.3, 131.5)
- 10 Pick-up points: p_1 = 44.54 (42.41, 46.67) & p_2 = 119.4 (34.87, 203.8)
- 12 Pick-up points: p_1 = 41.49 (39.12, 43.85) & p_2 = 200.3 (85.98, 314.7)

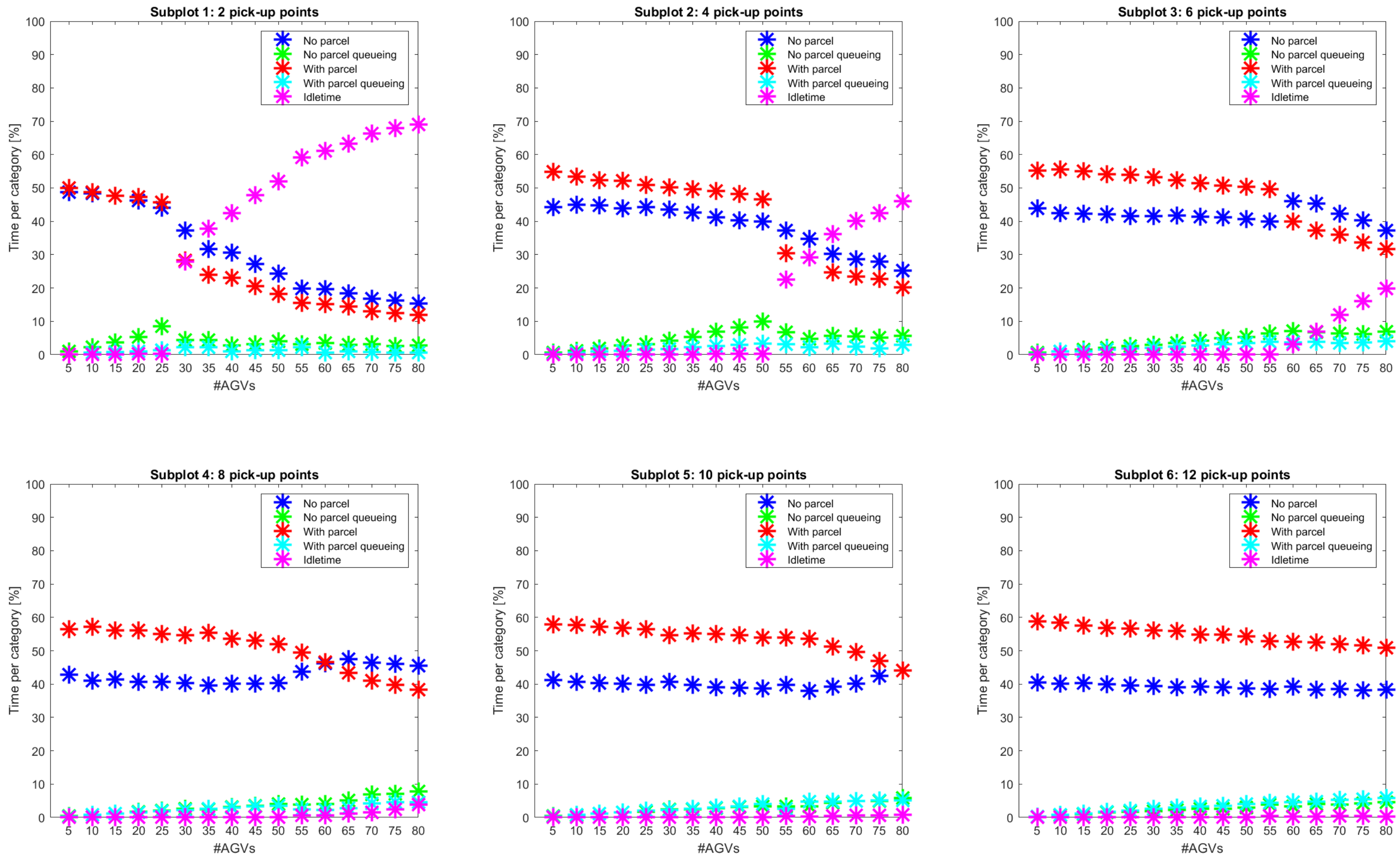


Figure 7.5: Influence pick-up points on time per category with 2,4,6,8,10,12 pick-up points

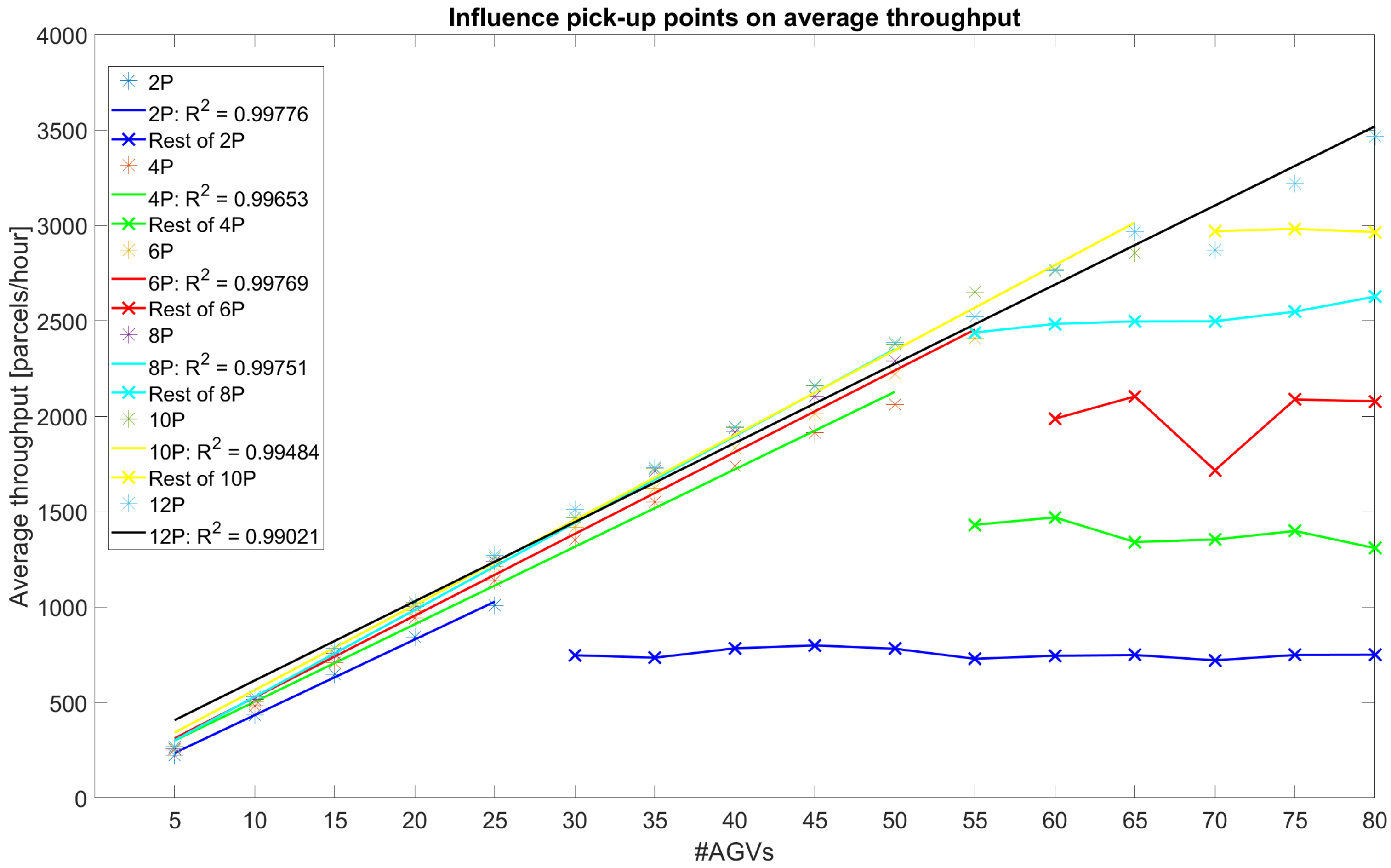


Figure 7.6: Influence pick-up points on throughput, maximum of 80 AGVs

7.1.4. Charging process: Influence of charging and ratio AGVs versus charging points

The differences due to the charging process can be seen in Figure 7.7. All runs are on the same map with the difference of additional charging points. The first run has the charging process disabled by setting the charging level of the AGVs to 1000% instead of 100% hereby the charging scheme is not activated. The simulations with 40 AGVs and with less than 6 charging points the AGVs crashed due to insufficient charge of the AGVs. As can be seen in Figure 7.7 the throughput of 0-5 charging points crashes to zero at times between 8 hours (the AGV capacity of 1 full run) and 11.8 hours with 5 charging points. This Figure also displays the difference between 1000% charge and the charging scheme start from 3 hours and 12 minutes as the charging is activated.

In Figure 7.8 is the averaged charge state of all AGVs displayed. The 1000% charge is displayed as a line of 100% to alter the scale of the Figure to be between 0% and 100 %. From the moment of 3 hours and 12 minutes a difference in average charge state can be seen. As no charging points leads to a simulation of 8 hours and 1-5 charging points slowly the average reaches zero as one for one the AGVs have insufficient charge to drive. The simulation with 6 charging points is significantly reaching zero and is not likely to last a long period off time after 16 hours (16.4 hours to be exact).

The differences in values between the runs are displayed in Table 7.3 and in percentages Table 7.4. Also the simulation with 6 charging points had an average of 6.73 charge state, which meant that a lot of AGVs had reached their bare minimum charge state and the kicking process of the AGV charging scheme was activated many times. Probably not the most efficient way and therefore at least 7 charging points, with a ratio of 5.71, are required to make an efficient run, see Figure Appendix G.B.

Several other insights are gathered by these Tables. Due to less operating AGVs (standing still on the charge points) the throughput decreases with increasing the amount of charge points (as well as due to the charging scheme). As less AGVs are in conflict with each other less re-routing/more optimal paths are travelled (distance travelled per job-cycle decreases), this increases the rated load distance. Hereby a faster service time is observed. In contrast with the waiting time for the parcels which significantly increases. As can be seen from the last row of Table 7.3 more then 8 pick-up points lead to a charge state above 30% and while still decreasing in other aspects.

Findings: A system could run for 16 hours with an AGVs versus charging points ratio of 6.67 but advisable is at least 5.71. Due to the need of charging a decrease of at least 7.54 % in throughput is measured.

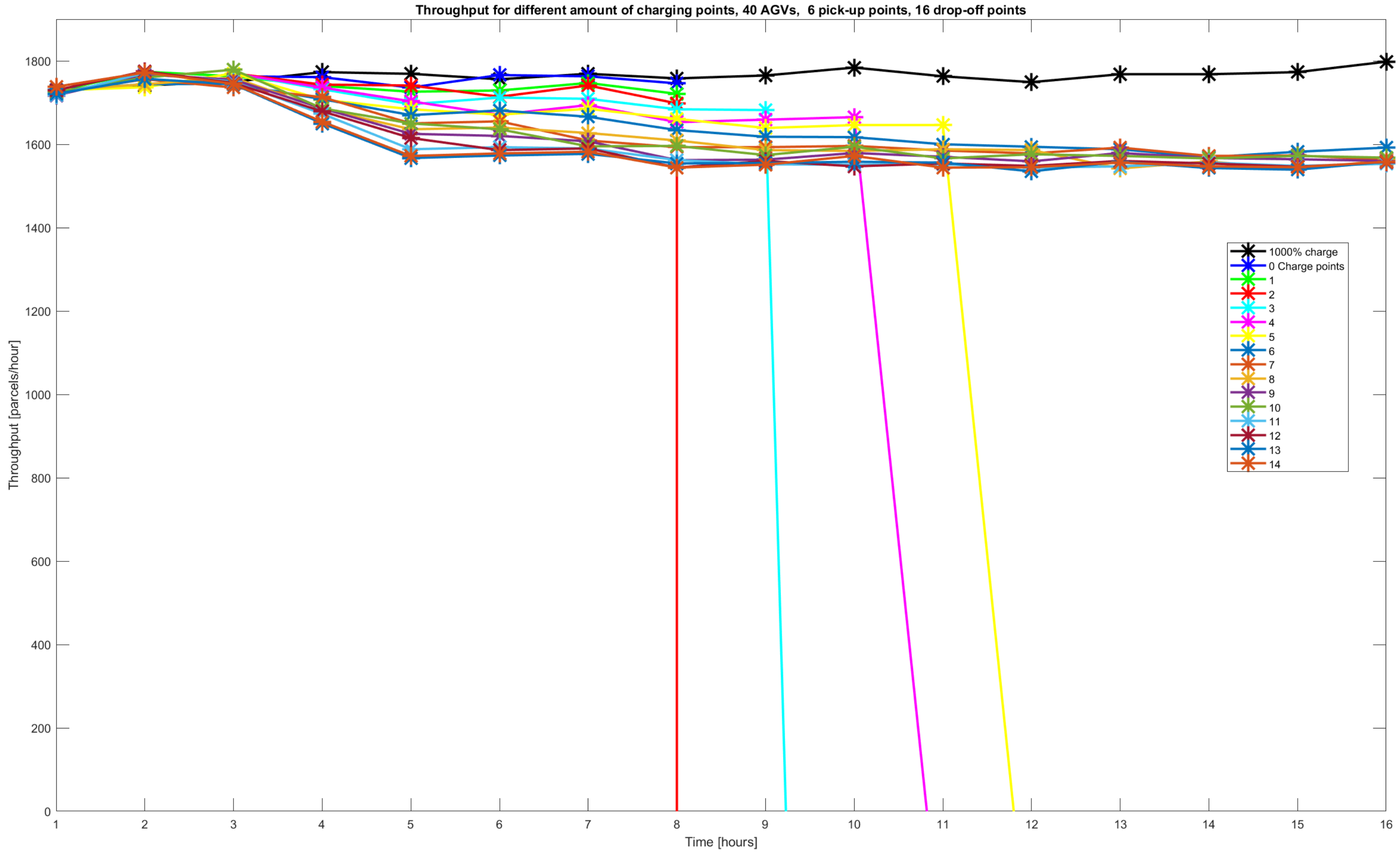


Figure 7.7: 40 AGVs, throughput of no charging versus increasing amount of charging points, 16 hours runs

