MASTER

# Improvement of a batch heuristic for the layer picking process to accomplish lead time reduction

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# Improvement of a batch heuristic for the layer picking process to accomplish lead time reduction

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# I. ABSTRACT

This master thesis describes heuristics that can be used to allocate complete trips to batches within the fast moving consumer goods operation of Kuehne + Nagel Veghel when lead time reduction is required. The different heuristics are compared with the current set of assignment rules in terms of key performance indicators and costs. The process of developing the multiple heuristics contains the analysis of the overall warehouse process, the comparison of historical batch performance and the analysis of the historical automated layer picking usage. The three steps of analyses identify improvement opportunities within the operation and batch performance influencers.

# II. ACKNOWLEDGEMENTS

This report is the result of the master thesis project I have performed as the final phase of the master program Operation Management and Logistics at the Eindhoven University of Technology. The research is done at the logistic service provider Kuehne + Nagel Veghel, where I worked, from May 2015 till December 2015, internally to fulfil the assignment.

First of all I want to thank my mentor and first supervisor Dr. L.P. Veelenturf. His guidance throughout the project was very valuable, since it was always possible to schedule meetings on short notice. During the meetings Mr. Veelenturf pointed me on important topics and points that needed more attention. The critical feedback I received was motivational and made me take extra steps to improve the research.

I also want to thank Dr. ir. R.A.C.M. Broekmeulen for being my second supervisor. His experience and knowledge about warehousing were added values to my research. In our meetings his questions made me rethink the underlying structure from the conclusions I had drawn. This was an important asset during the development of the research proposal.

Furthermore I want to thank the company Kuehne + Nagel Veghel for the possibility to do my master thesis research so up-close to the operation. I gained a lot of experience working in a company's environment. Especially I want to show gratitude to my company's suprvisor Ir. I. van der Meulen, Senior Logistic Engineer. The weekly meetings we had caused a lot of discussions and brainstorm sessions, which resulted in progression and further improvement of the project. I also would like to thank Ir. J. van Dongen for the temporarily supervision when Ir. I. van der Meulen was on his holidays. Within the company's warehouse operation I am grateful to the Operations Manager E. de Graauw and Site Manager M. de Bruijn for answering my questions and providing data. In particular E. de Graauw who was always eager to help me as quick as possible and provided me with necessary information while casually talking about "De Vleut", "Boskant" and "Carnaval". I would like to show my appreciation to all other employees of Kuehne + Nagel who contributed in some way to my master thesis project.

To conclude I want to thank my friends and family for their support and also their distractions during my study. With finishing this master thesis I am also ending my academic years. It's time for me to close this chapter and start living my life as a grownup.

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# III. EXECUTIVE SUMMARY

### Introduction

This report is a result of the master thesis research which was completed at the fast mover consumer goods warehouse of Kuehne + Nagel in Veghel. Five main order picking related processes can be found within this warehouse. The first process consists of the transport planning. The transport planning is leading for the other four processes and describes the departure times and trailer composition of trips at the outbound of the warehouse. The second process contains the picking of full pallets. Full pallet picking is done automatically or conventional based. When the pallets are picked automatically they are retrieved from the high bay, otherwise they are picked from the racking in the order pick hall respectively. The third process describes the layer picking. This process can be done manually or automatically with the automatic layer picker (ALP). Whether a product can be picked by the ALP depends on its characteristics. The process in which single case packs are collected is next. This process can only be done conventional based due to the difference in the products characteristics. The last process is staging. Staging is the storage of collected products, described by the previous three processes, before they depart to the customers' distribution centre.

The lead time distribution is an important topic within the operation. Three different lead time distributions occur: 48 hour, 24 hour and same day deliveries. The 48 hour lead time orders are received at day 1 and delivered at day 3. The 24 hour lead time orders are delivered at day 2 and the same day lead time orders at day 1 respectively. Order receipts are always done before 11:00, but the delivery of orders can be done throughout the whole day.

### Research proposal

It is thought that in the future the demand for the 48 hour orders will decrease and eventually all orders will be 24 hour or same day delivery (AH orders) variants. It is expected that this reduction of lead time will be beneficial for the operation due to the decrease in operational complexity. Furthermore it is thought that the lead time reduction increases the accuracy of the transport planning, and thereby reduces the costs of redundant handling. A big challenge within the lead time reduction is the use of the ALP. Batches that currently run on the ALP are built as large as possible because it is thought that this will increase the pick performance. The reduction of lead time will decrease the batch size. With this as a premise the design question of this master thesis project is formulated as:

*Design a batch planning heuristic for the layer picking process when only 24 hour and same day lead times orders occur that reduces the costs of the layer picking operation without reducing the current service level*

Within the research, batch heuristics are developed which can be used to compose batches for the layer picking process in the situation when 24 hour lead times are the maximum lead times that occur within the operation. Before the development of the heuristics the current automatic layer picking process is analysed in terms of approximated performance, batch allocation and batch performance. Comparison between the developed heuristics and current situation is done theoretical with the help of a deterministic picking model and 8 key performance indicators.

## Analyses of the batch allocation

The current operation is analysed based on the batch allocation per machine. This analysis also contains the utilisation of the ALP operation per day and the distribution of this utilisation during the day.

It is found that currently the mean ALP utilisation is approximately 66%. Although the ALP is idle for 34% of the time, still a remarkable percentage of 18% of the total amount of layers that could be picked with the ALP, is picked manually. Interviews with the operations staff explained that those layers are picked manually because those contain backorders. Backorders are orders for which the products are not present at the warehouse during the start of the automatic picking process. That is why they are picked manually. However, the products that are needed to fulfil the demand of backorders are received till 16:00. The utilisation analysis shows that after that time there is room to create small batches and pick the backorders automatically.

## Analysis of the batch performance

During the analysis of the batch performance historical data is used to find performance indicators which influences the batch performance positively as well as negatively. The analysis are done based on batch composition and product characteristics.

First the influence of batch size on pick efficiency is schematically represented. Batch size is defined as the amount of source pallets per batch. It was found that above 100 source pallets the variance in pick efficiency changes. The variance in batch efficiency is much larger for batches smaller than 100 source pallets. Secondly it is found that smaller batches perform better in terms of layers per hour than bigger variants. The mean batch efficiency is 97 and 76 layers per hour respectively. The weighted average pick efficiency is 82 layers per hour although 110 is specified.

The variable batch size is relatively superficial to explain the pick performance of the ALP. For that reason the variable pick profile is introduced. Pick profile is defined as the mean amount of layers per source pallet. It was found that an increase in pick profile resulted in an increase in pick efficiency. The pick profile can be increased by either increasing the order quantity per customer, or by allocating customers that require the same SKU, and thus the same source pallet, to the same batch. Increasing the pick profile by allocating customers that require the same SKU to the same batch is something that can be accomplished by the operation.

The term synergy is introduced. Synergy covers the positive effects during the composition of batches. Synergy contains two factors which decrease the amount of pallet movements within the ALP operation. First of all synergy tries to increase the pick profile as seen previously. Secondly it is preferred to decrease the amount of daughter pallet movements. Daughter pallet movements can be reduced by adding complete customers' orders to a batch and by smart sequencing. Smart sequencing can be achieved when for example a daughter pallet needs a layer from both the currently placed, and the following retrieved source pallet. Handling reduction is then achieved when the daughter pallet is not send to the daughter pallet buffer but left in the machine during the source pallet change.

## Gap analyses

It was found that there is a big difference between the theoretical and historical pick performance and ALP utilisation. It is specified that a round 20% delay time is allowed within the operation. These 20% contains 15% machine delay and 5% operational delay, which are commonly used numbers within the industry. The technical service department found that the delay time sometimes exceeded the 50%.

## Scenario's

In total six heuristics are compared with the baseline model with the help of a deterministic model. The baseline model contains the historical batches. These batches are composed based on limited transport information. The first heuristic contains the current 48 hour lead time situation and the current batch rules, in which new batches are made based on the fully known transport information. For the new 24 hour situation 4 new heuristics are created. The first is based on the current batching rules where composition of batches is done sequential. Batches are alternately allocated to one of the two ALP's. The second heuristic is based on the current batching rules but batches are created parallel for botch ALP's and have equal batch sizes. The third and fourth heuristic within the situation with lead time reduction, composes batches based on the found synergy factor. In the third heuristics batches have equal batch sizes. This is not the case with the fourth heuristic. Also the situation is simulated in which all layers are picked manually to see the effect of the use of the ALP on costs.

## Experimental setup

The experimental setup, to compare the heuristics, contains two historical weeks. The first week, week 26, represents a week with a picking load of 12534 layers. The second week, week 16, represents a week with a high picking load of 14636 layers. When translating the current 48 hour lead time into the new 24 hour lead time situation, it is assumed that the customers receive their orders on the same day, but the placement of the customers' orders moves one day forward. The 24 hour and same day deliveries do not change.

Because it is indicated that process improvements can be made, simulations are done to analyse the impact of those improvements on the pick performance. The costs per layer is the most important performance indicator in this respect. The decision coefficient on which the allocation of batches is made deviates from 82 till 115 layers per hour.

## Results

First of all it was found that the use of the ALP is beneficial for the operational costs. Compared to the baseline model the costs per layer are more than 60 cent higher when picking all layers manually. Secondly it can be concluded that within the current 48 hour lead time situation there is room for improvements in terms of costs. This can be accomplished by increasing the amount of trip information and by picking 24 hour and AH orders together within the same pick cycle. As a result the amount of picked layers will increase. The disadvantage is the increase of trips that need to get stored at alternative locations due to the exceedance of the maximal rack occupancy.