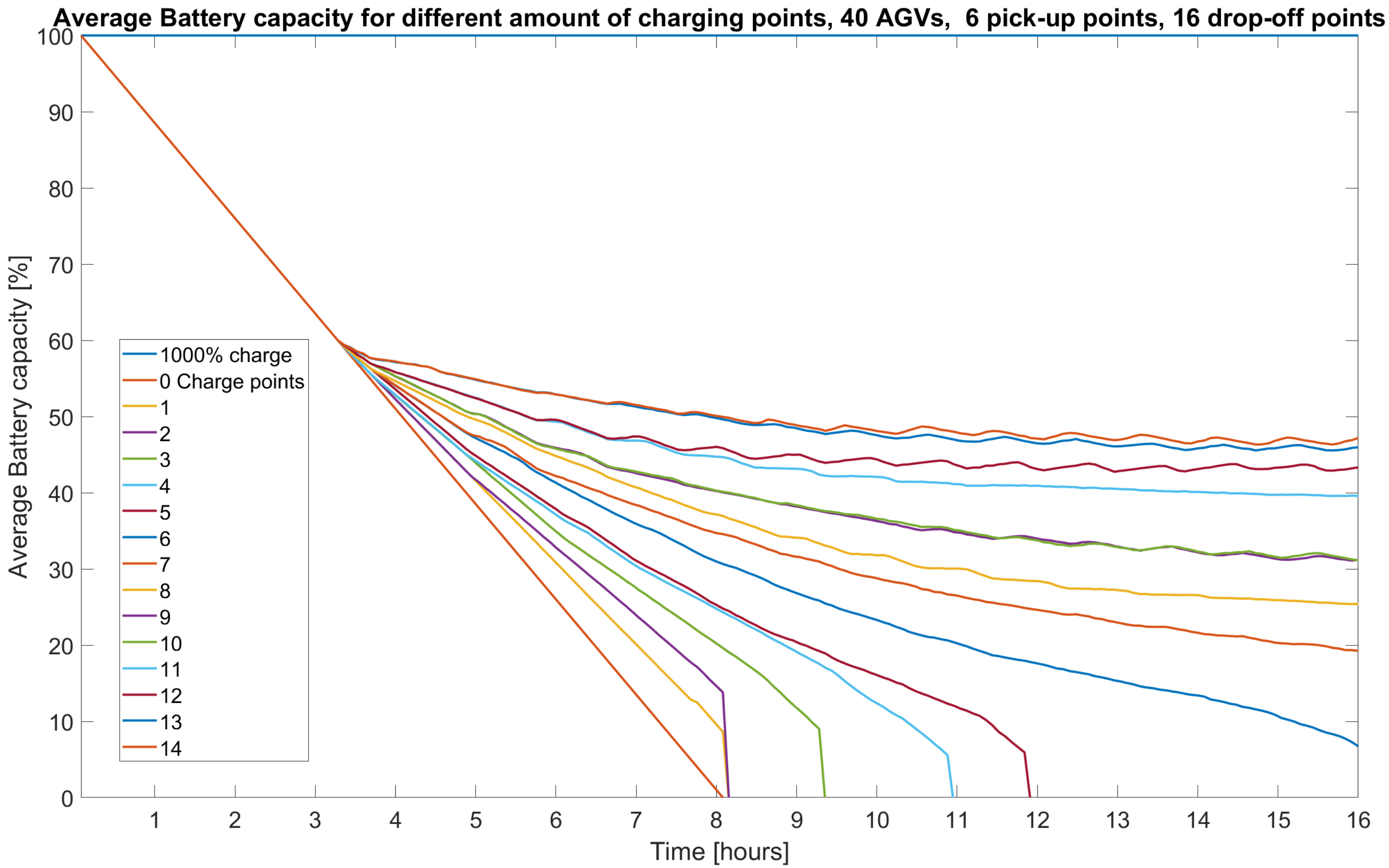


Figure 7.8: 40 AGVs, averaged charge capacity over 16 hours runs (if applicable)

Amount of charging points	**No charging**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Ratio AGVs VS charging points	*No charging*	6.67	5.71	5.00	4.44	4.00	3.64	3.33	3.08	2.86
Average throughput [parcels/hour]	1763	1646	1630	1623	1617	1625	1603	1605	1596	1600
Average rated load distance [%]	55.38	56.69	56.82	56.82	56.97	56.81	56.97	56.95	57.04	56.91
Average service time per parcel [s]	42.82	42.53	42.78	42.48	42.72	42.33	42.73	42.27	42.70	42.22
Average waiting time per parcel [s]	44.18	47.69	48.20	48.42	48.63	48.35	49.11	49.02	49.32	49.21
Average distance travelled per AGV [km]	40.51	36.97	36.44	36.36	36.04	35.64	35.74	35.73	35.53	35.63
Average distance travelled per job-cycle [m]	919.2	898.4	894.2	896.0	891.6	877.2	891.9	890.5	890.6	890.8
Average Chargestate after 16 hours [%]	100.00	6.73	19.25	25.43	31.20	31.13	39.58	43.33	45.98	47.18

Table 7.3: No charging versus charging with varying amount of charging points

Amount of charging points	**No charging**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Ratio AGVs VS charging points	*No charging*	6.67	5.71	5.00	4.44	4.00	3.64	3.33	3.08	2.86
Average throughput [parcels/hour]	1763	-6.64%	-7.54%	-7.94%	-8.28%	-7.83%	-9.08%	-8.96%	-9.47%	-9.25%
Average rated load distance [%]	55.38	2.37%	2.60%	2.60%	2.86%	2.57%	2.86%	2.83%	2.99%	2.75%
Average service time per parcel [s]	42.82	-0.68%	-0.08%	-0.79%	-0.23%	-1.15%	-0.21%	-1.29%	-0.29%	-1.39%
Average waiting time per parcel [s]	44.18	7.94%	9.10%	9.61%	10.07%	9.45%	11.17%	10.96%	11.65%	11.40%
Average distance travelled per AGV [km]	40.51	-8.74%	-10.06%	-10.26%	-11.03%	-12.04%	-11.77%	-11.80%	-12.29%	-12.05%
Average distance travelled per job-cycle [m]	919.2	-2.26%	-2.72%	-2.52%	-2.99%	-4.57%	-2.96%	-3.11%	-3.11%	-3.09%
Average Chargestate after 16 hours [%]	100.00	-93.27%	-80.75%	-74.57%	-68.80%	-68.87%	-60.42%	-56.67%	-54.02%	-52.82%

Table 7.4: No charging versus charging with varying amount of charging points differences in percentiles

7.2. Case 2: $3000\, m^2$

In this test case an area of $3000\, m^2$ is created by a width of $75\, m$ and length of $40\, m$ with 10-20 pick-up points and 10-30 drop-off points which should have 3 distribution options as otherwise no 90 drop-off locations would fit on the map. In Figure Appendix G.C can be seen that the AGVs travel quite a while with a parcel of top of it. With adding more AGVs more queueing and re-routing is formed. In Figure Appendix G.F can be seen that the relation between AGVs and throughput is still linear with the linear formula: $p_1 \cdot x + p_2$. This is with coefficients (with 95% confidence bounds): $p_1 = 30.16\,(28.98, 31.33)\&\, p_2 = 676.2\,(431.2, 921.1)$. Though lower (probably) due to longer distances to travel, it is indeed possible to meet the required throughput of $6000\,\frac{parcels}{hour}$. The Figures of case 2 are added in appendix G to increase the readability of this report. The values and insights found with these simulations are stated in the following subsections.

7.2.1. Feasible lay-out

As in section 7.1.1 described is the 2-sided configuration chosen to be optimal for these experiments. This setup is used for the $3000\, m^2$ lay-out as well.

7.2.2. Feasible amount of pick-up points: Differences due to ratio of drop-off points and pick-up points

As can be seen in Appendix G the time spend per category is relatively equal for all drop-off points. These simulations are done with 120 AGVs. With 5 drop-off points enormous queueing and deadlocking occurred and optimization of the map was required to fix this problem, therefore it was excluded for these simulation runs. With 10 drop-off points some times queueing occurs as can be seen in Figure G.C in Subplot 3 and Subplot 6. The Subplots with at least 15 drop-off points show no significant deformities to be excluded.

In Figure Appendix G.D is the throughput per drop-off point and pick-up point combination given. Here the most reliable and equal values are found with the use of 20 drop-off points. Therefore 20 drop-off points will be used for the evaluation of the next subsection as the amount of drop-off points should not affect the results.

Findings: 10 drop-off points are not enough to sufficiently run a system. If more drop-off points are required additional length could be added to the area or investigations into an optimized lay-out for drop-off points could lead to more possible drop-off locations.

7.2.3. Feasible amount of pick-up points: influence on throughput due to amount of pick-up points

In Figure Appendix G.E is the time per category shown. Each Subplot is analysed starting with 10 pick-up points. A decrease in rated load time can be seen due to an excessive increase in queueing time with no parcel due to queueing before the pick-up points, this starts to significantly increase from around 110 AGVs. In subplot 2, 12 pick-up points, from 160 AGVs the queueing (waiting time) leads to a less efficient system. In Subplot 3 (14 pick-up points) and 4 (16 pick-up points), from 170 AGVs, some queueing in front of the pick-up points leads to idle time. This happens as all parcels are claimed for AGVs to collect and no job is temporarily found for the remainder of AGVs. In Subplot 5 (18 pick-up points) is queuing without parcel happening from 170 AGVs to around 10 % still better than previous plots but in Subplot 6 (20 pick-up points) the least queuing is visible although starting with 200 AGVs.

These findings are combined with Figure Appendix G.F, which displays the linearity in the averaged throughput of the system with a certain amount of AGVs. The systems are linear until 150 AGVs for 10,14,16 pick- up points. The systems are linear until 160 AGVs for 12 pick- up points. And untill 170 AGVs for 20 pick-up points. Due to queuing and re-routing as found in Figure Appendix G.E described above the system drops in efficiency when too many AGVs are added. An average of 35.85 parcel per AGV per hour is found.

- 10 Pick-up points: p_1 = 35.85 (34.38, 37.32) & p_2 = 282 (148.5, 415.6)
- 12 Pick-up points: p_1 = 36.61 (35.37, 37.85) & p_2 = 266.6 (146.9, 386.4)
- 14 Pick-up points: p_1 = 36.58 (34.91, 38.24) & p_2 = 270.2 (118.7, 421.7)

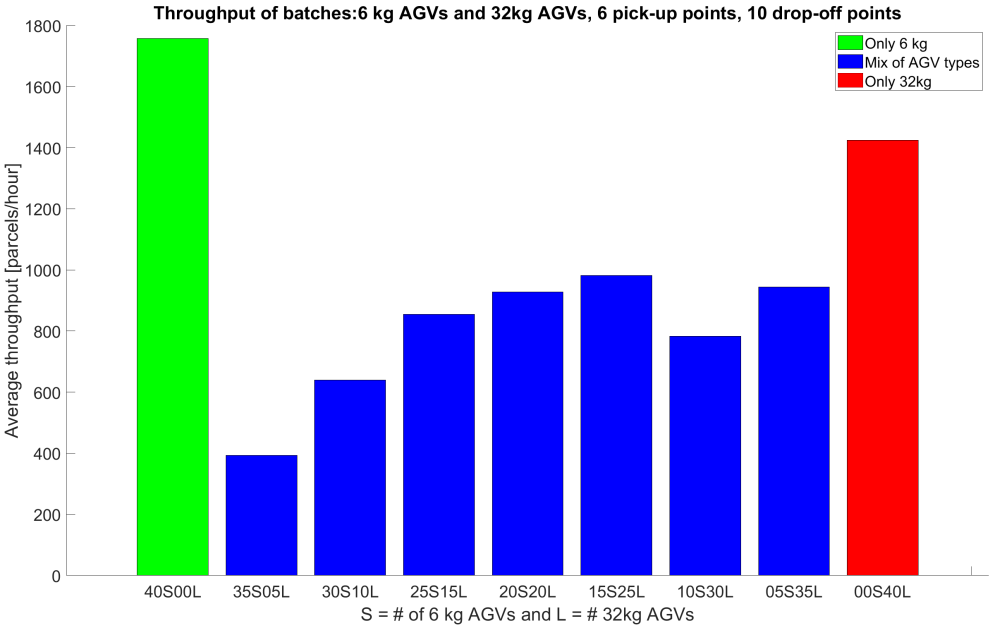


Figure 7.9: 40 AGVs, Multi-type AGV with 6 kg and 32 kg AGVs

- 16 Pick-up points: p_1 = 33.65 (31.49, 35.81) & p_2 = 442 (220.8, 663.1)
- 18 Pick-up points: p_1 = = 36.93 (35.01, 38.84)& p_2 = 270.4 (96.17, 444.6)
- 20 Pick-up points: p_1 = 35.49 (33.92, 37.06) & p_2 = 344.6 (183.7, 505.5)

Findings: A system consisting from 150 AGVs need at least 12 pick-up points and from 170 AGVs 18 or 20 pick-up points are advisable depending on the requirements of the design. The system is (reliably) capable of a throughput of 6000 parcel per hour from 16 pick-up points. It should be noted that an optimized routing algorithm could also reduce queueing.

7.2.4. Charging process

As can be read in subSection 7.1.4 is the sufficient ratio AGVs versus charging points at least 5.71. As in this model the ratio keeps the same for an increasing amount of AGVs this investigation is sufficient for each size of the model. The increase is done linear as well as if the amount of AGVs is uneven a ratio of at least 5.71 or better is used by rounding the amount of charging points always up to more using the C# ceiling command.

7.3. Multi-type AGV system

For this test set two types of AGVs are used on the $1000m^2$ area. These are the 6 kg and 32 kg AGVs with a nodesize of 0.8 m and in total 40 AGVs. First a test is done with only small parcels to establish how the area could be utilized. In Figure 7.9 is the data influence of waiting to collect a certain parcels influencing the overall performance of the system. In Figure 7.10 is the throughput of the system utilized. As can be seen only using 32 kg versus only using 6 kg AGVs decreases the throughput as they are slower in acceleration and top speed. The best throughput is found around the 15 6 kg and 25 32 kg AGVs. Therefore if such a system would not require a high throughput but does have a large variety of parcel weight and maximum length this solution will provide the use of less 32 kg AGVs which is more beneficial in terms of costs. An increase of efficiency could be achieved if a pre-sort in weight and parcel size is done. This would mean less waiting time for the smaller AGVs but increases the difficulty and expenses of the system.

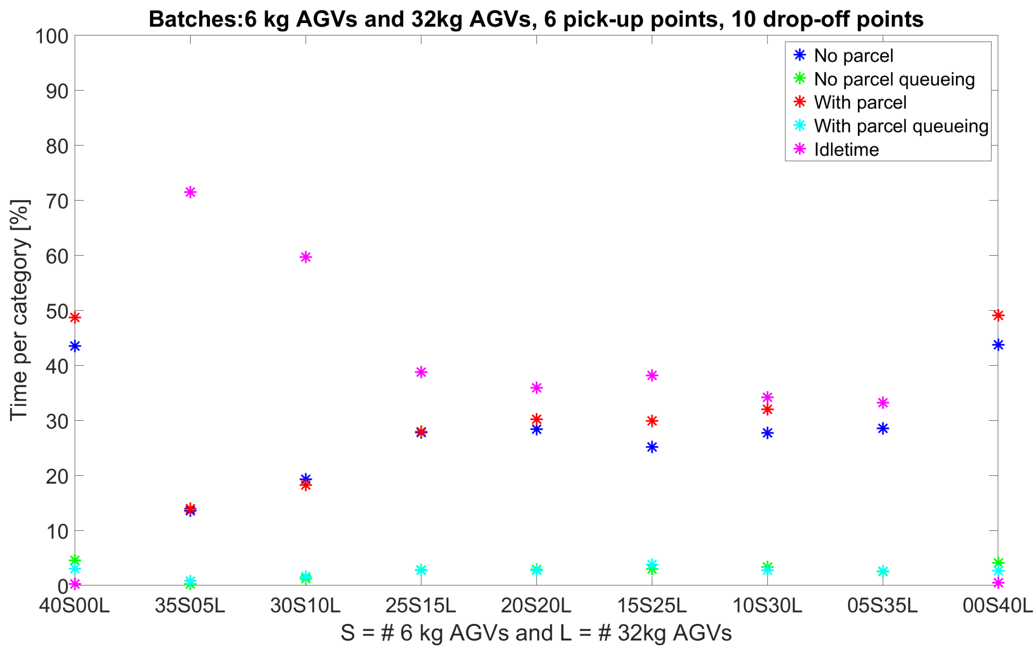


Figure 7.10: Throughput 40 AGVs, Multi-type AGV with 6 kg and 32 kg AGVs

7.4. Conclusions from the experiments

Firstly a significant influence of the placement of pick-up points and drop-off points is demonstrated. The placement shortens the distance between delivering a parcel and collecting a new parcel. Also with the use of grid-routing (either X or Y movement) limits the possible options for shortest path routing. Therefore the use of only one-side of an area for pick-up points creates waiting times. Placing the pick-up points on all four sides is the most efficient but if it is practical depends on the purpose of the building. After selecting the 2-sided lay-out the influence of the amount of pick-up points and AGVs on the $1000m^2$ area is inspected.

The ratio 2 and 4 pick-up point of between until 10 drop-off points leads to queueing as well as idle AGVs. As well as having only 2 drop-off points available heavy queueing appears. From 5 till 50 AGVs is a linearity found with an average of 42.62 $\frac{parcels}{AGV}$ for the selection 4,6,8,10,12 pick-up points. This linearity fades due to queueing and lack of available parcels after increasing from 55 AGVs. Though linearity is found for the 10,12 pick-up points the queueing times significantly increases for the set of 80 AGVs. Though the influence of the size of the working area/distance between these ”special” (drop-off and pick-up) points must be examined as well.

The influence of charging in an AGV lithium-battery based system is examined. A ratio of between 5.71-5 AGVs per charging points is advisable with this charging scheme. To prevent shut down of AGVs or excessive expenses on chargers. During the absence of multiple AGVs on the charging points is the overall performance of the system increased. Which also leads to the conclusion that the system benefits when unnecessary AGVs are temporarily removed from the area or placed outside of the commonly used routes.

Looking at a scalable case of $3000m^2$ a match with at least 15 drop-off points is required to prevent queueing and re-routing at the drop-off locations. At least 16 pick-up points are required to keep 160 AGVs running without too much queueing at the parcel collection process at the pick-u points.

The test case of $3000m^2$ matches the 6000 parcels per hour throughput and improvement in either a smaller area or higher throughput could be made, depending on the requirements of such a system. While taking into consideration the price and other factors of such an AGV system. At a total of at least 170 AGVs and 16 pick-up points is a reliable (with this model) 6000 parcels per hour parcel sortation system possible.

A scalable model is made for simulating a multi-AGV parcel sortation center. These results can be used in the process of designing an AGV based parcel sortation center. In the next subsection a multi-type AGV system is analysed. This is a system working with 2 types of AGVs on the same area.

The situation of using two types of AGVs on the same area is looked at. Still improvements could be made, but a quick analysis points out the points of interest of such a system. The queueing due to 6 kg AGVs which are unable to collect the excessive parcels. This can for example be tackled in the pick-up point process (for example with human labour interaction). As well as in a pre-sortation of smaller parcels to a selection of pick-up points or even to a specific area with only 6 kg AGVs.

8 Conclusions and recommendations

This report aimed to answer the main research question: How to feasibly design scalable multi-AGV parcel sortation systems taking influential design parameters into account? To answers this the sub-questions are formulated and investigated. *What is the configuration of conventional parcel sortation systems?* The conventional parcel sortation systems are facing challenges of package variety, volume, automation integrations, customer expectation and space utilization. These challenges could can be solved by upgrading or expanding existing systems. Though these conventional parcel sortation systems can be fixed either in their building capacity or in their circular, cross or U-shape with closed-loop or fixed amount of inlets and outlets. These existing systems are therefore less flexible for current or future expansions.

Which characteristics of AGV systems are relevant for modelling a parcel sortation system? The use of AGVs for a parcel sortation system is very flexible in space utilization as well as in (future) upgrading or expanding of such a system. The increased availability, research and mass-production lead to lower acquisition costs, as well as maintenance costs and potential energy consumption costs combined with facility space costs and personnel costs, operating costs. These AGVs are battery powered and therefore the charging process of the AGVs are relevant. This includes the reduced productivity of AGVs (currently less are able to operate) due to charging. The facilitated routing of purchased AGVs needs to be assessed, simulated by an A* search algorithm. As well as the task allocation process by a market- auction-based algorithm. These AGVs use grid-routing, meaning either X- or Y-movement, but not both at the same time.

Which requirements and design parameters need to be considered for modelling a parcel sortation system? As the AGVs are purchased from other companies a selection of applicable AGVs with, a rated load of 6 kg, 32 kg and 70 kg, are used. These are averaged to attain various aspects of AGVs, for example, parcel dimension, charge capacity, maximum acceleration and speed. The design parameters are the amount of AGVs, amount of charging points, drop-off point locations, amount of drop-off points, pick-up point locations and amount of pick-up points. The A* routing algorithm is used in combination with task allocation by a market- auction-based algorithm.

Which model characteristics are required to create an experiment to evaluate which design parameters are the most influential in terms of the key performance indicators An object-oriented based model is made in c# with the use of Visual Studio. A centralized controller, RCS, is created to control all the AGVs from the same access point. Elements of the model are the AGVs (RCS), parcels, pick-up points (parcel collection), drop-off points (parcel distribution from AGV), charging points (AGV battery charging) and waiting points (location for AGVs to wait for a new job). Deadlock and gridlock are prevented by anti-deadlocking. The dispatching is done by an existing market- auction-based algorithm already used for AGVs with grid-routing. A charging scheme is created to load the lithium based AGVs between 1% and 70%. A workflow for the RCS is created to determine the action of the AGVs: completing a job of parcel collection, scanning, driving and unloading at its destination or charging versus driving to a waiting point close to a new job of collecting a parcel. An experimental plan is used to verify if the model functions correctly. The application of multiple types of AGVs on one grid is presented.

Which experimental setup can be used to simulate the influence of the design parameters in a scalable multi-AGV sortation system?. Two different test cases are used to evaluated the influence of the different design parameters. An area of 1000 m^2 and an area of 3000 m^2 is created by a lay-out generator. This generator can create three different lay-outs with a specific amount of input values (amount of pick-up points, drop-off points, AGVs). First verification is done on the model with the use of a test plan. Then an experimental plan is created which uses these three lay-outs. First a feasible lay-out can be found with the use of simulations and the KPIs. After which a feasible amount of drop-off points in ratio with the amount of pick-up points can be found. Using the outcome of this a feasible amount of pick-up points is established. The last step is looking for a feasible amount of AGV charging points.

What are impacts of the influential parameters to the design of scalable sortation systems? Several simulations are conducted with the model. First a case with a lay-out of 1000 m^2 area is analysed. To scale this system a lay-out with a 3000 m^2 area is used. The data is configured in tables and graphs. The influence of changing the placement of the pick-up points and drop-off points are examined with the use of the lay-out generator. Collecting parcels from not only one or two sides of the model but four sides is the most efficient. This in terms of throughput, average rated load distance and distance required to get an average throughput of > 1600 $\frac{parcels}{hour}$. The influence of the pick-up points and increased congestions in queueing and re-routing is investigated by a two-sided layout. Linearity is found from 5-50 AGVs after which decreasing in efficiency by adding more and more AGVs into the system is found by the 10 and 12 pick-up points. At an average linearity of 46.76 $\frac{parcels}{hour}$ to an linearity of 39.86 $\frac{parcels}{hour}$. Versus non-linearity in the other pick-up points. The ratio of pick-up points to drop-off points is investigated which should function at least 6 pick-up points and ranging of 4 till 16 drop-off points depending on the spacing between these points.

The ratio of, at lowest, of 5.7 AGVs versus charging points and 4.4 to have a reliable system without AGVs shutting down during a 16 hour period. The lay-out with 3000 m^2 can suffice for a throughput of 6000 $\frac{parcels}{hour}$ with the use of at least 170 AGVs. Multi-AGV test shows that depending on the pick-up points and required system throughput can lead to lower costs in a multi parcel system.

8.1. Recommendations

Suggestions and recommendations for further research are conducted in this section. In this report a lot of variables are assumed as constants to simplify the model as well as narrow the scope of this research. Though several of these could be investigated if for example the selection of a type of AGV is required or if the pick-up point process itself is investigated. Efficiency increase could be found by looking at the process of collecting parcels. Because when the number of AGVs increases, more queueing is discovered in the experiments. Examples of potential improvements are: queueing underneath pick-up points to eliminate routing obstacles as well as being able to distribute multiple parcels at the same time per pick-up point.

The model has endless possibilities and as this research is not an optimization. With a more elaborate/complete plan a higher efficiency could be generated from the same amount of AGVs. When adding more elements to the market- auction-based algorithm a more elegant task allocation process could be created.

The implementation of using multiple types of AGVs on the same grid could be more elaborately investigated. By looking into the task allocation of these two kind of groups of parcels, idle time could be significantly decreased. This could for example be achieved by the mentioned pre-sort or alternative ways to distributing parcels on top of AGVs.

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Appendix

Appendix A: Scientific Research Paper

Feasibility of a Large-scale Multi-AGV based Parcel Sortation Systems

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Abstract

This paper presents insights in the feasibility of large-scale multi-AGV based parcel sortation systems. A simulation model is created to look at the influence of different aspects of such an Automated Guided Vehicles system. The model uses several design parameters and KPIs to determine the level of influence. Important aspects of this research are: the charging process of the AGVs, influence on pick-up points (parcel collection) and drop-off points (parcel destinations) and multiple types of AGVs on the same map. The AGVs will be modelled by an A algorithm and uses grid-routing (either X or Y -movement at the same time). These kind of AGVs are controlled by an centralized robot control system. The task allocation the AGVs is done by a market- auction-based algorithm. After the model is created several tests are conducted which show the significance of the various system aspects.*

I. Introduction

The parcel sortation industry is growing and investments are made to keep up with the demand and increased pressure. This is observed to deliver more volume, quicker and with more accuracy and flexibility [1]. More smaller distribution points closer to the potential clients are build on strategic locations (e.g. nearby largely populated areas), local depots. These developments lead to many challenges in this particular area of expertise. The top 5 challenges facing post and parcel operations,discussed at the National Postal Forum in Baltimore (May 2017), are the following [2]: package variety, volume, automation integration, customer expectation and space utilization. To utilize this are new alternatives investigated due to old systems which are difficult to upgrade or expand. the use of Automated Guided Vehicles (AGVs) promises more flexibility in integrating in set building as well as when looking long-term. These are small battery operated vehicles which are very flexible in terms of building lay-out and future expansions (adding more AGVs).

i. Literature

Parcel sortation facilities have an increasing package variety in their processes. This means a large variety in parcel dimensions as well as weight. Many types of package options for the smaller and less heavy object such as:

Letters, soft packs, poly bags and totes [3]. The traffic flow of AGVs in a parcel sortation system is being controlled by a Material Flow Controller (MFC) [4]. The scheduling is done in the MFC system and then send to the AGV control system. This system is also called Robot Control System (RCS) and has the task to execute the planned sequence of motions and forces in the presence of unforeseen errors [5]. A general lay-out of such AGV sortation system is sketched in Figure 1.

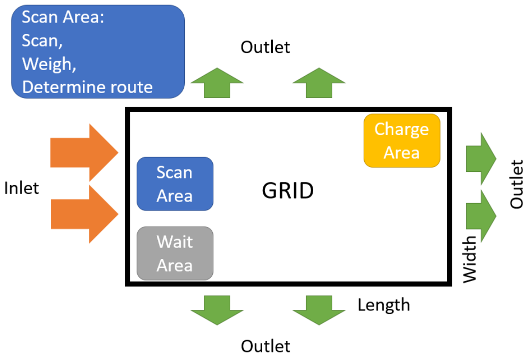

Figure 1: *Example of an AGV layout can be used for grid or free-ranging*

The location of the AGVs is send to the RCS. Multiple solutions to identify the current location of an AGV are available, though the smaller AGVs commonly use either Frequency IDentification (RFID) or Quick Response (QR) code labels [6]. Most AGVs are battery powered to induce an electric motor. The use of an electric motor adds the possibility for higher efficiency energy usage and is a relatively good choice to reduce noise pollution [7]. The values of the battery capacity as well as maximum speed, acceleration and distribution capabilities are averaged over several existing AGVs [8] [9] [10] [11].

ii. Research question

The lack of literature in the field of parcel sortation systems combined with AGVs (though some systems already exist) participates in this research. The main research objective is: ***How to feasibly design scalable multi-AGV parcel sortation systems taking influential design parameters into account?*** Sub-questions are drafted to split and structure the main research question. Already answered by the literature study: *What is the configuration of conventional parcel sortation systems?* and *Which characteristics of AGV systems are relevant?* Leaving the sub-questions: *Which requirements and design parameters need to be considered for modelling a parcel sortation system? Which model characteristics are required to create an experiment to evaluate which design parameters are the most influential in terms of the KPIs? Which experimental setup can be used to simulate the influence of the design parameters in a scalable multi-AGV sortation system? What are impacts of the influential parameters to the design of scalable sortation systems?*

iii. Project boundaries

As many parameters could influence such a parcel sortation system the object of this research is to find the most influencing aspects and therefore cuts are made. Many AGV specifics are set as constants, within 2 groups. The AGV payloads are ranging around 6 kg (small parcel and, 32 kg max weight EU [12]. The discharge rate (lithium battery) of the AGVs is set at a rate of 1 % is equal to $\frac{8\,[hours]\cdot 3600\,[seconds]}{100\,[\%]} = 288\,[\frac{seconds}{\%}]$. The charging is implemented at a charge rate of $\frac{1.5\,[hours]\cdot 3600\,[seconds]}{100\,[\%]} = 54\,[\frac{seconds}{\%}]$. The assumption is made that each AGV will charge 10% before leaving, if not forced to leave due to other circumstances, as otherwise AGVs will make many trips to the charging points reducing efficiency.

II. Methods

The remainder of this paper is structured as follows. The design parameters and KPIs are elaborated. The dispatching process and some routing is explained. The work process of the AGV is described by the workflow. Followed by the verification. Several results are depicted and explained. Finally a short discussion is stated.

i. Design parameters and KPIs

The design parameters are: # AGVs, charging points, pick-up points (parcel collection) and drop-off points (parcel destinations). The following KPIs are used to evaluate the influence of the design parameters: amount of charging stations, deadlocking %, empty load (no parcel on top of AGV), rated load distance (parcel on top of AGV), idle % (no job for the AGV available), peak capacity %, space utilization and waiting time % (queueing and re-routing).

ii. Dispatching and routing

The routing of the AGVs is simulated with the use of an A* algorithm. It claims a specific area, e.g. a square with a QR code in the middle, called a node. This node is only accessible for the next AGV when the previous AGV completely left the node and send the RCS the next location relieving this node of its claim. The task allocation is provided by a market- auction-based algorithm [13]. This algorithm, see Figure 2 and Figure 3, is provided by the paper: Priority Based Multi Robot Task Assignment. This also uses a grid-based routing technique, either X or Y-movement per moment of time.

$$C_{ij} = | \text{Robot[i].pos}_i - \text{Task[j].pos}_j |; \quad 0 <= i < n; 0 <= j < m$$

Figure 2: *Cost*$_{Method}$ *(Robot$_i$,Task$_j$) [13]*

$$bid_{ij} = \begin{cases} \dfrac{1}{e^{|x_i - x_j| + |y_i - y_j|}} & x_i \mathrel{!}= x_j \text{ AND } y_i \mathrel{!}= y_j \\ \dfrac{\frac{1}{e^{|x_i - x_j|}} + \frac{1}{e^{|y_i - y_j|}}}{2} & x_i = x_j \text{ OR } y_i = y_j \\ & x_i = x_j \text{ AND } y_i = y_j \end{cases}$$

Figure 3: *Bid*$_{Method}$ *(Robot[i].pos$_i$,Task[j].pos$_j$) [13]*

iii. Workflow of AGVs

The RCS uses the following workflow for each AGV, as displayed in Figure 4. If an AGV is operational it is applicable for receiving a job. If a parcel is available, the charge state is sufficient, the AGV can handle the weight and size of the parcel and the AGV is the closest to the parcel the job (depending on task assignment) is assigned to this AGV. Unless the charge state drops below bare minimum charge state (as described in subsection 5.7) it drives and completes the job set for it.

The AGV drives to the pick-up point. The parcel is loaded onto the AGV, time passes. The AGV sends the closest scanner and scale combination from which the RCS receives the end-destination. The AGV is send to the drop-off point onto which it unloads the parcel, time passes. The AGV is set available for another job. If no (applicable) parcel-job is available the AGV will either go charge, or drive towards a waiting point. These points will be placed at strategic points. The AGV awaits a new job or will leave the waiting point (as time passes and the charge state decreases) to the charging point (not likely but a possibility).