Furthermore it is found that the lead time reduction to 24 hours can be accomplished without increasing the costs. In fact, costs will decrease due to the decrease of trips that need to get stored at alternative locations and the increase in the accuracy of the transport planning.

The heuristic, which is based on the current batching rules, performs comparable with the heuristic in which synergy is combined with variable batch sizes. It is found that heuristics that compose batches with variable batch sizes outperform heuristics with fixed sizes.

The heuristics in which synergy is introduced do not increase the pick efficiency. Synergy does not show any effect when the composition of batches is done based on complete trips. This is because synergy does not change significantly when a trip is added to a batch that contains customers that do and customers that don't have SKU's in common with customer that are already within the batch.

Last it is found that when process improvements are implemented 95% of all layers can be picked automatically. Then also the costs per layer are reduced with approximately 9 cents. Process improvements have more effect on the heuristic that is based on the current batch method as on the new synergy heuristics. The difference is on average 13% in costs per layer.

### Conclusions and recommendation

The main conclusion of the research is that lead time reduction can be accomplished without introducing new difficult batch heuristics. A modified heuristic based on the current used batching rules performs such that the costs are reduced compared to the 48 hour situation. An accurate transport planning is key for the costs reduction.

It is recommended to develop a more dynamic simulation before implementing the lead time reduction. This new simulation could analyse the effect of the distribution of trip departure and stochastic processing times more deeply.

Next it can be concluded that the operation contains room for improvements in terms of the performance and utilisation of the ALP and in terms of operational changes.

- First of all it is recommended to reduce the amount of operational issues within the ALP operation. This will directly reduce the costs significantly.
- The reduction of lead time requires tight scheduling with strict deadlines per process. Exceeding specified event times can have a major impact on the overall pick planning due to the more tight sequencing of pick events. Cooperation between internal departments and with external customers is required to improve this process.

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# VIII. LIST OF ABBREVIATIONS

| | |
|---|---|
| ALP | Automatic layer picker |
| CS | Customer service |
| HB | High bay |
| MOQ | Minimal order quantity |
| OPH | Order pick hall |
| KPI | Key performance indicator |
| WMS | Warehouse management system |
| FEFO | First expire first out |
| THT | Dutch term for best before dates |
| DC | Distribution centre |
| $\Delta c$ | Savings |
| $B$ | Amount of broken pallets that needs to get processes at the outfeed of the ALP |
| C | Amount of case packs |
| $a, b, c, d, e, f, g$ | Regression factors |
| $c_{alp}$ | Costs of the physical automated layer picking |
| $c_b$ | Costs of the broken pallet handing at the outfeed of the ALP |
| $c_i$ | Costs of pallet handling at the infeed of the ALP |
| $c_m$ | Costs of manual layer picking |
| $c_r$ | Penalty costs of exceeding the maximal racking occupancy |
| $c_{total}$ | Total costs |
| $D$ | Amount of daughter pallets |
| $E_c$ | Pick efficiency of case pick |
| $E_w$ | Weighted ALP pick efficiency |
| $H$ | Amount of sandwich pallets |
| $K$ | Amount of customers |
| $I$ | Amount of retrieved source pallets at the infeed of the ALP |
| $L$ | Amount of layers |
| $n$ | The number of batches |
| $\eta$ | Efficiency |
| $S$ | Amount of SKU's |
| $T2$ | Amount of type 2 SKU´s |
| $t_b$ | Broken pallet handling at the outfeed of the ALP |
| $P$ | Amount of pallets per trip |
| $R$ | Maximum racking occupancy |
| $R_s$ | Amount of trips stored at the racking at second $s$ |
| $t_{dep,i}$ | Departure time of trip $i$ |
| $t_{ex}$ | Expected picking time |
| $t_{e,i}$ | Machine time of event $i$ |
| $t_f$ | Time that the picking needs to be finished before departure of the trip |
| $t_i$ | Processing time of pallets at the infeed of the ALP |
| $t_p$ | Utilization |
| $t_{o,i}$ | Time to change the footprint before pick $i$ |
| $t_r$ | Processing time of pallets that need to get stored at alternative |
| $t_{start}$ | Start time of a batch |
| $t_{t,i}$ | Layer transferring time of pick $i$ |
| $\tau$ | Maximal processing time from starting the batch till the departure of the trip |
| $u$ | ALP utilisation |
| $w_h$ | Hourly wage of an operator or picker |

# 1 PROJECT ENVIRONMENT

Before describing the research problem, a general insight will be given into the project environment. This project environment first describes the company at which the research is done. The main warehouse processes within the operation are mentioned. Lead time distribution is an important topic that influences those processes. Therefore the different order lead times that occur within the operation are discussed more deeply.

## *1.1 Kuehne + Nagel*

Kuehne + Nagel was founded by August Kuehne and Friedrich Nagel in 1890 and is originally German. Over the years Kuehne + Nagel has grown into one of the world's leading logistics service providers. In there are than 63,000 employees contracted worldwide, of whom more than 2,700 in the Netherlands.

### 1.1.1 Services

The services provided by the company worldwide can be divided into five categories. First Kuehne + Nagel is one of the largest airfreight forwarding specialists in the world. Every year nearly 1,000,000 tons of air cargo is processed. The second category is seafreight. Worldwide 7,500 seafreight specialists are ready to provide tailor-made solutions for every specific customer. The third category is overland logistics. This category includes groupage, specialized network and event solutions. Also full truck (FTL) solutions are an important theme. The fourth category is contract logistics. With 7 million square meters of warehouse across 65 countries Kuehne + Nagel is the world's leading company. Integrated logistics is the last category. Kuehne + Nagel creates lean, agile and demand driven supply chains by collaborative operating models within tailor made solutions. Kuehne + Nagel provides services in industries like aerospace, automotive, high-tech, retail, healthcare and many more (Kuehne+Nagel, 2015).

### 1.1.2 Geographic

The company has more than 1000 offices and warehouse locations in over 100 countries, from which 24 are located in the Netherlands. Rotterdam functions as the country headquarters. The earlier mentioned workforce is dedicated to offer customers integrated and end-to-end supply chain solutions. Because of the fact that 50% of the goods entering the European Union go through the harbour and airports of Rotterdam and Amsterdam, the Netherlands is the key logistic gateway to Europe. With a total warehouse space of more than 450,000$m^3$, the company is ranked with the world's top five players in contract logistics and number two within the Netherlands.

## *1.2 Warehousing*

The project focuses on the picking process of the warehouse operation in Veghel (NL). This warehouse mainly serves grocery stores and wholesalers. The general warehouse flow can be found in Figure 2. The warehouse operation includes five main processes that are related to the order picking: Planning, full pallet picking, layer picking, case picking and staging. Those topics will be explained within this paragraph.

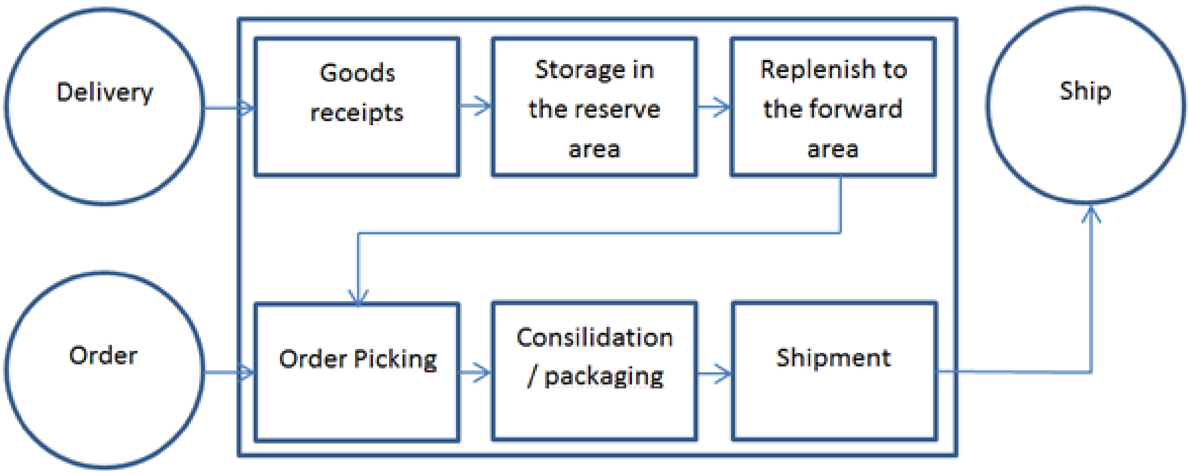


Figure 1 General warehouse flow (Chen, Gong, De Koster, & Van Nunen, 2010)

### 1.2.1 Transport planning

The transport planning is leading for the other four mentioned processes. Planning is done in three stages. The first stage is the route planning. With route planning orders are combined to create cost effective trips in observance of among other things traveling distance, traveling times and return shipments. Truck volume and delivery times are hard constrains within the route planning. The transport department determines which truck delivers which order. This is a hard constrain for the warehouse department.

The second stage covers capacity planning. Capacity planning allocates the trips to the vehicles. Vehicles are classified as own, subcontractors or charters. Vehicle occupations, rest, driving hours and customers' requirements need to be taken into account.