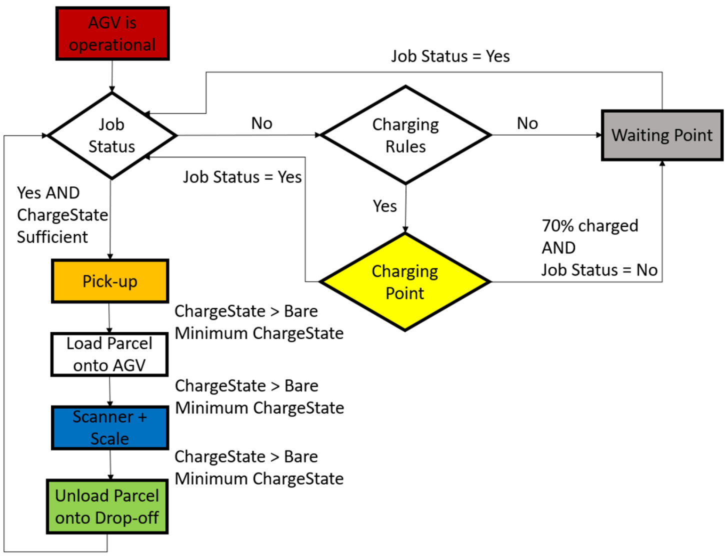

Figure 4: *Workflow Robot Control System*

Amount of charging points	No charging	6	7	8
Average throughput [parcels/hour]	**1763**	**-6.64%**	**-7.54%**	**-7.94%**
Average Charge state after 16 hours [%]	**100.00**	**6.73**	**19.25**	**25.43**

Table 1: *No charging versus charging with varying amount of charging points differences in percentiles*

iv. Verification

The model is verified with the use of an experimental plan. This includes the categories: AGV, Multi-AGV, Pick-up point, map generator as well as for verification of the KPIs. A sensitivity analysis used to verify the influence of the various design parameters.

III. Results

A lay-out of 1000 m^2 (case 1) created and experiments are done. As well as a 3000 m^2 (case 2) with width of 75 m and length of 40 $m$lay-out with 20 pick-up points and 50 drop-off points are 200 AGVs required to match the required throughput of 6000 $\frac{parcels}{hour}$.

i. Feasible lay-out

With the same amount of pick-up points and drop-off points are the following results found. With 40 AGVs the difference in throughput varies from 1-sided 1663$\frac{parcels}{hour}$, 2-sided 1834$\frac{parcels}{hour}$ and 4-sided 1901$\frac{parcels}{hour}$. The average rated load distance respectively increases from 55.5 %, 58.5 % till 64.3 %. Also the average distance travelled per job-cycle is: 176.08 m & 163.44 m & 141.83 m.

ii. Feasible amount of pick-up points

The influence of the increasing amount of AGVs from 5-80 with steps of 5 AGVs is investigated. This is in combination with the amount of: 2,4,6,8,10 and 12 pick-up points. An increase of rated load time happens as more pick-up points are available. It also shows the increasing queueing with more AGVs on the map. The linearity estimations with corresponding coefficient of determination (R^2) are found . It is concluded that the data sets of 8,10 and 12 pick-up points are linear with the following formula: Linear model $p_1 \cdot x + p_2$ and the coefficients (with 95% confidence bounds) are given in the list below. The 10P and 12P have an average increased throughput of 39.86 $\frac{parcels}{hour}$ per AGV with respectively $R^2 = 0.971$ & $R^2 = 0.990$.

The linearity of the the first 50 AGVs concludes the following. Here it can be seen that 4,6,8,10,12 the pick-up points are linear with the linear model formula, see Figure 5. The values found are displayed below, with an average of 44.62 $\frac{parcels}{AGV}$ for the selection 4,6,8,10,12 pick-up points and even an average of 46.76 $\frac{parcels}{AGV}$ for the selection 10 and 12 pick-up points. Therefore linearity if found on an 1000m^2 with 4,6,8 the pick-up points and 50 AGVs but afterwards queueing and re-routing creates non-linear behaviour. For case 2 a system consisting from 150 AGVs need at least 12 pick-up points and from 170 till 200 AGVs 18 or 20 pick-up points are advisable depending on the requirements of the design.

In another simulation set are the ratio of pick-up points versus drop-off points must be maintained from 6-12 pick-up points and 4-12 drop-off points to eliminate unnecessary queueing in front of pick-up points either drop-off points. Though the influence of the size of the working area/distance between these "special" points must be examined as well.

iii. Charging process

The differences of no charging process versus charging, with 40 AGVs, is displayed in Table 1. The average charge state of 6 charging points is insufficient as shut-down of AGVs is quite probable due to low battery capacity.

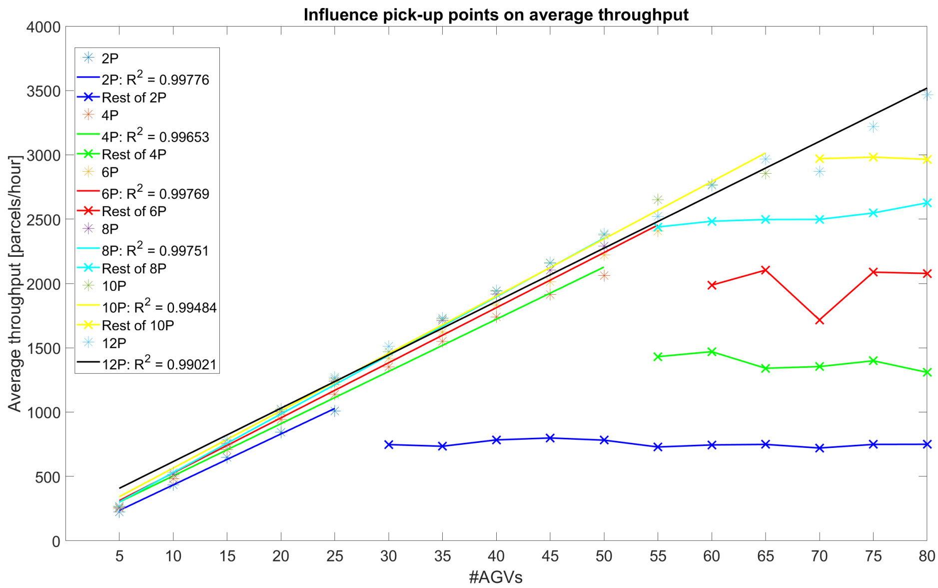

Figure 5: *2-sided influence pick-up points on time per category with 2,4,6,8,10,12 pick-up points*

Due to charging AGVs is a drop in the average throughput found of at least 7.64%. Though the average rated load distance (at least 2.60%)is more efficient with less AGVs in play reducing the possibility of queueing. The ratio of, at lowest, of 5.7 AGVs versus charging points and 4.4 to have a reliable system without AGVs shutting down during a 16 hour period.

iv. Multiple types of AGVs

In Figure 6 is the influence of having 2 types of AGVs (6 kg and 32 kg) on one map with a nodesize of 0.8 m and in total 40 AGVs visible. As can be seen only using 32 kg versus only using 6 kg AGVs decreases the throughput as they are slower in acceleration and top speed. The best throughput is found around the 15 6 kg and 25 32 kg AGVs. Therefore if such a system would not require a high throughput but does have a large variety of parcel weight and maximum length this solution will provide the use of less 32 kg AGVs which is more beneficial in terms of costs. An increase of efficiency could be achieved if a pre-sort in weight and parcel size is done. This would mean less waiting time for the smaller AGVs but increases the difficulty and expenses of the system.

IV. Discussion

Taking into consideration that various simplifications and assumptions due to the routing algorithm and charging delimit the reliability of the model. As well as only a small and large rectangular area is examined. Still the results and model itself can be seen as a first step in identifying the influence of certain design parameters in designing a parcel sortation system.

More specific research could be done, as this is not an optimization. Therefore if a more complete (design) plan is applied, possibilities of increasing the efficiency and gaining more insights of an AGV parcel sortation system are at hand.

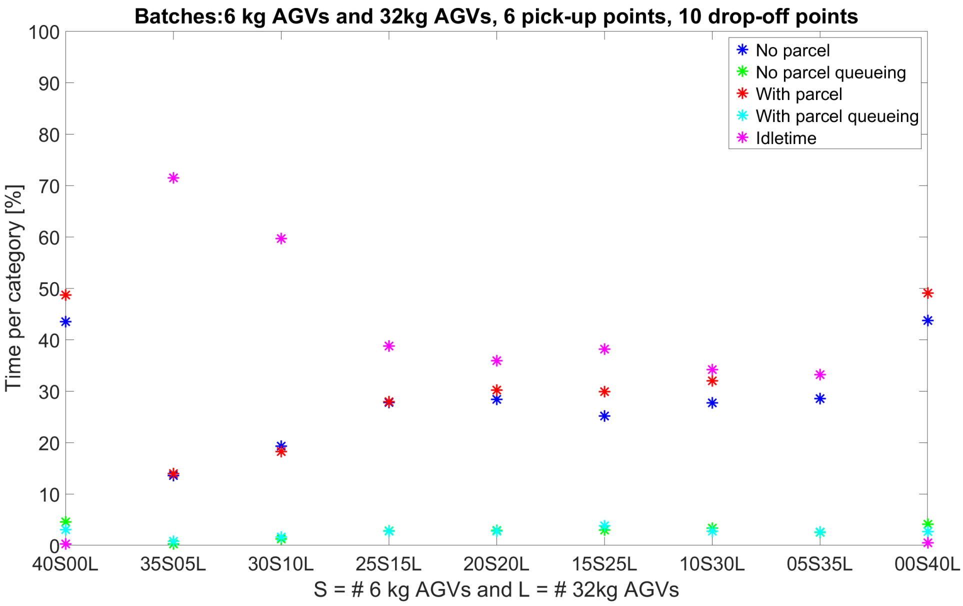

Figure 6: *40 AGVs, Multi-AGV with 6 kg and 32 kg AGVs*

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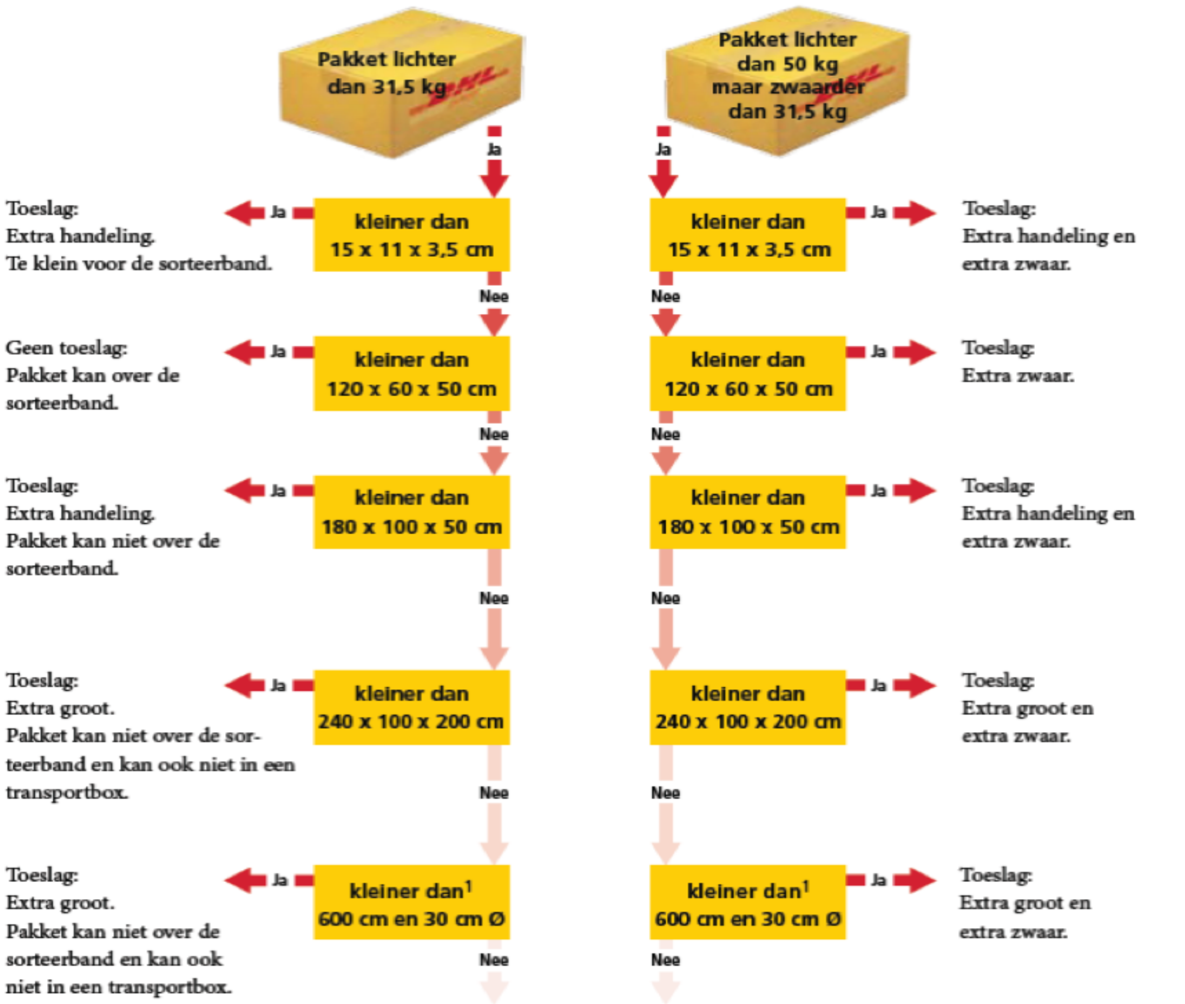
Appendix B: Parcel information

TOESLAGEN EN KORTINGEN

Pakketzendingen

Het kan zijn dat uw zending extra groot, zwaar, bewerkelijk of omvangrijk is. In dat geval betaalt u één of meerdere toeslagen (een zending kan bijvoorbeeld én extra groot én extra zwaar zijn).
Met onderstaand schema bepaalt u eenvoudig of u een toeslag kunt verwachten voor uw pakketzending.



Bel onze klantenservice: 0800-0552

1 Alleen mogelijk voor DHL EUROPLUS of Expresser (binnen de Benelux).

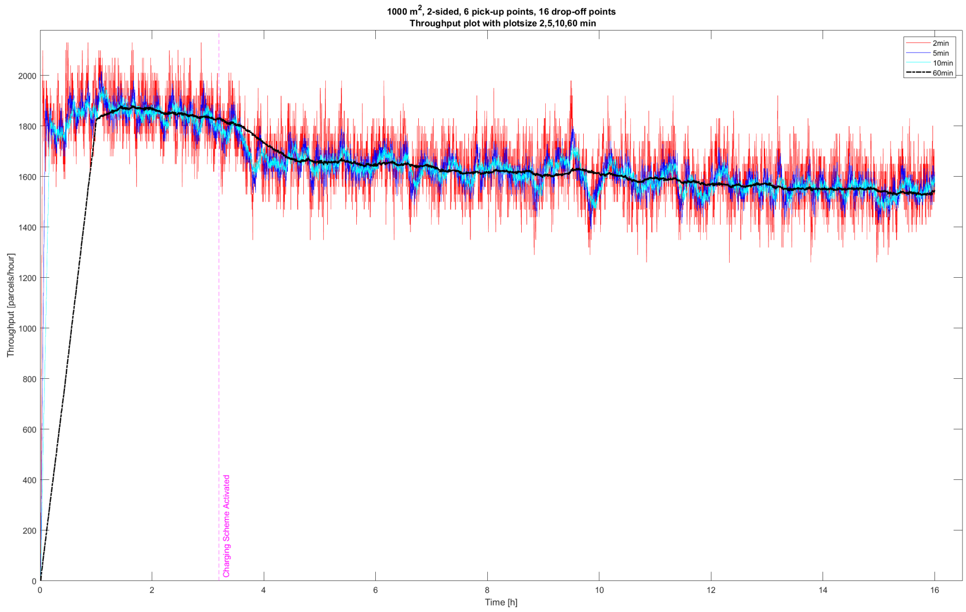
- Toeslag extra handeling kan ook van toepassing zijn indien een pakket vanwege de aard, vorm of verpakking niet over de sorteerband kan.
- Vermelding van afmetingen zijn altijd: lengte x breedte x hoogte.

DHL extra charge when parcel is out of bounds, extra charge is specified as: Extra handling: €3,00 addition, Extra groot: €35,00 addition, Extra zwaar: €35,00 addition [37]

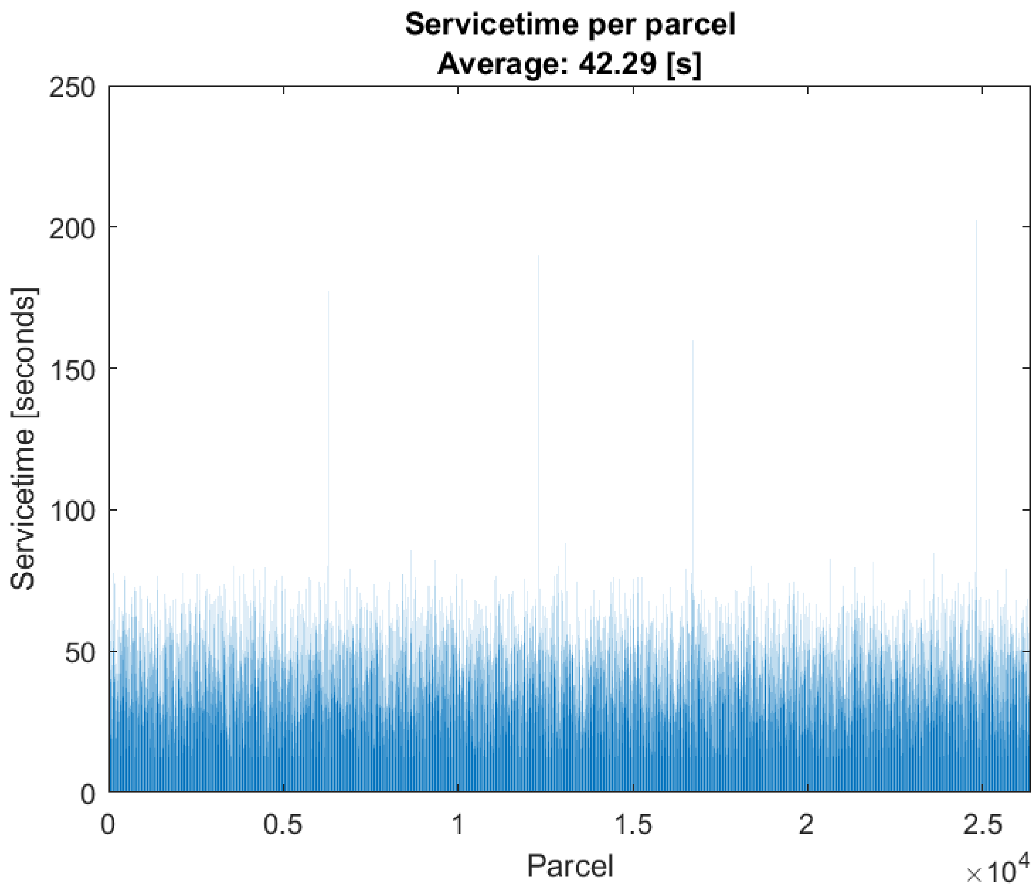
Appendix C: AGV specifications overview & calculation verification figures

Company	**Hikvision**	**Hikvision**	**Hikvision**	**Hikvision**	**Hikvision**	**Hikvision**	**Geek+**	**Geek+**	**Geek+**	**Geek+**	**Geek+**	**Gebhardt**	**Tompkins**	**Fetchrobotics**	**MIR**	**Total AGV average**
Name	MR-C3C-UB100B(H)	MR-C3C-UT030A(H)	MR-S1C-RN010A(H)	MR-S1C-TH005A1(H)	MR-S2C-TH020A1(H)	MR-S3C-TN100A(H)	S10	S20	S20T-H	S20C-H	S500c	Karis Pro	t-Sort	Rollertop	MIR100	
Speed [m/s]	1.2	1.2	3	2	1.5	1.5	3	3	2.5	2.5	3	1.2	2	2	1.5	2.07
Rated load acceleration [m/s^2]	0.4	0.4	1.3	0.8	0.8	0.6							1.5			0.83
Weight [kg]	170	255	13	25	75	210	12	42	70	75	210	60		85	62.5	97.46
Rated load [kg]	120	30	6	6	20	100	6	20	8	20	70	120	5	45	100	45.07
Positioning accuracy ± [mm]	10	10	5	5	5	10	10	10	10	10	10	10			10	8.85
Capacity [Ah]	20	20	7.5	18	20	20	6	6	12	12	6	25	20			14.81
Charging cycles	1500	1500	1500	1500	1500	1500							10000			2714.29
Endurance [h]	8	8	8	8	8	8								9	10	8.38
Charging time [h]	1.5	1.5	1.5	1.5	1.5	1.5								3.333333333	2.5	1.85
Type of distribution	4x Roller load:(4x 30 kg)	Roller	Flip cover	Flip cover	Belt	2x Belt	Belt	Belt	Flip cover	Belt	2x Belt	Lift table	Flip cover	Roller	Lift	

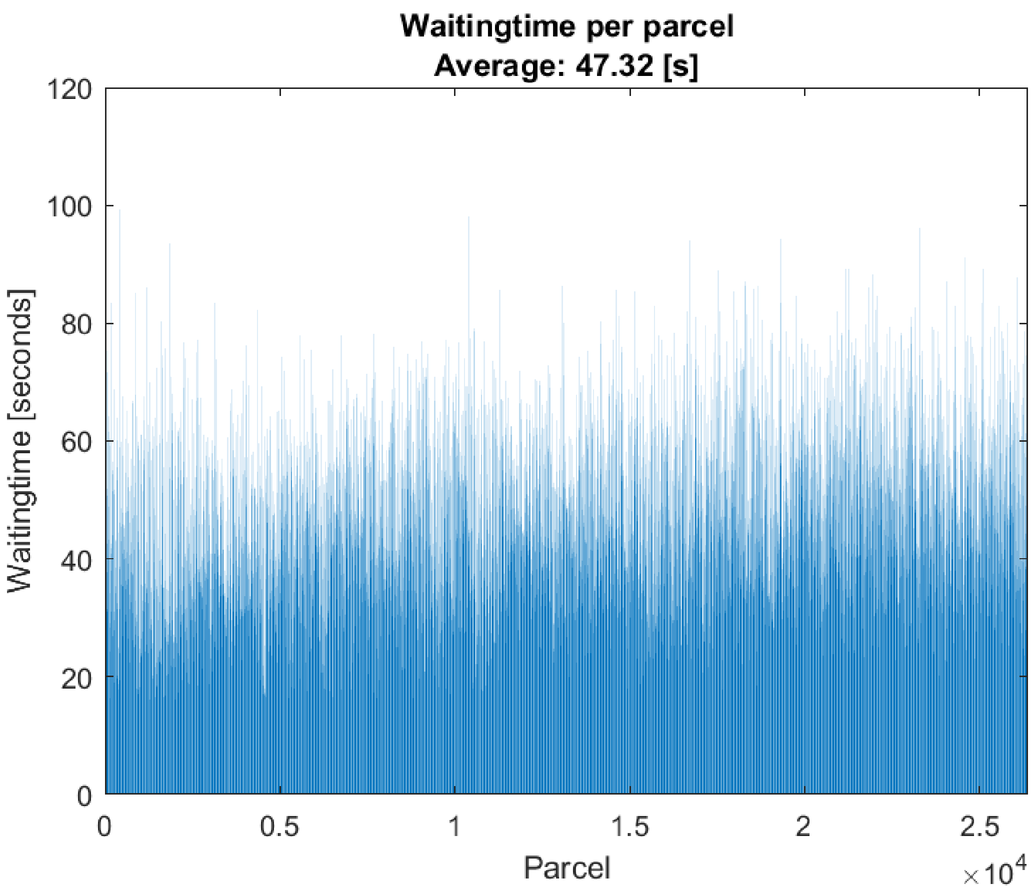
Appendix D: Examples of data retrieved from model



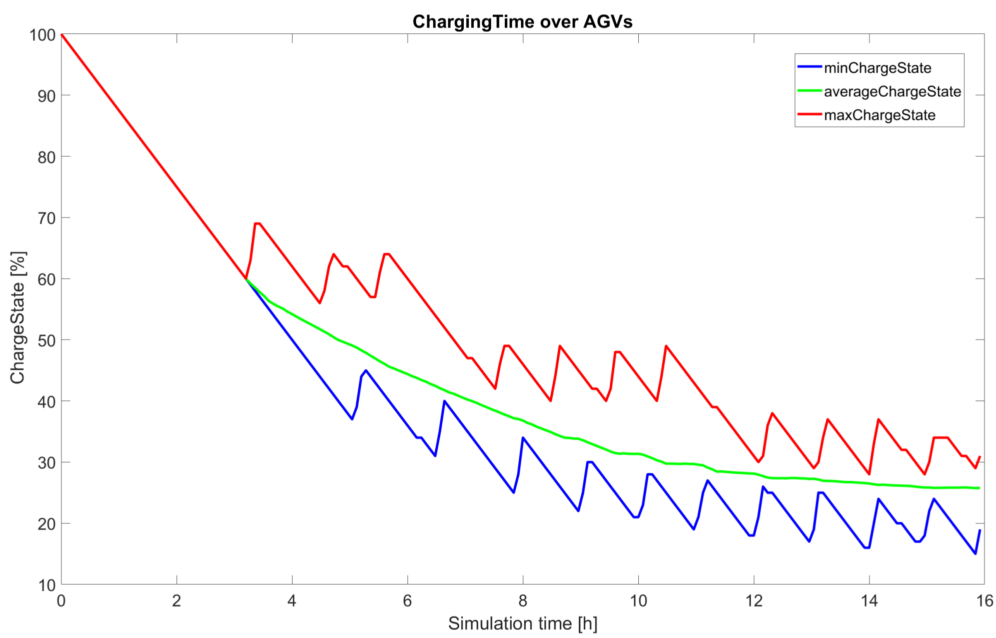
D.A: Example of 16 hour run with 2,5,10,60 minutes average mean



D.B: Example of 16 hour run, 40 AGVs difference of all parcels in service time [s]

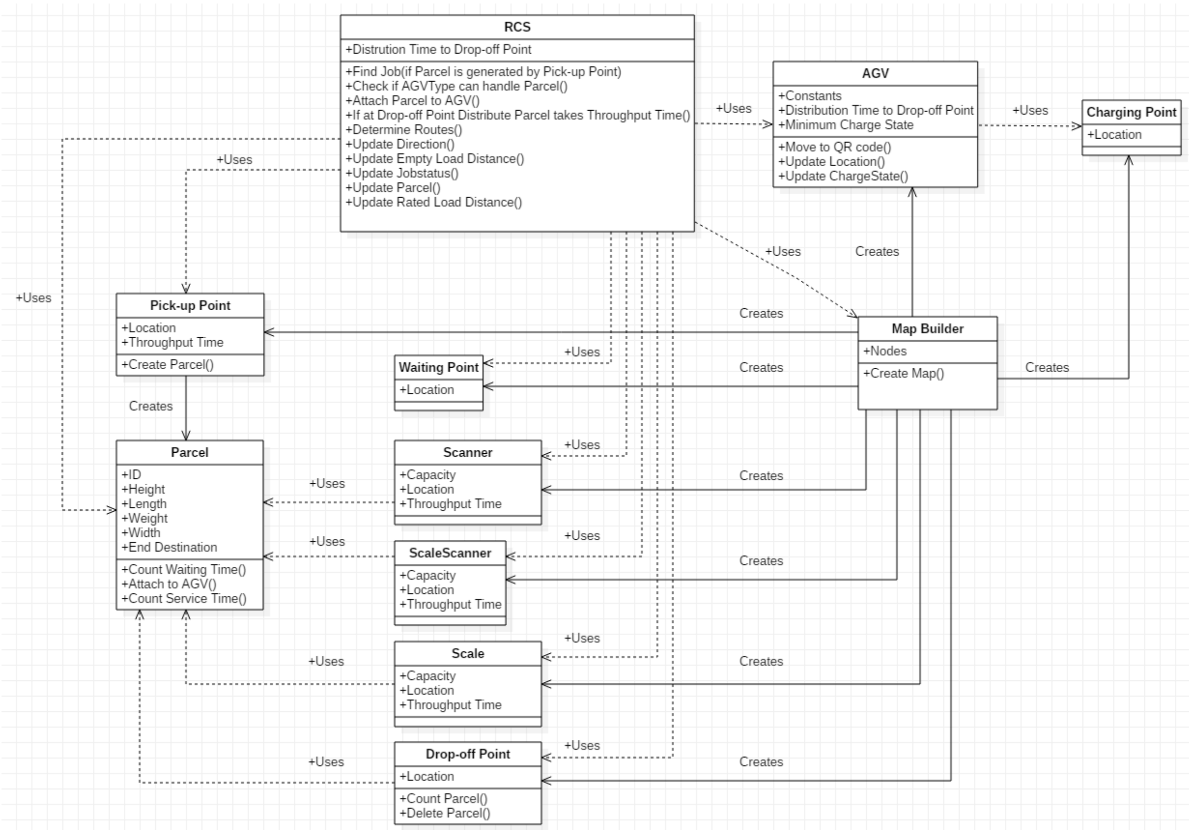


D.C: Example of 16 hour run, 40 AGVs difference of all parcels in service time [s]

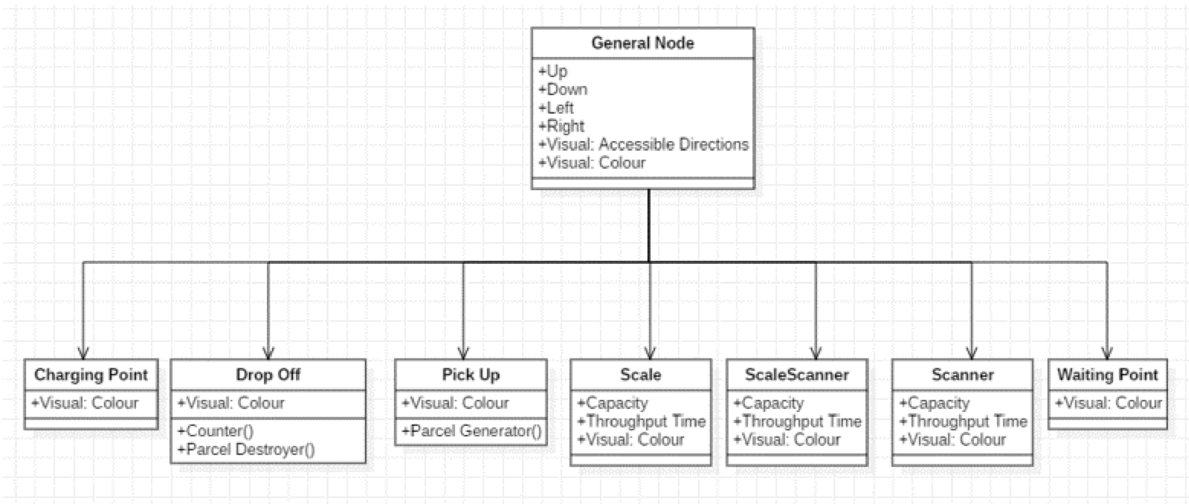


D.D: Example of 16 hour run, 40 AGVs minimum, average and maximum charges state over time