Also return deliveries are an important topic. The last planning is the real time planning. During the day last minute changes, due to delays and emergency shipments, can occur and need to be processed.

### 1.2.2 Full pallet picking

Full pallet picking can be done automatically or conventional based. With automatic picking full pallets are retrieved from the automatic high bay (HB) warehouse and send via a conveying system directly to the staging area. When full pallets are picked conventional, a picker retrieves pallets from the racking in the order pick hall (OPH) with a reach truck and transfers them to the staging area.

### 1.2.3 Layer picking

Also the layer picking process can be done automatically or manually. The automatic layer picker (ALP) is preferred because it picks faster and more cost efficient. Although these advantages to use the ALP is bound by a number of constraints and difficulties. Besides the limitation of having a maximum capacity, it has the difficulty of having the need for a complex planning algorithm to determine the batch composition and pick sequence. Due to the importance of the ALP it will be discussed more deeply in chapter 4.

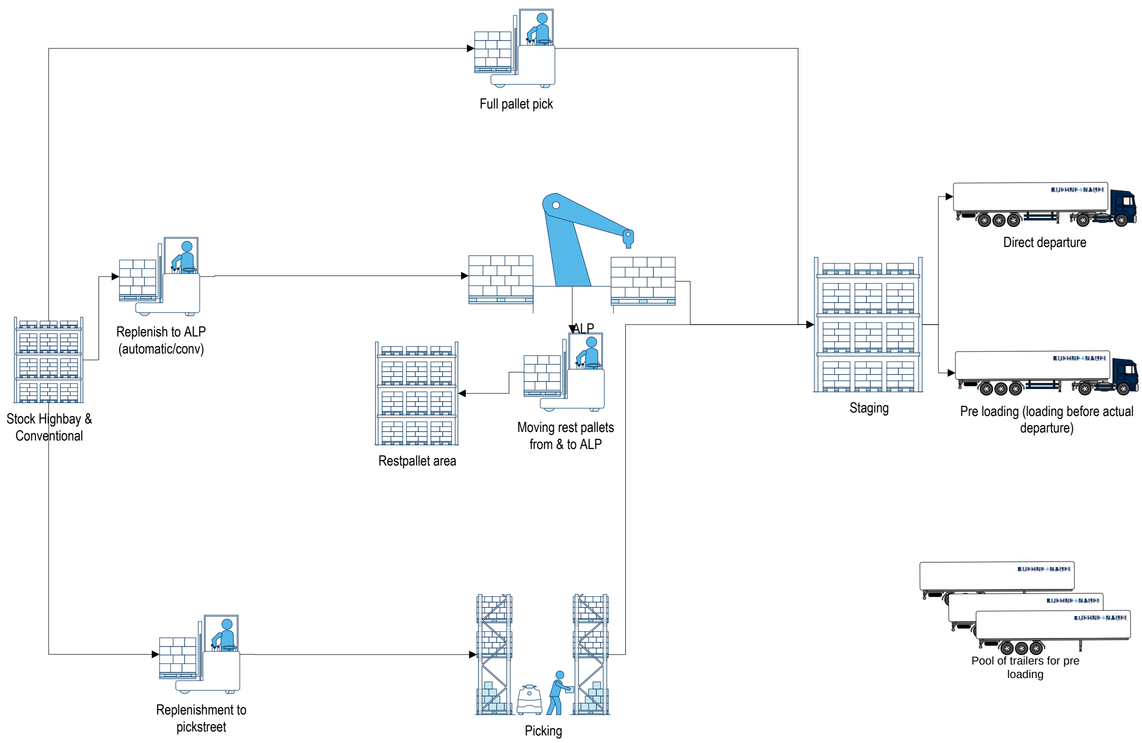


Figure 2 Warehouse operations Veghel (Van Schijndel & Van der Meulen, 2015)

### 1.2.4 Case picking

The fourth process is case picking, where case packs are picked manually. The picking quantities differ from single to multiple cases. For example when layers cannot be picked by the ALP due to physical constraints, they are picked manually. Also orders with a short lead time, emergency orders, can be picked manually because it could be that the throughput time of the ALP is too long to meet the delivery requirements. Picked case packs are consolidated on pallets before stored at the staging area.

### 1.2.5 Staging

The last process occurs at the staging area. At this location all pallets that are ready for shipment are stored in racking or are pre-loaded before actual departure. Single trips are allocated to single rack floors, so the amount of trips that can be stored at the same time is constrained by the amount of available racking floors. Due to resource capacity and space requirements, congestion within the flow of pallets commonly occurs. For example, the manual picking process is done with pallet handlers that cannot lift. When the pallet needs to be stored on the first or second floor of the staging area, the picker leaves the pallet on the ground floor in front of the storage location. A second picker moves the pallet with a forklift truck to the storage location on the first or second floor of the racking at a later time. While the pallet is stored on the aisle floor, locations at the racking behind the pallet cannot be entered.

Also the amount of trips that are picked together on the ALP can cause congestion at the staging area. As mentioned before, each trip is allocated to a single racking floor. When the amount of trips is bigger than the amount of available racking floors, orders need to be stored at alternative locations. These locations are within aisles or in the back of the warehouse.

## 1.3 *Lead time distribution*

In this paragraph the types of lead time distribution that occur within the operation are explained more deeply. The lead time distribution is an important topic within the operation due to it's major influence on the use of resources. The majority of the orders are picked with a 48 hours lead time. Other lead times that are considered for this research are 24 hours and same day deliveries. The same day deliveries are called AH orders, named to the main customer of this type of order. The 48 hour orders are defined as orders that are received at Kuehne + Nagel at day 1 and delivered at the customer at day 3. The 24 hour orders are received at day 1 and delivered at day 2 respectively. The AH orders are delivered on the same day as the order was placed. Thus, the absolute lead time measured in the amount of hours from receiving the customer's order till it's delivery can vary above and below the 48 or 24 hour depending on the order type.

The 48 hour orders that are received on day 1, are delivered together with the 24 hour orders received on day 2 and the AH orders received on day 3. Kuehne and Nagel receive new orders, of the three order types, every day. The total processing of orders from receiving till delivering is schematically represented in Appendix A. An schematically simplification for the planning and processing of orders which are picked automatically is given in Figure 3.

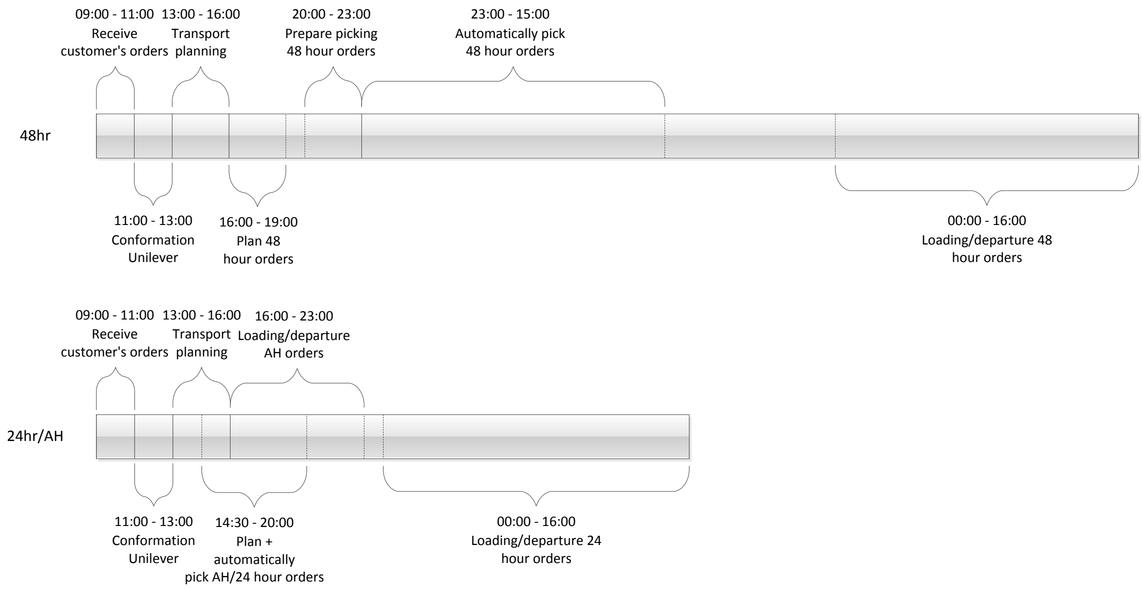


**Figure 3 Simplification of the order processing of automatically picked orders**

The 48 hr orders are received till 11:00 on day 1. When all orders are received, they are send to Unilever for conformation. The conformations of orders consist of an inventory check and inventory assignment to the customers. This conformation is often received round 13:00.

Now the transport department starts planning the trips. The transport planning consist of assigning orders to trucks and determining the corresponding departure times. The transport department first plans the 24 hr orders and after the 48 hr orders. The complete transport planning is often finished round 16:00.

At 16:00 the customer service department fixes all the orders and the warehouse operation can start. At 16:00 the warehouse department starts preparing the order picking. The picking cannot start before the trips allocation is known. During the warehouse preparations the pick, dock and ALP batch planning are made. When the warehouse preparations are done the manual picking can start. This process starts round 20:00 and the ALP picking process starts round 23:00. The three hours in between are used to fill the ALP buffers only the need for that much time seems to be unlikely. Probably this is a point that could be improved with further research.