Appendix E: Class diagrams



E.A: Class diagram



E.B: Class diagram with specifics for the sub-classes for nodes

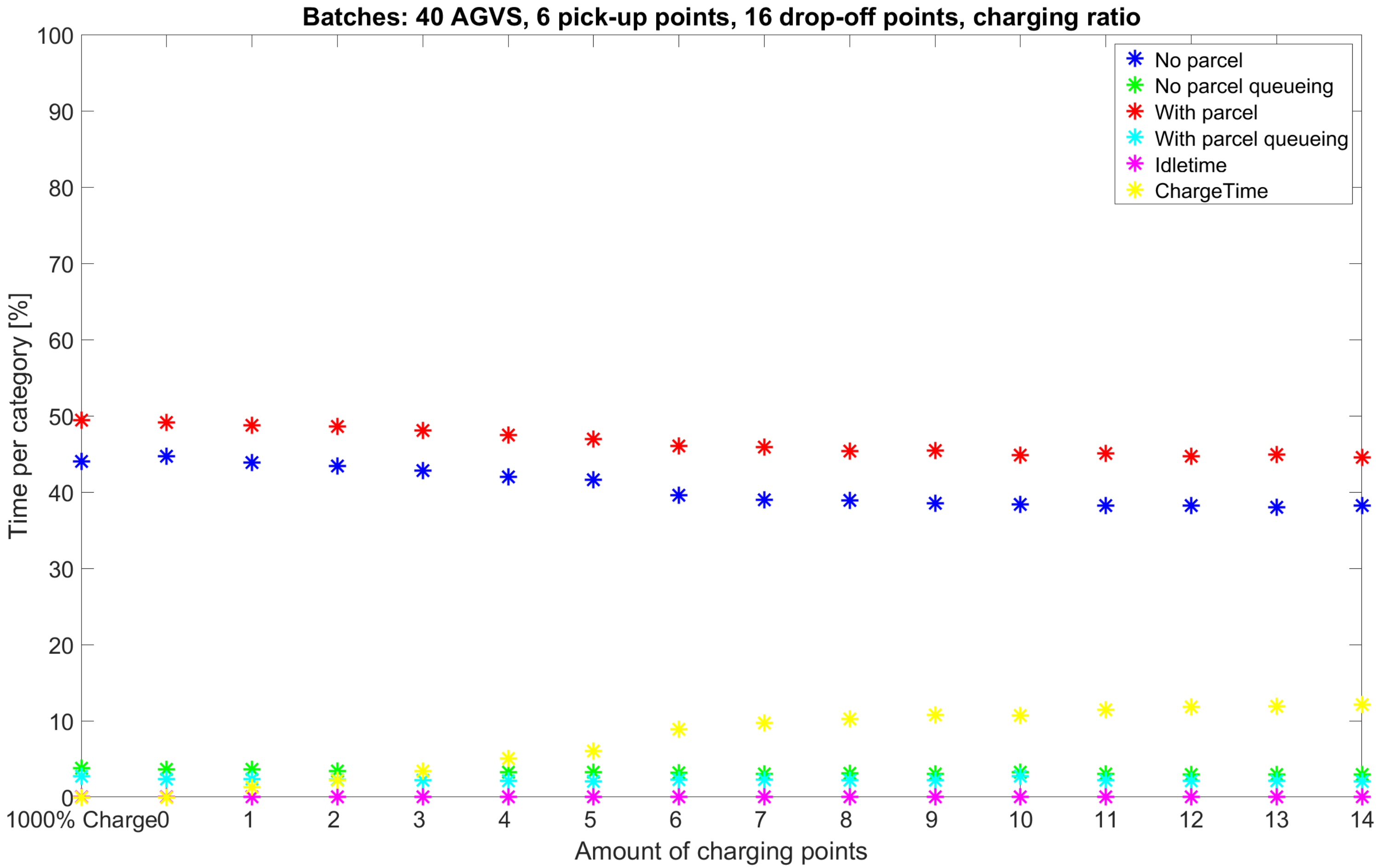
Appendix F: Confidential Appendix

Data-Set Parcels

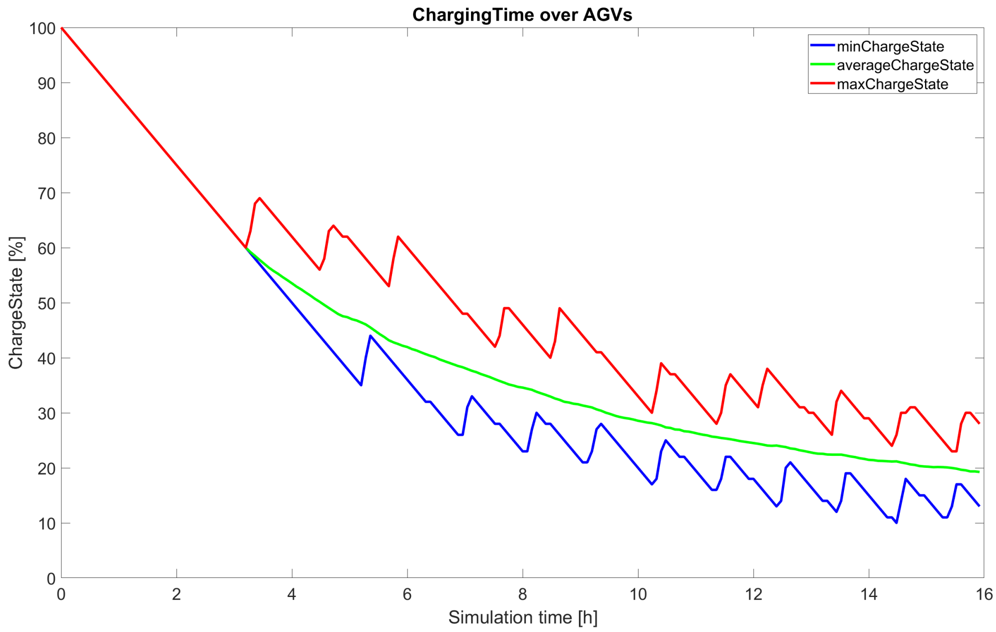
Implementation of model

Appendix G: Figures to support Chapter 7

Case 1: charging points

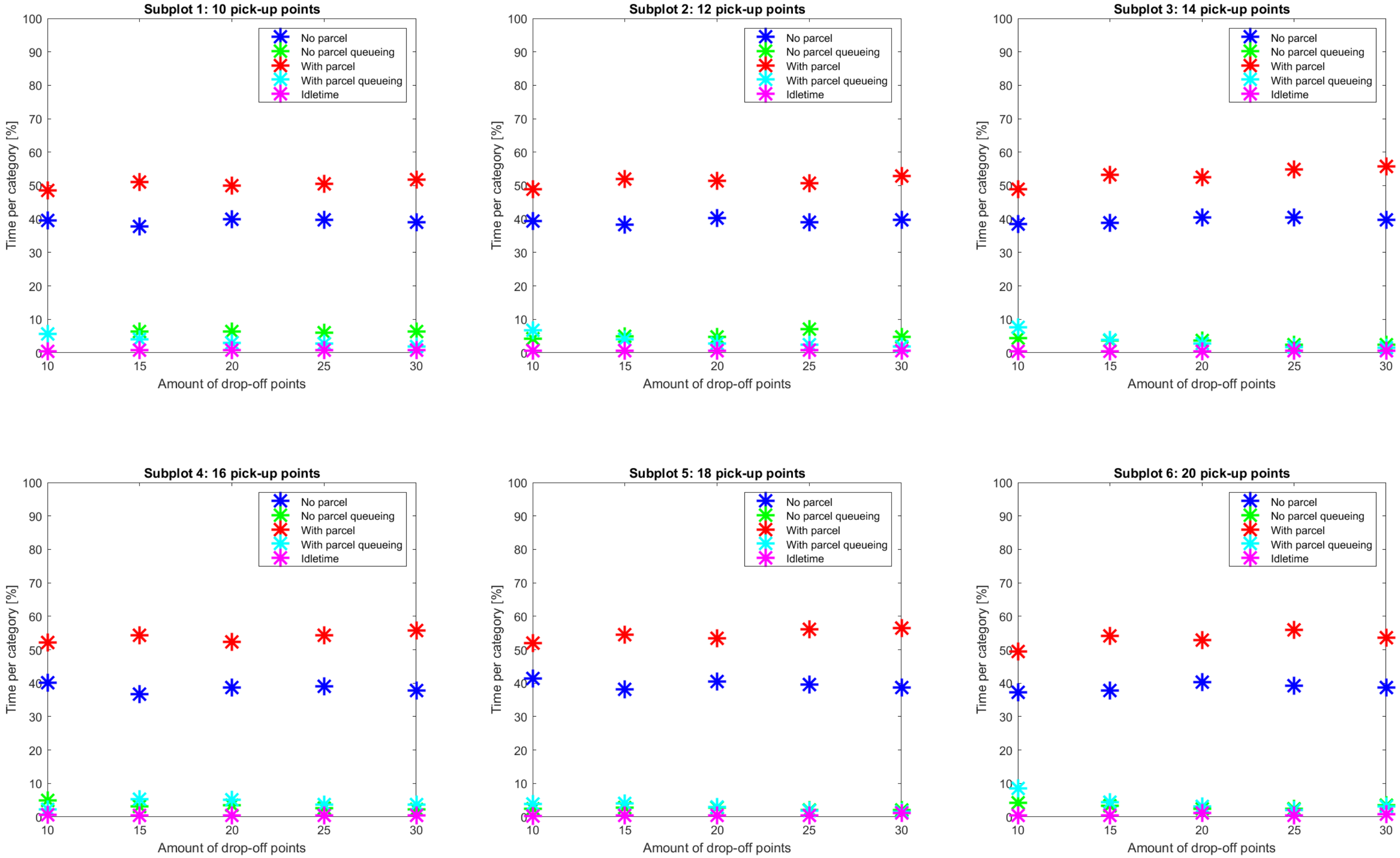


G.A: 40 AGVs, no charging versus increasing amount of charging points, 16 hours runs if applicable

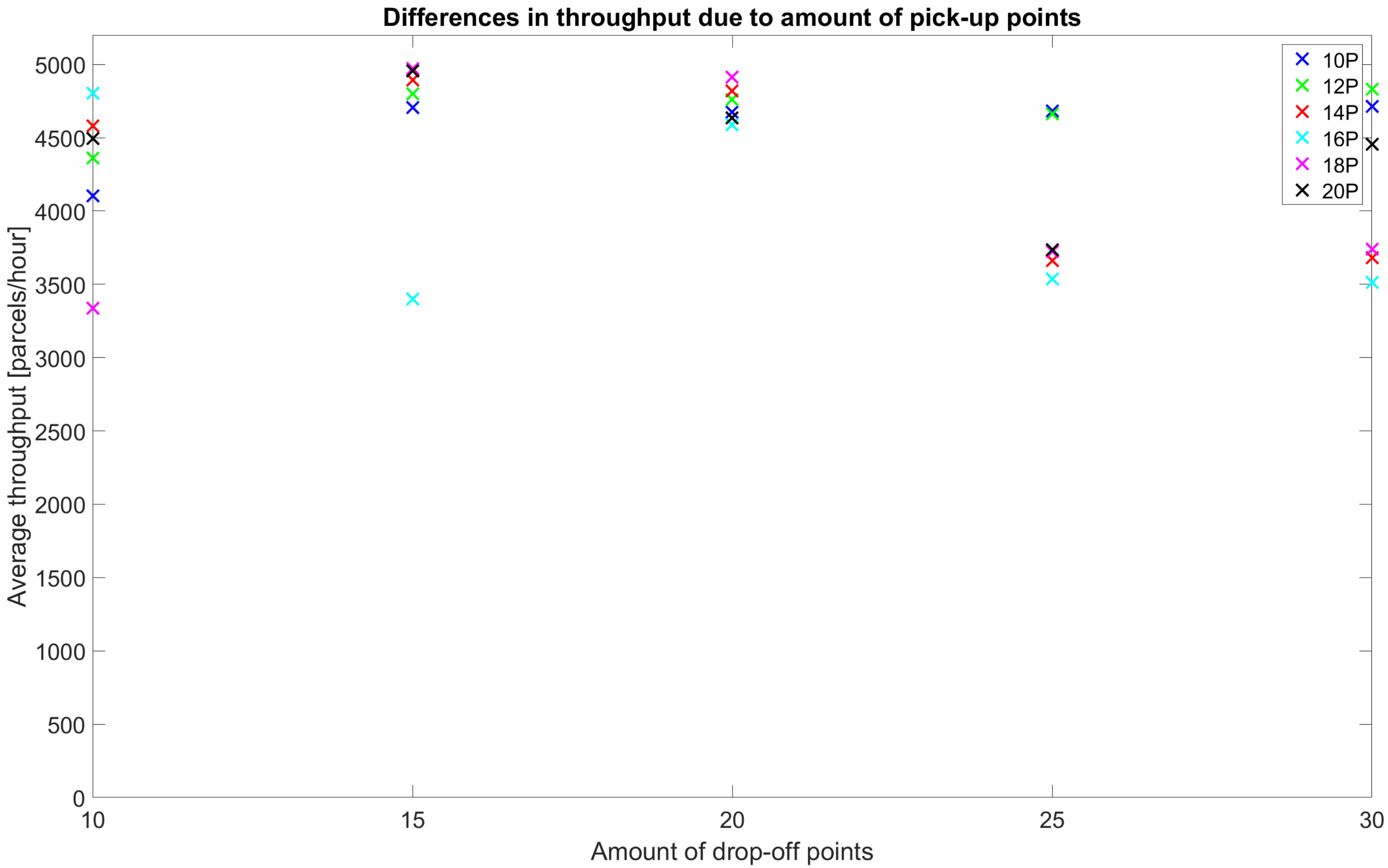


G.B: 40 AGVs, 7charging points, AGV vs charging point ratio of 5.71, 16 hours runs

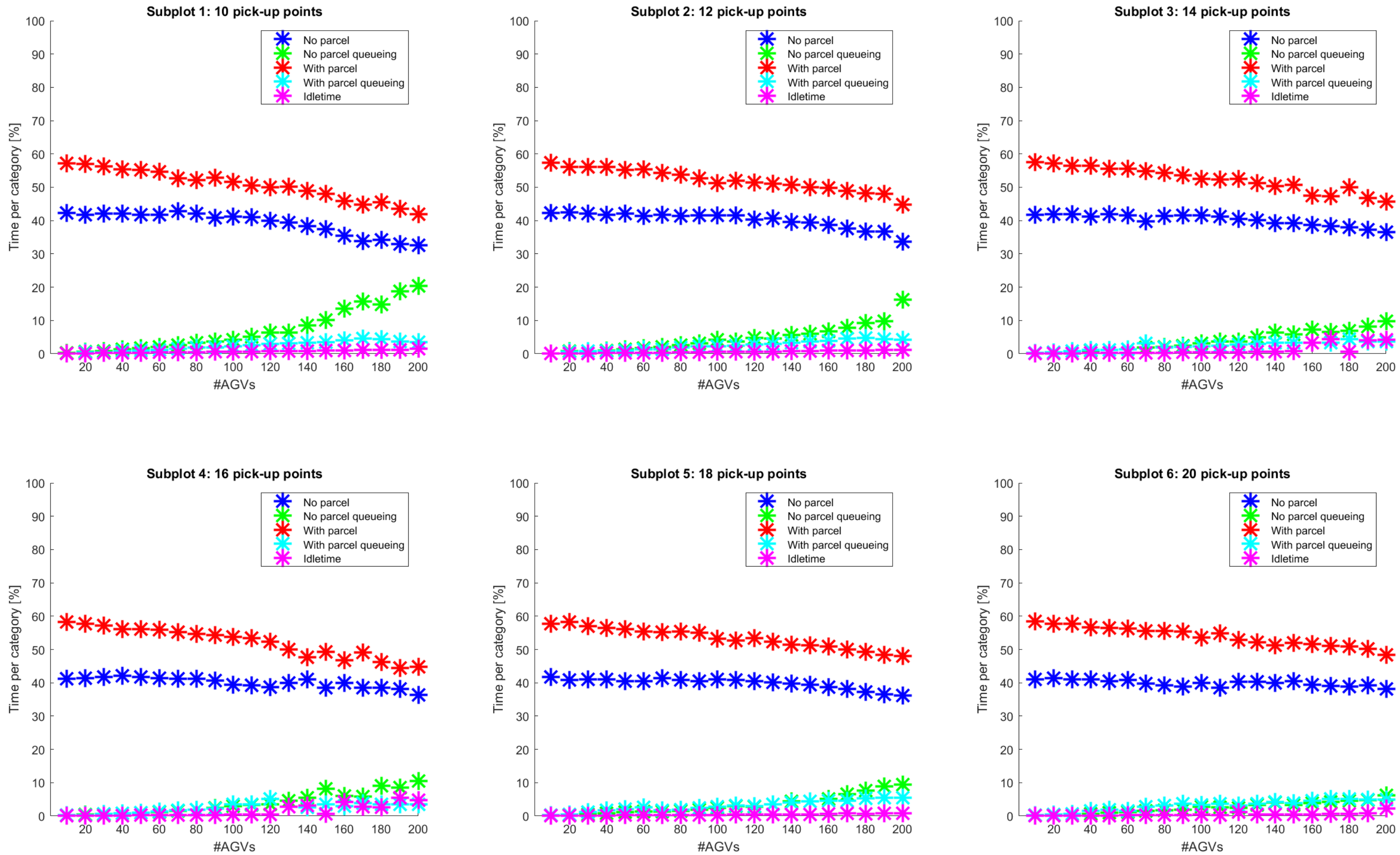
Case 2: 3000 m^2



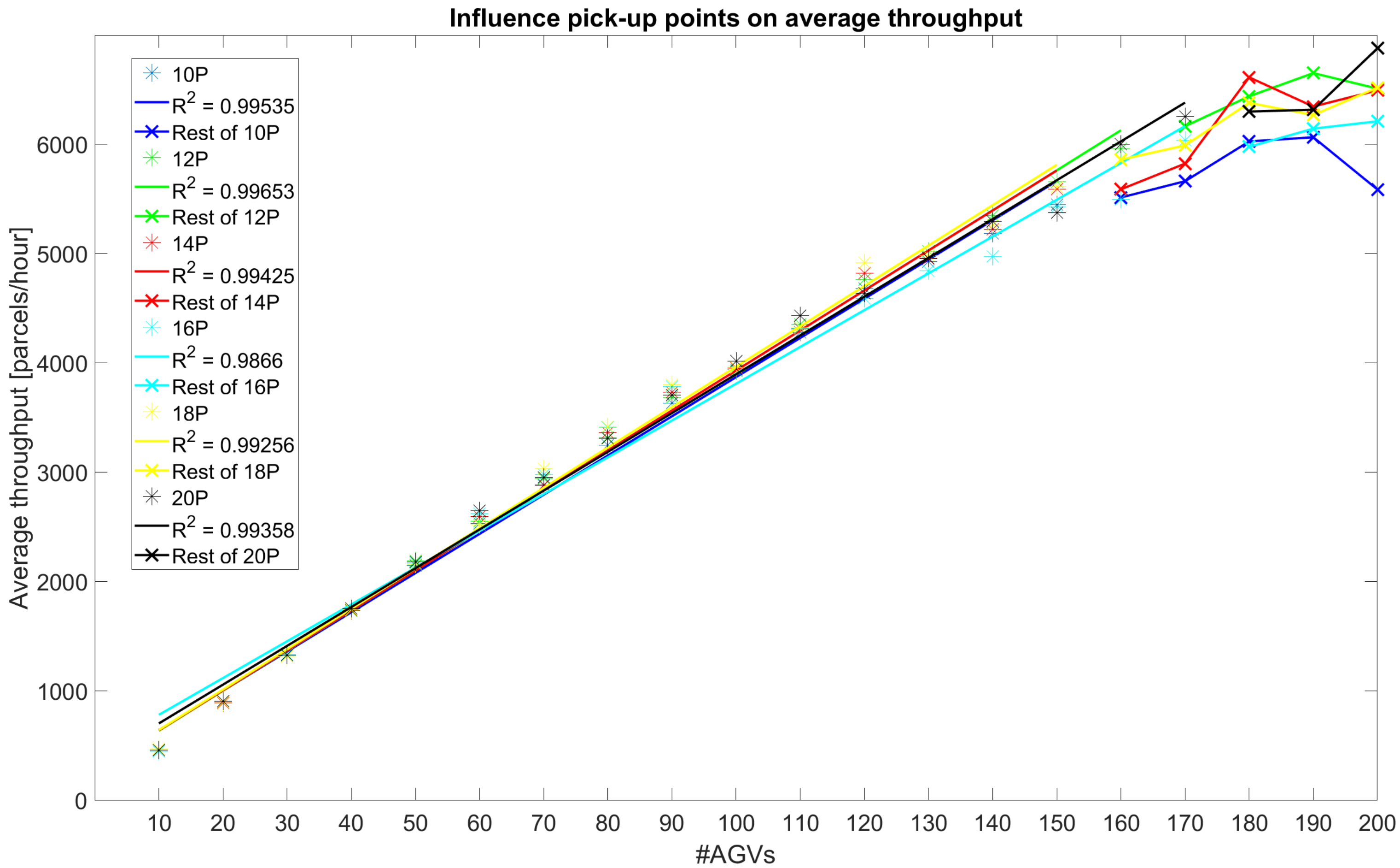
G.C: $3000m^2$ time per category 10-30 drop-off points



G.D: 3000m^2 throughput with 10-30 drop-off points



G.E: $3000m^2$ time per category 10-20 pick-up points



G.F: 3000m^2 throughput for 10-20 pick-up points

Appendix H: Pseudo code

Pick-up Process

```
{
    Randseed = Custom per Pick-up
    ParcelList containing parcels on Pickup point
    Throughput Time PickUp Point

// Generate Parcels at interval:
    Random(Randseed).Next(minimumDistributionTime, maximumDistributionTime)
    With:
        - Identifier
        - Dimensions
        - Weigth
        - Drop-off Location

    Drop-off Location = Random(Randseed).Next(1,TotalAmountOfDropOffs)
    ParcelList.Add(Parcel)
    {
        FOREACH AGVtype
            IF (Parcel Length <= AGV Max Parcel Length AND Parcel Height <= AGV Max
            Parcel Height AND Parcel Width <= AGV Max Parcel Width AND Parcel
            Weight <= AGV Load Capacity)
                IF (no AGV)
                    {
                        Request AGVType
                    }
                ELSE
                    {
                        Attach to AGV
                    }
            ELSE
                SKIP AGVType
    }
}
```

Scanner Process

```
{
    Throughput Time
}
```

Drop-off Process

```
{
    Throughput Time
    IF (AGV delivers Parcel)
        {
            Amount of Parcels delivered + 1
        }
}
```

Parcel Process
AGV Process for each AGV with a specific AGV-Type
Read scene

```
{
    While Attached to Pick-up
    {
        Count Waiting Time
    }
    While Attached to AGV
    {
        IF (Parcel != Delivered)
        {
            Count Service Time
        }
    }
}
```

```
IF (ChargeState >= Minimum Charge State && ChargeState >= Bare Minimum)
    Search for Job
        IF (Request AGVType AND Distance < Other AGVs && ChargeState >= Bare Minimum)
        {
            Job = True
            AGVList.Remove(AGV)
            IF (AGV Attached to Waitingpoint == True)
                {
                    WaitingPointList.Remove(waitingpoint)
                }
            Drive to Pick-up Point
            Count Distance ADD to Empty load distance
        }
            ELSE
        {
        Go to nearest Waiting Point
            {
                WaitingPointList.Add(waitingpoint)
                Count Distance ADD to Empty load distance
                Keep updating ChargeState >= Bare Minimum)
            }
        IF (Job == True && ChargeState >= Bare Minimum)
        {
            While At Pick-up Point && ChargeState >= Bare Minimum
                {
                    Wait Pick-up Point Throughput Time
                    Stick(Parcel) to AGV
                }
            AGVType Rated Weigth = AGVType Weigth + Parcel Weight
                {
                    AGV Rated Battery Discharge Rate = AGV Battery Discharge Rate * Factorization
                    Find(Closest Scanner)
                    Drive TO Scanner
                    Count Distance ADD to Rated load distance
                }
```

```
            While At Scanner Point && ChargeState >= Bare Minimum
                {
                    Wait Scanner Point Throughput Time
                    Receive Parcel Destination \\Drop-off Location
                }
            Drive TO Drop-off Point && ChargeState >= Bare Minimum
                {
                    Count Distance ADD to Rated load distance
                }
            While At Drop-off Point && ChargeState >= Bare Minimum
                {
                    Wait Drop-off Point Throughput Time
                    Job = False
                    AGVType Weigth = AGVType Weigth
                    AGVList.Add(AGV)
                }
        }
ELSE
    Charging Rules
        {
            Count Distance ADD to Empty load distance
            Count Waiting Time
        }
IF (Charge State = 0)
    {
        STOP
        Display error "AGV has no charge left"
    }
ELSE
    CONTINUE
```

```
{
    _NodePoints = GetNodes().ToList();

    minx.Value = Convert.ToInt32(Math.Round(_NodePoints.Min(node => node.X) - NodeWidth / 2) / NodeWidth);
    maxx.Value = Math.Round((_NodePoints.Max(node => node.X) - NodeWidth / 2) / NodeWidth);
    minz.Value = Convert.ToInt32(Math.Round(_NodePoints.Min(node => node.Z) - NodeDepth / 2) / NodeWidth);
    maxz.Value = Math.Round((_NodePoints.Max(node => node.Z) - NodeDepth / 2) / NodeWidth);

    nx = (int)(maxx - minx) + 1; // Changing it to integers
    nz = (int)(maxz - minz) + 1; // Changing it to integers
    Nodes = new Node[nx, nz];

    foreach (node in _NodePoints)
        {
            x = Convert.ToInt32((node.X - NodeWidth / 2) / NodeWidth);
            z = Convert.ToInt32((node.Z - NodeDepth / 2) / NodeDepth);
            node.Location = new Location(x + minx, z + minz);
            Nodes[x, z] = node;
        }
}
```