The loading process starts after the orders are picked. The precise start of the picking and loading operations depends among others on picking quantity, delays of previous picking batches and the arrival- and departure time of the trucks. Orders are delivered at the customers distribution centre within a fixed time window. This delivery window is customer specific and varies throughout the day.

The 24 hour orders are processed slightly different. This type of orders are received together with the 48 hour variant. But due to the fact that the transport department first plans trips for the 24 hour orders, the warehouse operation can start preparing the picking process round 14:00 instead of 16:00. This means that, firstly the manual picking can start earlier round 15:00 when necessarily. And secondly, when the ALP is not busy, it can be used for layer picking. The use of the ALP is often not possible due to the fact that the machines are used for the picking of the AH orders. Those orders have got the highest priority because they need to be delivered the same day. This picking of the AH orders starts right after the orders are confirmed by Unilever. When the ALP cannot be used for 24 hour orders, all orders will be picked manually. The needed time to plan trips depends on the amount of orders.

Although the processes, as described above, are theoretical sequenced properly, the practice proves different. First of all, the orders are not received till 11:00. Often the last order enters the system after 11:00. For this reason the orders are send around 11:30 to Unilever for conformation, thus the confirmation from Unilever is often received after 13:00.

The major problem for the transport department is the long order lead time of 48 hours. This department needs to make the transport planning for the morning on day 3 in the afternoon of day 1. In between the lead time of the 48 hour planning orders can get cancelled or changed, also 24 hour orders are added to the planning on day 2, which prevents making a route planning with high accuracy that early on day 1. This problem could, in theory, be solved by using only 24 hour orders. Also the return routes for the trucks need to be scheduled to increase trip efficiency. Return trips often consist of last minute deliveries or order left overs at external companies. Making an accurate route planning is even harder due to the last minute scheduling of return shipments.

After the route planning is complete, the warehouse prepares the pick and dock operation. Due to the fact that the route planning has a low accuracy, it is possible that production does unnecessary or wrong preparations. Wrong preparations can result in extra work. The extra work occurs during the picking and loading window. For example, transport plans trips at 07:00 without knowing which companies deliver these trips to the customer. When a subcontractor or external charter drives the trip for an affordable price, the orders will leave the docking area at 07:00 in the morning. When the subcontractor or charter does not offer an affordable price, Kuehne+Nagel will deliver the trip with their own trucks. But it is possible that Kuehne+Nagel's own trucks can only depart in the afternoon due to capacity restrictions. So the trip is prepared too early and will congest the material flow at the docking area.

# 2 PROBLEM DEFINITION

In the previous chapter the main processes within the warehouse operation are shown. The occurrence of 3 different order types has got a major influence on the operation. Each order type corresponds with its own sequence of events. Those 3 flows, which consist of planning and picking operations, increase the complexity of the overall warehouse operation. The layer picking process is seen as the bottleneck within this complex structure of events.

## 2.1 Research proposal

Currently the management thinks that the amount of 48 hour orders will decrease and eventually all orders will be the 24 hour variant. It is expected that this future trend will result in a decrease of complexity because the warehouse operation only contains 2 different processing flows although the introduction of new difficulties in terms of resource usages and capacity restrictions. An additional advantage of the lead time reduction could be the increase in planning accuracy of the transport department. The inaccuracy of the transport planning is currently a major problem as mentioned in paragraph 1.3. When the lead time is shortened the time that the transport department starts planning is more closely to the moment of the trucks departure. The more just-in-time the planning occurs, the more time effective and the more accurate the planning could be because more correct information is available (Kugel, 2015). The design question of this master thesis project is formulated as:

*Design a batch planning heuristic for the layer picking process when only 24 hour and AH lead times orders occur that reduces the costs of the layer picking operation without reducing the current service level.*

The meanings of the individual terms of the problem formulation are clarified in Table 1.

**Table 1 Clarification of terms**

| | | |
|---|---|---|
| Batch planning heuristic | : | Rules of thumbs to compose batches during the planning process. |
| Layer picking process | : | The process that includes the ALP 200, ALP 300 and the manual layer picking. |
| Service level | : | The percentage of orders that are picked completely before the planned departure time of the trip. This will be 100% in the research. |

## 2.2 Scope definition

In this paragraph the scope of the research will be defined. The scope is used to increase the feasibility and includes variables, constraints and limitations of the research. A schematic representation of the scope definition is given in Figure 4.

The full pallet and case pick are left out of scope. It is assumed that those processes cannot be improved any further. The research contains the orders that can be picked in layers by the ALP. Layers that cannot be picked automatically are left out of scope because the only option is to pick them manually. The manual layer picking is a simple operation. Manpower can be in- and decreased easily. The disadvantages are the costs in terms of hourly wages.

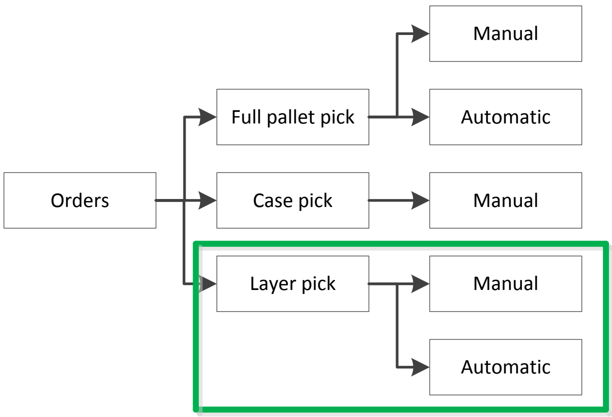


Figure 4 Schematic representation of the research scope

### 2.2.1 Performance measures

Besides the advantage of the reduction of order lead time on planning accuracy 8 other key performance indicators (KPI's) get special attention when comparing different batch plan heuristics.

- Maximum racking occupancy at the docking area, $R$: It occurs that when a trip is completely picked, the departure of the trip is rescheduled to a later time. The already picked trips need to wait within the racking until it can be loaded. However, it could be possible that the racking is needed to store a following trip. That trip now needs to be stored at an alternative location. Storing trips at alternative locations results in extra pallet handling and thereby in extra costs. The use of new batch heuristics influences racking occupation and the influence of trips that are rescheduled. This KPI is measured in trips per simulation.

- Amount of retrieved source pallets at the infeed of the ALP, $I$: Source pallets that are retrieved at the infeed of the automatic layer picking process are associated with manual handling. The more source pallets needed at the ALP operation, the more handling is required. A low amount of source pallets is preferred to reduce the costs. This KPI is measured in pallets per simulation.

- Amount of broken pallets that needs to get processes at the outfeed of the ALP, $B$: Broken pallets are associated with manual handling. An increase in the total amount of broken pallets also increases the amount of manual handling and consequently the amount of costs. Changing the amount of batches and corresponding batch sizes changes also the amount of created broken pallets. The example of Table 2 will clarify this more deeply. This KPI is measured in pallets per simulation.

  There are two trips planned. Those two trips together contain 100 pallets, which are composed with 400 different SKU's. Using method 1, both trips are picked together in one batch. Method 2 splits the trips into two separate batches. Due to the fact that some SKU's are needed for both, more source pallets are needed. In the worst case no source pallets are picked empty, so all source pallets become broken pallets. For method 1, 400 broken pallets need to be handled. Due to the SKU's that are needed within both batches, 450 broken pallets need to be handled for method 2. Method 2 increases the amount of outfeed handling with 50 pallets.

Table 2 Example of the creation of broken pallets

| | Method 1 | Method 2 | |
|---|---|---|---|
| Amount of batches | 1 | 2 | |
| Amount of source pallets | 400 | 150 | 300 |
| Amount of daughter pallets | 100 | 50 | 50 |
| Amount of broken pallets | 400 | 450 | |

- ALP utilization, $t_p$: The percentage of time that the ALP operation is busy with picking layers. Both ALP's need to be used as much as possible. The amount of products that can be picked by the ALP can limit this number., which indicates the decrease of manual picking costs.

- Amount of layers picked by the ALP, $L$: The automated layer picking operation is, compared to the manual variant, much less expensive. For that reason it is preferred that many layers are picked automatically as possible.

- Efficiency, $\eta$: Efficiency is defined as the mean amount of layers picked by one ALP per hour during operation periods. So the time that the operation is idle is not taken into account. The pick efficiency of batches is related to the amount of source and daughter pallet movement within the operation. The fewer movements are required to pick the same amount of layers, the higher the pick efficiency will be. Time reduction saves costs, and thus is preferred.

- Savings, $\Delta c$: The costs of the layer picking process that is done manually and automatically need to be lowered. New heuristics with costs higher than current situation are not preferred. Fixed costs are not taken into account and savings are used as a performance indicator. In paragraph 7.4.1 costs calculations, that are included within the savings, are explained.

- The number of batches, $n$: A low number of batches is preferred. The amount of batches is an indication of the planning complexity within the operation.

### 2.2.2 Assumptions

The research that is done is based on theoretical analyses. Because theory differs to practical implementations, due to simplification and the lack of practical information, assumptions need to be made. The main assumptions are listed below.

- There are no capacity restrictions in terms of operators and pickers. The amount of those employees can be in- or decreased instantaneous.
- Trips depart always on time from the warehouse to the customer. Secondly, the warehouse needs 90 minutes to inspect the picked quantities and load the volumes into the trucks. Thus, the picking needs to be finished 90 minutes before the departure time of the trucks.
- It is assumed that the manual pickers perform constantly with a pick efficiency of 330 cases per hour. The corresponding costs are 23 euro per hour and it is assumed that those costs do not differ during the day or per employee.
- Two operators always staff the 2 automated picking machines. Each operator has an hourly wage of 23 euro per hour.

- Due to the lack of source pallet information it is assumed that only full pallets are retrieved at the infeed of the ALP.
- The pallet handling at the in- and outfeed of the automated layer picker is measured in handling time. The amount of time needed to retrieve or process a pallet equals 98 seconds at the in-, and 84 seconds at the outfeed respectively as can be seen in Appendix B.
- The pallets that need to be retrieved at the infeed of the ALP are always present in the warehouse, no backorders occur. The pallets that need to be processed at the outfeed can always be stored within the broken pallet area. So, no capacity restrictions are applied on this area.
- It is operational not possible to use a source pallet in different batches when those batches run within the same picking cycle. It is assumed that the lock status, described in paragraph 4.5, cannot be bypassed.
- Another operational assumption is that both ALP's cannot work together and can be seen as complete separate operations.
- It is assumed that the order behaviour of the customers does not change when the lead time reduction is introduced. The ordered volume that needs to be delivered at the customers distribution centre on a specific day remains the same. What does change, is the time to collect the ordered volumes from the warehouse. This is described more thoroughly in paragraph 8.4.
- Negative picking is not taken into account. Negative picking is the occurrence that the source pallets turn into a daughter pallet and vice versa.

  Negative picking can occur when a big amount of layers needs to be picked from the source pallet. For example, imagine a source pallet with 10 layers and a daughter pallet that needs nine. Then it is more efficient to move only one layer instead of moving 9 layers from the source pallet to the daughter pallet. The source pallet is then processed as a daughter pallet and vice versa. This is not taken into account because the choice to pick negative is purely based on the operator's judgment at the ALP operation during the picking process. Negative picking is not registered anywhere and no hard rules are used for determination.

- The occurrence of THT fall is not taken into account. THT is the Dutch term for best before dates. A fall in THT occurs when SKU's with an earlier THT are delivered at the customers distribution centre than SKU's that are delivered at an earlier moment in time. Due to the fact that the THT problem is difficult to understand an example is given below for clarification.

  Customers apply specific rules for the acceptance of SKU's. Some accept a THT fall of a few days and others do not accept any fall. The main cause of THT falls is the use of multiple pallets of the same SKU on different locations. For example, in practice it can occur that one SKU is picked at the ALP 200, the high bay and at the manual picking area at the same moment in time. At each of those picking locations a single pallet is required. In Table 3 an example situation is outlined.

Table 3 Example outline - Fall in THT

| | | | | |
|---|---|---|---|---|
| Pallet ID | : | A | B | C |
| Customer DC | : | 1 | 2 | 3 |
| Picking method | : | ALP 200 | High bay | Manual |
| Picking quantity[pallets] | : | ½ | 1 | ¼ |
| THT | : | 10/06/2016 | 20/07/2016 | 30/08/2016 |

In the example, three picking methods are used at the same time. The pallets used at these locations have got different THT's. Before the picking, on 01/05/2016, the three pallets are unbroken. After the required quantities are picked ½ of pallet A is send to DC1, the complete pallet B is send to DC2 and ¼ of pallet C is send to DC3. The leftover from pallet A and C are left in storage. On another day, 08/05/2016, customer 2 places another order of ½ pallet. The leftover from pallet A is then completely send to customers DC2. Due to the fact that DC2 already received SKU's with THT 20/07/2016 and now receives SKU's with THT 10/06/2016 an THT fall of 40 days occurs. It is preferred that inventory with earlier THT is sold first before selling inventory with later THT because it reduces the SKU's chance to expire. When DC2 accepts the THT fall of 40 days it will not result in any problems for Kuehne + Nagel. But when the THT fall is not accepted, the SKU's are send back to Kuehne + Nagel. Return shipments result in additional costs for Kuehne + Nagel.

## 2.3 Research steps

The steps taken in this research to develop a batch heuristic that can be used for the layer picking process within a 24 hour lead time situation corresponds with the chapters of this paper. In this paragraph those research steps will be deliberated. In the first step, chapter 3, an literature review is given to get a better understanding of the operational warehouse processes and to get more knowledge of applicable researches that were done in the past. The topics order picking and order batching will get the focus of the review. Also researches that were done at the company in previous years are mentioned.

Secondly, the theory behind the automated layer picker is given. Chapter 4 first classifies the operation according to the literature. Secondly the order batching is described and third the physical picking process is explained. The automated layer picking process is challenging due its complexity. For that reason also the features and challenges are described. In chapter 5 the current layer pick operation is analysed to get more insight in the current performance and possibilities. These analyses contain the batch allocations and the batch performances. It is tried to define key variables that positively influence the pick performance. Also gap analyses are done between the specified and actual operational delays.

The information from previous chapters is used to develop batch heuristics in chapter 6. The heuristics are based on different batch composition processes. Those heuristics are tested with the help of an deterministic model. This model and corresponding settings are described in chapter 7. The comparison of the batch heuristics is done in chapter 8. Within these three chapters a distinction is made between 24 hour and 48 hour lead time situations. In the last chapter, chapter 10, the conclusions from the research are given. Also recommendations are given to Kuehne + Nagel, limitations of the research are given and areas for future research are empathized.

# 3 LITERATURE REVIEW

The most important subjects for the research are order picking and order batching. Order batching is the method of grouping a set of orders into a number of sub-sets, each of which can then be retrieved by a single picking tour (De Koster, Le-Duc, & Roodbergen, 2007). Many research is done to order batching due to the fact that the batching problem is NP-hard in most situations (Schilders, 2015). Although a solution needs to be found many heuristics are develop (van Giersbergen, 2015). Next to the topics of order picking and order batching this chapter will discuss previous researches at the same company and provide the contribution of this master thesis to the literature.

## *3.1 Order picking*

Order picking is relatively labour intensive, which mainly depends on the storing layout and pick requirements. Four pick layouts are possible (De Koster, Le-Duc, & Roodbergen, 2007). The first layout is broken case pick. This variant is also known as single item pick. The second layout is case pick. Cases contain multiple single items, which are grouped in one case pack. The third layout is layer pick. Layers contain multiple case packs, which are stacked in one horizontal layer on a pallet. Last, pallet pick can occur in which full pallets are collected. Single item and case pick are the most resistant variants toward automation. Those resistance in caused by the variety of SKU's and corresponding characteristics such as dimensions and weight.

For the determination of the pick sequence, routing and batching the pick density is an important topic. The pick density is defined as the amount of picks per foot of travel (Bartholdi & Hackman, 2002). According to economics of scale the higher the pick density, the most costs efficient the pick. One way to increase the pick density is batching orders together. Smart order consolidation could reduce traveling time and product handling. Pick density has multiple definitions with in general the meaning. For example, pick density can also be defined as the amount of layers that are transferred per pick within automated layer picking systems (Kuehne+Nagel, 2015).

Order picking methods can be classified into two groups. The first is manual picking. Manual picking can be subdivided into picker-to-part, part-to-picker, and put systems (De Koster, 2004). In picker-to-part systems the picker moves to the parts and collect the required amount of products on pallets or boxes. Contrarily, with part-to-picker systems automated storage and retrieve systems are used to bring the products to the picker. After the picker collects the right amount of products, the leftovers are automatically stored again. Put systems are a combination of the previous two subgroups. Put systems automatically retrieve items from storage locations, secondly a picker distributes those items over multiple customers' orders. Put systems are therefore also known as order distribution systems.

## *3.2 Batching of orders*

As mentioned before order batching is important to increase the pick density. There are multiple decision variables, which determines the batching strategy. Departure time of the order and storage place of the items is one of them (Gu, Goetschalckx, & McGinnis, 2010). Batching on the departure time of orders is called wave or window picking. Within this picking method all orders that need to depart before a predetermined time are picked together. Zone picking is based on the storage place of the items. This method batches orders whereby the storage locations of the products within those orders are in the same region.

Within the batches that are created with wave or zone batching methods, smaller sub batches can be created to improve the picking efficiency. The creating of sub batches can be based on for example seed or savings heuristics.

Seed heuristics consists of two phases. In the first phase seed section rules define a seed order for each batch (De Koster, Le-Duc, & Roodbergen, 2007). A seed order is the customer's order to which other customer's orders are added. The selection of the seed order depends on the situation and specific decision rules. For example, the seed order can be the order with the longest picking tour, the order with the earliest delivery time, the order with the largest number of product positions or just a random order from the list. After a seed order is selected congruency rules are used to build the batch. Those rules decide which order is added to the seed order. Those rules for example are based on the number of aisles that have to be visited, the sum of the traveling time, amount of common items or the amount of single pallets that need to be collected.

## 3.3 Earlier theses

In the past more studies were done by students of the University of Technology Eindhoven about Kuehne + Nagels' operation in Veghel. The first research analysed the operation from the viewpoints of handling and time pressure (Zbinden, 2002). The researcher concluded first of all that the operation contains a lot of redundant handling and hardly any pressure of time. Secondly the researcher concluded that the lead time can become almost twice as short as in the analysed situation with a set of operational changes that are relatively easy to implement. Examples of those changes are: batch size reduction, improved process sequencing and delayed order picking.