Appendix I: Matlab code

Matlab Code

```
close all
clear
clc
%% Coen Heemskerk Rolling Average Througput plots

Files=dir('*.xlsx*');

%%Variables

array = repmat(1:6, length(Files), 1)';
ExtractArray = repmat(1:6, length(Files), 1)';

for l = 1: length(Files)
    excelName = Files(l).name;
    dataset = xlsread(excelName);
    excelName2 = excelName(1:length(excelName)-5);
    if(isempty(dataset))
        break
    else
    time = dataset(:,5);
    throughput = (1:length(time));
    actualtime = round(max(time)/3600);
    actualhours = 1:actualtime;
    actualthroughput = (1:actualtime);

    for j =1 : actualtime
        for i=1 : length(time)
            if(time(i) > (j-1)* 60*60 && time(i) < j * 60*60)
                actualthroughput(j) = actualthroughput(j) + 1;
            end
        end
    end
    disp([excelName2,' Throughput each hour: ',
        num2str(actualthroughput), ' [parcels/hour]'])
    disp([excelName2,' Average throughput: ',
        num2str(mean(actualthroughput)), ' [parcels/hour]'])

    %% 4 calculations

%2 min
    time2 = dataset(:,5);
    minutes = 2;
    plotsize = minutes * 60;
    throughput2 = (1:length(time2));
    for i=1 : length(time2)
       reference = time2(i);
       throughput2(i) = 1;
           for j = 1 : length(time2)
               if(time2(j) <  reference &&
                   time2(j) > reference - plotsize)

                  throughput2(i) = throughput2(i) + 1;
               end
           end
    end
```

```
    for i=1 : length(time2)
        throughput2(i) = throughput2(i) * (60/minutes);
    end
    for i=1 : length(time2)
        time2(i) = time2(i) / (3600);
    end

    time5 = dataset(:,5);
    minutes = 5;
    plotsize = minutes * 60;
    throughput5 = (1:length(time5));

%5 min
    for i=1 : length(time5)
       reference = time5(i);
       throughput5(i) = 1;
           for j = 1 : length(time5)
                 if(time5(j) <  reference &&
                     time5(j) > reference - plotsize)

                   throughput5(i) = throughput5(i) + 1;
                 end
           end
    end
    for i=1 : length(time5)
        throughput5(i) = throughput5(i) * (60/minutes);
    end
    for i=1 : length(time5)
        time5(i) = time5(i) / (3600);
    end
%10 min
    time10 = dataset(:,5);
    minutes = 10;
    plotsize = minutes * 60;
    throughput10 = (1:length(time10));
    for i=1 : length(time10)
       reference = time10(i);
       throughput10(i) = 1;
           for j = 1 : length(time10)
                 if(time10(j) <  reference &&
                     time10(j) > reference - plotsize)

                   throughput10(i) = throughput10(i) + 1;
                 end
           end
    end
    for i=1 : length(time10)
        throughput10(i) = throughput10(i) * (60/minutes);
    end
    for i=1 : length(time10)
        time10(i) = time10(i) / (3600);
    end
%1 hour
    time60 = dataset(:,5);
    minutes = 60;
    plotsize = minutes * 60;
```

```
    throughput60 = (1:length(time60));
    for i=1 : length(time60)
       reference = time60(i);
       throughput60(i) = 1;
           for j = 1 : length(time60)
                 if(time60(j) <  reference &&
                     time60(j) > reference - plotsize)

                    throughput60(i) = throughput60(i) + 1;
                 end
           end
    end
    for i=1 : length(time60)
        throughput60(i) = throughput60(i) * (60/minutes);
    end
    for i=1 : length(time60)
        time60(i) = time60(i) / (3600);
    end



%% Chargestates figure 1
    chargestate = dataset(:,16);
    chargestatetime = dataset(:,15);
    chargestatetime =(chargestatetime(~isnan(chargestatetime)));

    minchargestate = 101:101+length(chargestatetime)-1;
    averagechargestate = zeros(1,length(chargestatetime));
    maxchargestate = zeros(1,length(chargestatetime));
    amountofAGVs = 0;

    for i=15 :2: size(dataset,2)
        amountofAGVs = amountofAGVs +1;
        chargestatetime = dataset(:,i);
        chargestatetime =(chargestatetime(~isnan(chargestatetime)));

         for j = 1: length(chargestatetime)
            chargestate=(chargestate(~isnan(chargestate)));
                if (chargestate(j) < minchargestate(j))
                    minchargestate(j) = chargestate(j);
                end
                if (chargestate(j) > maxchargestate(j))
                    maxchargestate(j) = chargestate(j);
                end
           averagechargestate(j) = averagechargestate(j)+ chargestate(j);
        end
    end

    for i = 1 : length(chargestatetime)
        averagechargestate(i) = averagechargestate(i) / amountofAGVs;
    end

    %% Plot Figure
    h(1) = figure;
    plot(time2,throughput2,'r',time5,throughput5,'b',
    time10,throughput10,'c');
```

```matlab
hold;

plot(time60,throughput60,'k -.','LineWidth',1.5)
maximum = max(throughput2);
Xline = xline(3.2,'m--','Charging Scheme Activated');
Xline.LabelVerticalAlignment = 'bottom';

if (max(throughput5) > (max(throughput2)))
    maximum = max(throughput5);
end
if (max(throughput10) > maximum)
    maximum = max(throughput10);
end
if (max(throughput60) > maximum)
    maximum = max(throughput60);
end

YMAX = maximum+50;
XMAX = max(time2)+0.5;
axis([0 XMAX 0 YMAX])
legend('2min','5min','10min','60min')
title({num2str(excelName2);
    ' Throughput plot with plotsize 2,5,10,60 min'});
xlabel('Time [h]');
ylabel('Throughput [ parcels/hour]');

 h(2) = figure;
subplot(2,2,1)
plot(time2,throughput2,'r',time5,throughput5,'b',
time10,throughput10,'c');
hold;
Xline = xline(3.2,'m--');

plot(time60,throughput60,'k -.','LineWidth',1.5)
axis([0 XMAX 0 YMAX])
legend('2min','5min','10min','60min')
title({num2str(excelName2);
    ' Throughput plot with plotsize 2,5,10,60 min'});
xlabel('Time [h]');
ylabel('Throughput [ parcels/hour]');
subplot(2,2,2)
plot(time2,throughput2,'r');
hold;
Xline = xline(3.2,'m--');
plot(time60,throughput60,'k -.','LineWidth',1.5)
axis([0 XMAX 0 YMAX])
legend('2min','60min')
title('Throughput plot with plotsize 2 min');
xlabel('Time [h]');
ylabel('Throughput [ parcels/hour]');
subplot(2,2,3)
plot(time5,throughput5,'b');
hold;
Xline = xline(3.2,'m--');
plot(time60,throughput60,'k -.','LineWidth',1.5)
axis([0 XMAX 0 YMAX])
```

```
    legend('5min','60min')
    title('Throughput plot with plotsize 5 min');
    xlabel('Time [h]');
    ylabel('Throughput [ parcels/hour]');
    subplot(2,2,4)
    plot(time10,throughput10,'c');
    hold;
    Xline = xline(3.2,'m--');
    plot(time60,throughput60,'k -.','LineWidth',1.5)
    axis([0 XMAX 0 YMAX])
    legend('10min','60min')
    title('Throughput plot with plotsize 10 min');
    xlabel('Time [h]');
    ylabel('Throughput [ p arcels/hour]');

    %% AGV Empty Load Distance
    EmptyLoadDistance = dataset(:,7);
    EmptyLoadDistance =(EmptyLoadDistance(~isnan(EmptyLoadDistance)));
    amountOfAgvs = length(EmptyLoadDistance);
    RatedLoadDistance = dataset(:,8);
    RatedLoadDistance =(RatedLoadDistance(~isnan(RatedLoadDistance)));
    totalDistance = EmptyLoadDistance + RatedLoadDistance;
    EmptyLoadDistance1 =(EmptyLoadDistance(~isnan(EmptyLoadDistance)));
    RatedLoadDistance1 =(RatedLoadDistance(~isnan(RatedLoadDistance)));
    for i = 1 : amountOfAgvs
        EmptyLoadDistance1(i) = EmptyLoadDistance1(i) /
        totalDistance(i) * 100;
    end
    for i = 1 : amountOfAgvs
        RatedLoadDistance1(i) = RatedLoadDistance(i) /
        totalDistance(i) * 100;
    end
    overallTotalDistance = sum(totalDistance);

%Means
    MEmptyLoadDistance1 = mean(EmptyLoadDistance1);
    MRatedLoadDistance1 = mean(RatedLoadDistance1);

    y = [EmptyLoadDistance1, RatedLoadDistance1];
     h(3) = figure;
    bar(y,'stacked')
    legend('Empty load distance','Rated load distance')
    title({num2str(excelName2);' Empty vs Rated load distance' ;
['Average Empty Load Distance: ',
sprintf('%.2f',MEmptyLoadDistance1), ' [%]'];
['Average Rated Load Distance: ',
sprintf('%.2f',MRatedLoadDistance1), ' [%]'];
['Average AGV Distance is: ',
num2str(overallTotalDistance/amountOfAgvs), ' [m]'];
['Overall Total Distance is: ',
num2str(overallTotalDistance),' [m]']});
    xlabel('AGV');
    ylabel('Empty vs Rated load distance [%]');
    axis([0 length(EmptyLoadDistance) + 1 0 100])

%% AGV Empty Load time
```

```
EmptyLoadTime = dataset(:,9);
EmptyLoadTime =(EmptyLoadTime(~isnan(EmptyLoadTime)));
EmptyLoadWaitingTime = dataset(:,10);
EmptyLoadWaitingTime =
(EmptyLoadWaitingTime(~isnan(EmptyLoadWaitingTime)));

amountOfAgvs = length(EmptyLoadTime);
RatedLoadTime = dataset(:,11);
RatedLoadTime =(RatedLoadTime(~isnan(RatedLoadTime)));
RatedLoadWaitingTime = dataset(:,12);
RatedLoadWaitingTime =
(RatedLoadWaitingTime(~isnan(RatedLoadWaitingTime)));
Idletime = dataset(:,13);
Idletime =(Idletime(~isnan(Idletime)));
ChargeTime = dataset(:,14);
ChargeTime =(ChargeTime(~isnan(ChargeTime)));

totalTime = EmptyLoadTime + EmptyLoadWaitingTime +
RatedLoadTime + RatedLoadWaitingTime + Idletime + ChargeTime;

EmptyLoadTime1 =(EmptyLoadTime(~isnan(EmptyLoadTime)));
EmptyLoadWaitingTime1 =
(EmptyLoadWaitingTime(~isnan(EmptyLoadWaitingTime)));
RatedLoadTime1 =(RatedLoadTime(~isnan(RatedLoadTime)));
RatedLoadWaitingTime1 =
(RatedLoadWaitingTime(~isnan(RatedLoadWaitingTime)));
Idletime1 = (Idletime(~isnan(Idletime)));
ChargeTime1 = (ChargeTime(~isnan(ChargeTime)));
for i = 1 : amountOfAgvs
    EmptyLoadTime1(i) = EmptyLoadTime1(i) / totalTime(i) * 100;
end
for i = 1 : amountOfAgvs
    EmptyLoadWaitingTime1(i) = EmptyLoadWaitingTime1(i) /
    totalTime(i) * 100;
end
for i = 1 : amountOfAgvs
    RatedLoadTime1(i) = RatedLoadTime1(i) / totalTime(i) * 100;
end
for i = 1 : amountOfAgvs
    RatedLoadWaitingTime1(i) = RatedLoadWaitingTime1(i) /
    totalTime(i) * 100;
end
for i = 1 : amountOfAgvs
    Idletime1(i) = Idletime1(i) / totalTime(i) * 100;
end
for i = 1 : amountOfAgvs
    ChargeTime1(i) = ChargeTime1(i) / totalTime(i) * 100;
end

y = [EmptyLoadTime1,EmptyLoadWaitingTime1,RatedLoadTime1,
    RatedLoadWaitingTime1,Idletime1,ChargeTime1];
 h(3) = figure;
bar(y,'stacked')

MEmptyLoadTime1= mean(EmptyLoadTime1);
MEmptyLoadWaitingTime1 = mean(EmptyLoadWaitingTime1);
```

```
    MRatedLoadTime1 = mean(RatedLoadTime1);
    MRatedLoadWaitingTime1 =mean(RatedLoadWaitingTime1);
    MIdletime1 = mean(Idletime1);
    MChargeTime1 = mean(ChargeTime1);
    title({num2str(excelName2) ; ' Empty vs Rated load time' ;
        ['Average Empty Load Time: ',
        sprintf('%.2f',MEmptyLoadTime1), ' [%]'];
        ['Average Empty Load Waiting Time: ',
        sprintf('%.2f',MEmptyLoadWaitingTime1), ' [%]'];
        ['Average Rated Load Time: ',
        sprintf('%.2f',MRatedLoadTime1) , ' [%]'];
        ['Average Rated Load Waiting Time: ',
        sprintf('%.2f',MRatedLoadWaitingTime1), ' [%]'];
        ['Average Idle Time: ',
        sprintf('%.2f',MIdletime1), ' [%]'];
        ['Average Charge Time: ',
        sprintf('%.2f',MChargeTime1), ' [%]']});
    legend('EmptyLoadTime','EmptyLoadWaitingTime',
    'RatedLoadTime','RatedLoadWaitingTime','Idletime','ChargeTime')
    xlabel('AGV');
    ylabel('Empty vs Rated load time [%]');


%% Values for overall figure
    axis([0 length(EmptyLoadTime1) + 1 0 100])
    array(1,l) = MEmptyLoadTime1;
    array(2,l) = MEmptyLoadWaitingTime1;
    array(3,l) = MRatedLoadTime1;
    array(4,l) = MRatedLoadWaitingTime1;
    array(5,l) = MIdletime1;
    array(6,l) = MChargeTime1;

%% Parcel Waiting and Service Time
    servicetime = dataset(:,3);
    waitingtime = dataset(:,4);
    amountOfParcels = 1:length(servicetime);
    averageservicetime = mean(servicetime);

    h(4) = figure;
    bar(amountOfParcels,servicetime)
    xlabel('Parcel');
    ylabel('Servicetime [seconds]');
    title({'Servicetime per parcel'; ['Average: ',
        sprintf('%.2f',averageservicetime), ' [s]']})
    averagewaitingtime = mean(waitingtime);

    h(5) = figure;
    bar(amountOfParcels,waitingtime)
    xlabel('Parcel');
    ylabel('Waitingtime [seconds]');
    title({'Waitingtime per parcel'; ['Average: ',
        sprintf('%.2f',averagewaitingtime), ' [s]']})

%% Charging
    % AGV Charging
    ChargingTime = dataset(:,15);
```

```matlab
    ChargingTime =(ChargingTime(~isnan(ChargingTime)));
    ChargingState = dataset(:,16);
    ChargingState =(ChargingState(~isnan(ChargingState)));
    ChargeStates = NaN(length(ChargingTime), amountofAGVs);
    for i = 1 : amountofAGVs
        %i = 1 : 2 : size(dataset,2) - 15
        tempChargingState = dataset(:,14 + 2 * i);
        tempChargingState =(tempChargingState(~isnan(tempChargingState)));
        for j = 1 : length(ChargingTime)
            ChargeStates(j,i) = tempChargingState(j);
        end
    end

    averageChargeState = mean(ChargeStates')';
    minChargeState = min(ChargeStates')';
    maxChargeState = max(ChargeStates')';
    ChargingTime = ChargingTime / 3600;
     h(6) = figure;

     plot(ChargingTime, minChargeState, 'b', ChargingTime,
     averageChargeState, 'g',ChargingTime, maxChargeState, 'r');

     xlabel('ChargingTime [h]');
     ylabel('ChargeState [%]');
     title('ChargingTime over AGVs');
     legend('minChargeState','averageChargeState','maxChargeState')

%% Extract data for overall figures
    ExtractArray(1,l) = mean(actualthroughput);
    ExtractArray(2,l) = MEmptyLoadDistance1;
    ExtractArray(3,l) = MRatedLoadDistance1;
    ExtractArray(4,l) = averageservicetime;
    ExtractArray(5,l) = averagewaitingtime;
    ExtractArray(6,l) = overallTotalDistance/amountOfAgvs;

%% Save Figures for (possible) later editing
     extension = '.fig';
     savefig(h,strcat(excelName2,extension))

    end
end

%% Plot multiple runs in 1 graph

    x = 1:length(Files);

    h(7) = figure;

    y = array(1,1:length(Files),1);
    plot(x, y, 'b*-', 'LineWidth', 2, 'MarkerSize', 15);
    hold

    y = array(2,1:length(Files),1);
    plot(x, y, 'g*-', 'LineWidth', 2, 'MarkerSize', 15);

    y = array(3,1:length(Files),1);
```

```
    plot(x, y, 'r*-', 'LineWidth', 2, 'MarkerSize', 15);

    y = array(4,1:length(Files),1);
    plot(x, y, 'c*-', 'LineWidth', 2, 'MarkerSize', 15);

    y = array(5,1:length(Files),1);
    plot(x, y, 'm*-', 'LineWidth', 2, 'MarkerSize', 15);

    title('Batches:6 kg AGVs and 32kg AGVs,
    6 pick-up points, 10 drop-off points');
    set(gca,'FontSize',20)
    set(gca,'XTick', x)
    legend('EmptyLoadTime','EmptyLoadWaitingTime','RatedLoadTime',
    'RatedLoadWaitingTime','Idletime','ChargeTime')
    xlabel('S = # of 6 kg AGVs and L = # 32kg AGVs');
    ylabel('Time per category [%]');
    axis([1 length(Files) 0 100])
    xticks(1:length(x));
    xticklabels({'40S00L';'35S05L';'30S10L';'25S15L';'20S20L';
        '15S25L';'10S30L';'05S35L';'00S40L'});



%% save overall figure
    extension = '.fig';
    savefig(h,strcat(excelName2,extension))

%% Figure
    figure;

    x= 0:5:40;
    y = ExtractArray(1,1:9);
    fitobject1 = fit(x',y','poly1')
    a = plot(fitobject1,x,y,'*');
    a(1).MarkerSize = 15;
    a(2).Color = 'b';
    a(2).LineWidth =2;
    hold on
    R = corrcoef(x,y);
    Rsq1 = R(1,2).^2;

    y = ExtractArray(1,6:10);
    fitobject2 = fit(x',y','poly1')
    a = plot(fitobject2,x,y,'*');
    a(1).MarkerSize = 15;
    a(2).Color = 'g';
    a(2).LineWidth =2;
    R = corrcoef(x,y);
    Rsq2 = R(1,2).^2;

    y=ExtractArray(1,11:15);
    fitobject3 = fit(x',y','poly1')
    a = plot(fitobject3,x,y,'*');
    a(1).MarkerSize = 15;
    a(2).Color = 'r';
    a(2).LineWidth =2;
```

```
    R = corrcoef(x,y);
    Rsq3 = R(1,2).^2;

    y=ExtractArray(1,16:20);
    fitobject4 = fit(x',y','poly1')
    a = plot(fitobject4,x,y,'*');
    a(1).MarkerSize = 15;
    a(2).Color = 'c';
    a(2).LineWidth =2;

    R = corrcoef(x,y);
    Rsq4 = R(1,2).^2;

    y=ExtractArray(1,21:25);
    fitobject5 = fit(x',y','poly1')
    a = plot(fitobject5,x,y,'*');
    a(1).MarkerSize = 15;
    a(2).Color = 'm';
    a(2).LineWidth =2;
    R = corrcoef(x,y);
    Rsq5 = R(1,2).^2;

    y=ExtractArray(1,26:30);
    fitobject6 = fit(x',y','poly1')
    a = plot(fitobject6,x,y,'*');
    a(1).MarkerSize = 15;
    a(2).Color = 'k';
    a(2).LineWidth =2;
    R = corrcoef(x,y);
    Rsq6 = R(1,2).^2;

    title('Influence pick-up points on average throughput');
    xlabel('#AGVs');
    ylabel('Average throughput [parcels/hour]');
    RS = 'R^2 = ';
    legend('2P',[RS num2str(Rsq1)]);
    set(gca,'FontSize',20);

%% Alterations for multi-AGV
    figure
    x= 0:5:40;
    y = ExtractArray(1,1:9);
    bar(y,'stacked')
    title('Throughput of batches:6 kg AGVs and 32kg AGVs,
    6 pick-up points, 10 drop-off points');
    ylabel('Average throughput [parcels/hour]');
    set(gca,'FontSize',20);
    xticks(1:length(x));
    xticklabels({'40S00L';'35S05L';'30S10L';'25S15L';'20S20L';
        '15S25L';'10S30L';'05S35L';'00S40L'});
    xlabel('S = # of 6 kg AGVs and L = # 32kg AGVs');
```