The second researcher analysed the unnecessarily handing that is caused by time pressure and leads to inefficiency within the operation (Mos, 2002). The research describes possibilities for cost reduction. One of those costs reductions can be achieved by a better alignment between order quantities and packaging units. Secondly, pre-work during less busy periods shows positive effects.

Last, a research was done which describes the order picking process at Sligro Food Group N.V. This operation is comparable with the order picking process of Kuehne+Nagel (Schilders, 2015). This research suggested that the order picking process could be improved by updating the order- and delivery schedule for its stores and the algorithm that is used to create batches that have to be picked in the distribution centre. Updating the algorithm ensures that stores with similar ordering patterns are picked at the same time. This leads to substantial expected costs savings.

## 3.4 Contribution to the literature

In the past a lot of research is done to order batching within warehouses or distribution centres. But operations, where most part is automated with a high bay or automated layer picker, are not analysed that much. In fact, problems that occur due to automated layer picking or corresponding restrictions are barely found in the literature. This research will provide an analysis of the effect of lead time reduction on the batching problem of the layer picking process within a warehouse. The research will also give a preferred batch heuristic in the specific situation of Kuehne+Nagel Veghel and do suggestions for further research.

# 4 AUTOMATED LAYER PICKING PROCESS

The ALP is purchased to decrease manual picking, increase overall pick efficiency and naturally decrease overall costs. Within the operation two ALP's are situated. Those two machines are called the ALP 200 and ALP 300. Although the name does suggest it, there is no difference between those machines.

## 4.1 Classification of the ALP

The ALP process can be qualified as a sequence of three handling steps. The first is collecting products from the order pick hall, further referred to as OPH, or high bay (HB) and bring them to the infeed of the ALP. Collecting is done manually from the OPH and automatically from the high bay respectively. The second handling contains the physical picking by the picking machine. The layer picker retrieves the inserted pallets via a conveyor system from a buffer area and partly consolidates them into full pallets which are accommodated according to customers' orders. The last handling step contains the processing new created pallets and the processing of the retrieved pallets that are not consolidated into new pallets. The so-called broken pallets are stored into a broken pallet area manually.

To ALP process is classified according to an order picking hierarchy (De Koster, 2004), which can be found in the literature review chapter 1.4 (van Giersbergen, 2015). Two processes are distinguished for the qualification: Collecting of pallets and the physical picking of the ALP. The classification can be found in Table 4.

**Table 4 Classification of the ALP process**

| | Collecting the pallets | | Physical picking of the ALP |
|---|---|---|---|
| | **From OPH** | **From HB** | |
| **Retrieving method** | Manual | Machine | Machine |
| **Picking method** | Picker-to-part | | Part-to-picker |
| **Sort method** | Sort-after-pick | | Sort-while-pick |

Collecting the pallets is a picker-to-part system because an operator or crane collects pallets from the OPH or HB and puts them into the ALP buffer. The ALP buffer is used to sort the inserted pallets into the right picking sequence for the ALP: Sort-after-pick.

The physical picking of the ALP can be seen as a part-to-picker system because the collected pallets are brought to the layer-picking machine. During the picking process the ALP consolidates layers with the same destination on the same pallet. Thus, the sortation of the picked items is done while picking: Sort-while-pick.

The picking method of the physical picking of the ALP, part-to-picker, is combined with wave picking (GU, Goetschalckx, & McGinnis, 2007). The first picking wave on the ALP starts every day round 23:00 and contains 48 hour orders. A second wave starts in the afternoon between 14:00 and 15:00. This wave contains AH or 24 hour orders. Depending on the size of the second wave it could be possible to pick a third wave. This wave only contains small 24 hour batches.

## *4.2 Batching*

Before discussing the configuration and the physical picking process, the translation of incoming customer orders into ALP batches is clarified.

The ALP produces in batches. A batch is a collection of trips. A trip is a collection of orders that are delivered by one truck to one or multiple destinations. Last, an order consists of pallets with single or a composition of SKU's. Not all SKU's can be picked at the ALP. Physical product properties and customer requirements determine the picking strategy. It is possible that a product does not have the right shape or the customer does not want the product to be grabbed by the ALP machine. Every single SKU has got an electronic ALP profile that covers those properties.

The size of the batch is limited. The ALP must complete the picking before the departure of the first trip that is included into the batch. So picking occurs in a predetermined time window. Currently the 48hr orders are divided into four batches, two batches for each ALP. The batches are automatically consolidated by the warehouse management system taking into account the ALP profiles and expiration dates. Currently all four batches are created at once before the start of the ALP picking. Also the 24 hour batches are picked by the ALP when possible as mentioned before. A KPI of 110 layers per hour is used within the batch planning.

The algorithm that is used to compose batches is based on seed heuristics (De Koster, Le-Duc, & Roodbergen, 2007). The seed selection rule that defines a seed trip for each batch is based on the departure time of the corresponding trip. The rule is that the trip with the first departure time is used as seed trip. Trips are added based on the sequence of departure times where trips with early departure times are added before trips with later departure times. The time window in which the picking takes place depends on the size of the batch. In this manner it can also be seen as time window batching.

It is tried to do the picking according to the FEFO, first expire first out. The pallets with SKU's that expire first will be used before other pallets of the same SKU. When a pallet is assigned to a batch it gets the status locked. When a pallet is locked it cannot be assigned to other batches till the lock status is removed. Removing the lock status occurs when the pallet is send to the outfeed of the ALP process. Due to the fact that sequential batches are currently planned together, it is possible that the second batch uses a new full resource pallet of a certain SKU for layer picking. Although the first batch creates a broken pallet of the same SKU that theoretically also could have been used instead. This is because the lock status prevents assigning an already assigned pallet to another batch. Waiting with planning the batches till the last moment could resolve this problem. A second solution could be the introduction of a lock status based on layers next to pallet lock. The lock status of the pallet avoids that a pallet is assigned to different batches that are picked at the same time on different machines. And the lock on layers gives the opportunity to assign pallets to sequential batches respecting the amount of layers that is located at that pallets and the amount of layers that will be picked in the sequential batches. But in practice this includes high investments into soft- and hardware because current resources cannot be used for such strategies.

The warehouse management system starts with assigning all early trips to the ALP 200. When the time window of the first batch for the ALP 200 is filled, the WMS starts assigning trips to the first batch of the ALP 300. Those trips are the trips that departure after the trips assigned to the ALP 200.

When also the time window for the first batch of the ALP 300 is filled, the WMS starts assigning the trips that departure right after the already assigned trips to the second batch of the ALP 200. Same goes for the second batch of the ALP 300. Thus, the composition of batches is based on departure time of the trips.

**Algorithm 1 Steps for determining the pick sequence**

| | | |
|---|---|---|
| Step 1 | : | Order the list of needed source pallets based on footprint type |
| Step 2 | : | Order the list of needed source pallets based on stack class from lowest to highest without violating the previous order settings. |
| Step 3 | : | Order the list of needed source pallets based on stack class sequence from lowest to highest without violating the previous order settings. |
| Step 4 | : | Start picking scenario. |
| Step 5 | : | Retrieve source pallet. |
| Step 6 | : | Retrieve daughter pallet. |
| Step 6a | : | If a daughter pallet for corresponding customer is available in the daughter pallet buffer, retrieve the daughter pallet from the daughter pallet buffer. Else retrieve an empty pallet and go to step 7. |
| Step 6b | : | Check whether extra layers can be placed on that daughter pallets based on the maximum allowed height of the daughter pallet and layer height. If no, send the daughter pallet to the outfeed, retrieve an empty pallet and go to step 7. If yes, go to step 6c. |
| Step 6c | : | Check whether the maximum crushability is not violated when the maximum amount of allowed or maximum amount of requested layers are placed. When the maximum crushability is violated send the daughter pallet to the outfeed, receive an empty pallet and go to step 7. Else go to step 7. |
| Step 7 | : | Transfer the maximum amount of allowed or maximum amount of requested layers from the source pallet to the daughter pallet. |
| Step 8 | : | Check whether all requested layers from the source pallet are transferred. If yes, send the source pallet to the outfeed. If not go to step 6 and retrieve a new daughter pallet. |
| Step 9 | : | If there is a source pallet left from which layers need to get picked, go to step 5. |
| Step 10 | : | The pick sequence in terms of pallet movements and layer transferring is now determined and can be applied on one of two ALP's. |

## *4.3 Picking sequence*

After the WMS is finished composing trips to batches, the picking sequence will be determined. The pick sequence is the sequence in which layers from source pallets are transferred to daughter pallets. The source pallets are the pallets from which layers are picked. The daughter pallets are the pallets on which the picked layers are placed.

The picking sequence depends on two factors: product characteristics and footprint. First of all the pick sequence is important because it improves the pick efficiency due to the reduction of pallet movements. Secondly the pick sequence can reduce the pallet handling before and after the ALP operation. For example, the source pallet is always sent to the outfeed when it is used at the ALP machine. When the pick sequence is not careful chosen, that products are damaged or extra pallet handling occurs.

There are 4 parameters important within the pick sequencing process. The first is the stack class of a SKU. Stack class is a classification of the weight of a layer SKU's. The heavier the product the lower the stack class. Stacking occurs with the layers with high stack classes at the bottom. The second variable is stack class sequence. This variable is a classification for the amount of surface area of the pallet that is filled by one layer. The lower the stack class sequence the higher the fill rate of the layer. Stacking occurs with layers with high fill rates at the bottom. The third variable is crushability. Crushability of the layer is the maximum amount of weight that is allowed to be placed on a specific layer of SKU's. When the amount of weight placed on top of a specific layer violates the crushability factor, no extra layers are placed on that specific daughter pallet. The last parameter is the footprint of the daughter pallet. Within a batch, the daughter pallets with the same footprint are picked sequential after each other till all daughter pallets with that type of footprint are completely composed.

Within the pick sequence also the placements of sandwich pallets, the amount of daughter pallets and the needed source pallets will be determined. Sandwich pallets are pallets that are placed between two layers to separate new placed layers from the already placed ones. Separation is done based on three main reasons. The first reason is between two different products. Secondly it is based on different expiration dates of the same product. And last, based on customer specific requirement. An example of the third reason is when the customer has storage spaces in which maximal three layers can be placed. Then, after every third layer a sandwich pallet will be positioned. The steps within the pick sequencing process are the same for each batch. Those steps are given in Algorithm 1.

## *4.4 Picking process*

When the batch compositions and pick sequences are known the ALP's can be prepared for picking. Now the practical picking process will be discussed. The configuration of the ALP's is schematically represented below in Figure 5. The dotted line marks one of the two ALP's. An schematically representation of the pallet and layers flows is given in Figure 6.

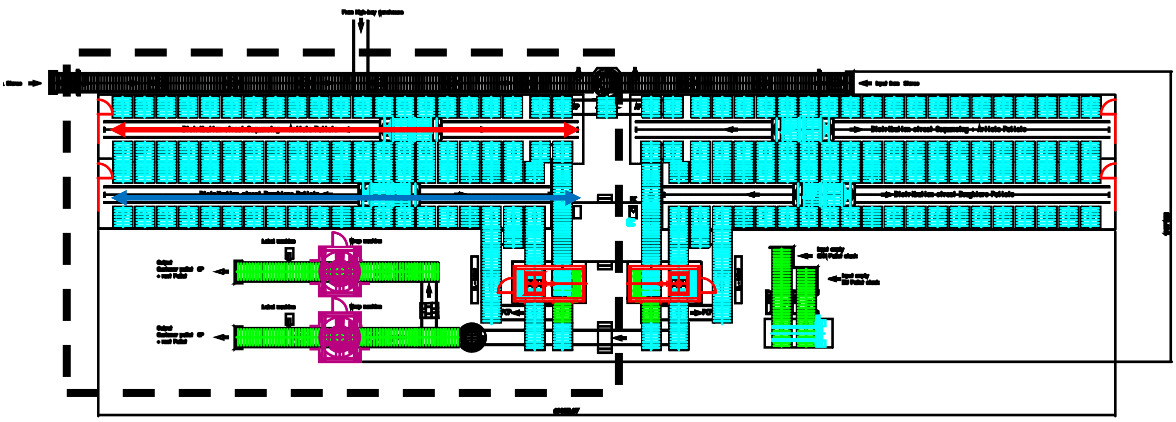

Figure 5 Schematically representation of the ALP process

The source pallets enter the ALP system on the infeed conveyer. This conveyer is represented in black. Incoming source pallets come from the order picking hall or the high bay. Pallets from the high bay are automatically transported to the ALP infeed by a conveyer lane. The pallets from the order pick hall are retrieved manually with a lift truck. When the source pallets enter the ALP system they are stored in one of the buffers. Because pallets are retrieved from different locations the source pallets are not always inserted in the preferred sequence, this is called the sequencing problem. Next to the buffer for source pallets, the ALP system contains a buffer for daughter pallets. The buffers contain 40 and 38 buffer places respectively. The red arrow flags the 40 buffer places for source pallets and the blue arrow the buffer places for daughter pallets respectively. In general more than 300 different source pallets are needed to complete a batch. But due to the fact that there are only 40 buffer places for source pallets available, the infeed of pallets continues while the ALP is operational. The free spaces in the buffer are not filled directly. New pallets are inserted in the systems when 9 places are free. The 9 pallets that are used to fill the source buffer are called a sub-batch. Refilling by sub-batches instead of single pallets is done to increase the picking efficiency at the infeed. Pallets from the sub-batch are retrieved from the high bay, the bulk storage or broken pallet area. Due to retrieving the 9 pallets from different locations it is practically impossible to enter those into the ALP with the preferred sequence. The source pallet buffer intercepts this problem.

The red square represents the ALP machine. An operator starts the automatic picker when the source pallet buffer lane is filled sufficiently. First a source pallet is retrieved from the buffer at the machine. Secondly a daughter pallet is placed besides the source pallet. When the daughter pallet is already located within the system and contains picked layers it is retrieved from the buffer area. When the daughter pallet is not already located within the system, an empty pallet is placed besides the source pallet.  Empty pallets are stored in a third buffer located at the ALP machine. Those pallets consist of the same footprint type. When a change of footprint occurs, an operator replaces the stored empty pallets with new empty pallets of another type.

A mechanical arm picks a complete layer from the source pallet by vacuum and places the layer at the daughter pallet. This action is repeated till the required amount of source layers is placed on the daughter pallet. There are two types of ALP programs available: Type 1 and Type 2. Type 1 limits the machine to pick only one layer at a time. Type 2 allows the machine to pick two layers at a time. Which program type is used differs per picked layer because it depends on product characteristics.

When no more layers from the currently placed source pallet are needed, the source pallet is send to the outfeed. A source pallet is never send back to the source pallet buffer due to the fact that the buffer is only used to intercept the sequencing problem of source pallets at the ALP infeed as described earlier. When the source pallet is needed to fill more daughter pallets the pallet located at the machine does not move, but the daughter pallet is send to the daughter pallet buffer when it needs layers from other source pallets or it is send to the outfeed when it is done. The new daughter pallet that needs the current placed source pallet can be retrieved from the daughter pallet buffer area or from the empty pallet buffer as described before.

It is possible that all layers are picked within the operation, in other words the pallet is picked empty. When this occurs the source pallet is recycled. This means that the empty pallet is send to the empty pallet buffer allowing it to be used as a new daughter pallet during the picking process.

The outfeed of the system consists of two conveyor lanes, represented green in the figure. Both conveyor lanes contain wrapping machines, the purple squares, to seal finished daughter pallets. After daughter pallets are sealed they are stored at the staging area. When source pallets are send to the outfeed, they are stored in the broken pallet area. The processing of pallets at the outfeed occurs always manual with lift trucks.

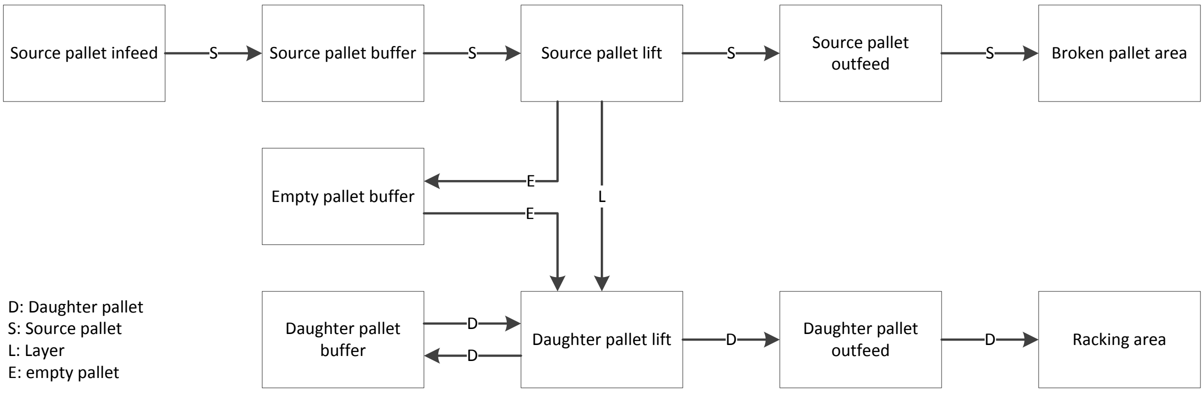


**Figure 6 Flow diagram ALP operation**

Figure 6 shows the volume flows within the ALP operation. The volume of incoming source pallets correspond with the amount of source pallets send to the broken pallet area, and the amount of empty picked pallets at the source pallet lift. The amount of daughter pallets send to the racking area equals the amount of retrieved empty pallets from the empty pallet buffer. The amount of daughter pallets can be higher or lower than the amount of source pallets at the infeed. This depends on the amount of customers and batch size. The amount of source pallets send to the broken pallet area depends on the amount of empty picked pallets. The ratio daughter and source pallet is 1:1.7 on average. Further on average 5.1 layers are transferred per daughter, and 3.2 layers per source pallet respectively.

## *4.5 Features and challenges*

The biggest challenge that needs to be tackled is the ALP batch composition. Poor batch composition increase among others the amount of broken pallet handling, the amount of THT problems and the required storage space.

The size of the batch is directly linked to the amount of space at the racking area that is needed to store pallets. When large batches are used, it is possible that a pallet, needed for a trip that departs relatively late to the customer, is finished relatively early at the ALP. Which causes long storage times at the racking area. It is possible that pallets from trips that depart relatively early, are finished almost last at the ALP. Just in time order processing cannot be applied in this case.

# 5 ANALYSES OF CURRENT SITUATION

In the previous chapter the theory behind the ALP operation is given. In this chapter the current performance of the automatic layer picking process in analysed. First the current batch allocation will be analysed. With this analysis it is tried to find areas for improvement within the usage of the ALP's. Secondly, a formula to approximate the expected picking time is developed. And third variables that influence the pick efficiency will be discussed. Those performance influencers can support the areas of improvements within the ALP usage.

## *5.1 Batch allocation*

In this paragraph the allocation of historical batches on the 2 ALP's will be mapped. The allocation is directly associated with machine utilization and the amount of picked layers.

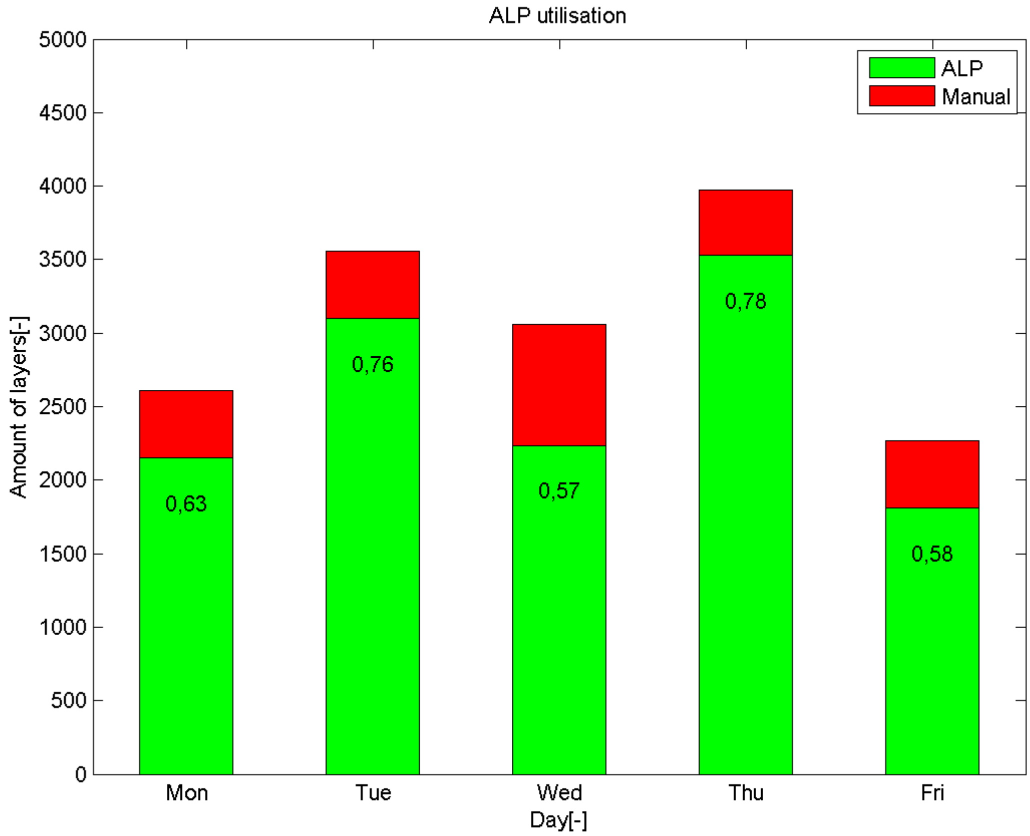


Figure 7 Amount of layers picked by the ALP translated into ALP utilization

### 5.1.1 ALP utilization

Figure 7 shows the amount of layers that are picked by the ALP in the first week of June in green. The red blocks are the amount of layers that theoretically could have been picked by the ALP, but are picked manually at the same day. The numbers within the green bars represent the total utilization of both ALP's on that day. The total amount of layers picked within this week is 12822.

Although the high amount of automatic picked layers, the graph shows relatively large red bars and low utilizations. There are still a lot of layers that could have been picked by the ALP, but are picked manually. In fact the total mean utilization of the machines that week is 66%.

Interviews with operations staff revile that the red bars contain backorders. Backorders are products that are not on hand when orders for those products are received at Kuehne + Nagel. Although the products are not on hand, the customers' orders are accepted because it is expected that the warehouse will receive those products during the day. Backorders are not assigned to a batch when those contain products that are not on hand yet. The warehouse uses 16:00 as a cut-off point. When the products are still not on hand after this time, the backorders will not get collected.

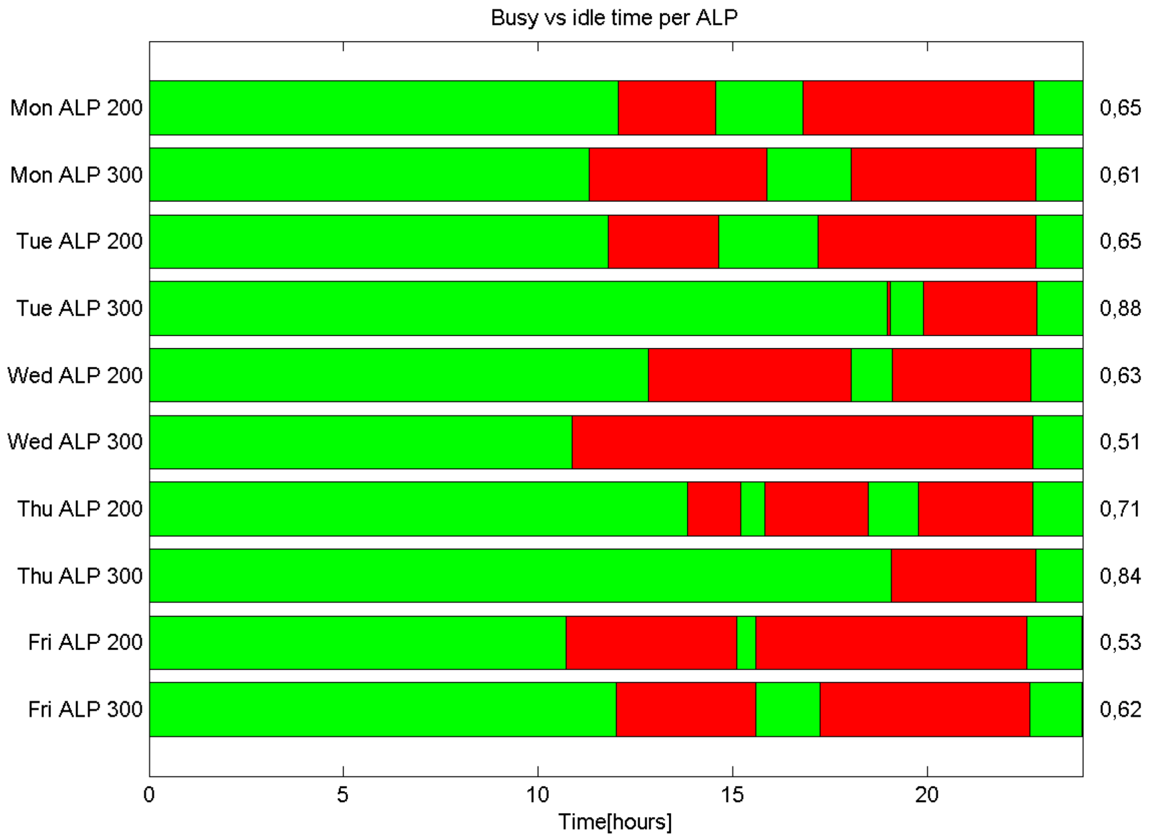


**Figure 8 Graphically representation of the ALP's utilization in terms of busy and idle time**

The idle time occurs between the end of one and the start of new picking waves. The picking wave represents time windows in which the ALP is busy. The first wave starts round 23:00, the second wave between 14:30 and 16:00; and the last picking wave between 18:00 and 19:00. When keeping in mind that the orders are known round 14:00, lead time reduction could be achieved in the evening.

Low utilization and layers, that are picked manually, triggers to do more research. Figure 8 shows the busy and idle times of the ALP's during the day. On Monday both batches are finished at 12:00. So the 24 hour and AH orders can be picked on both layer pickers. On Tuesday one batch is much longer than the other one. So the special AH orders are picked on the ALP that is finished first. On the start of the evening a small 24 hour batch is picked. Wednesday can be compared with Monday although there is no 24 hour order picked in the afternoon. On Thursday there is one very large batch on one ALP. The other ALP finishes a smaller 48 hour, an AH and a 24 hour batch. The behaviour of the ALP's on Friday can be compared with Monday.

Previously it is mentioned that the red bars in Figure 7 represent backorders. The size of the red bars can be found in Table 5. In paragraph 7.2 a weighted pick efficiency of 82 layers per hour is found. Based on this performance measure, the expected additional picking time to pick the manually picked layers can be calculated. Those times are also given in Table 5. The expected additional pick times are round 3 hour per ALP on all days except Wednesday. On this day the additional time should be 5 hours per ALP. On every day the backorders could easily be picked between 16:00 and 23:00 by one or both ALP's.

Table 5 Additional picking time per ALP for manual picked layers

| Day[-] | Manual picked layers [Layers] | Additional time [hours/ALP] |
|---|---|---|
| Monday | 458 | 2,8 |
| Tuesday | 458 | 2,8 |
| Wednesday | 823 | 5,0 |
| Thursday | 445 | 2,7 |
| Friday | 457 | 2,8 |

### 5.1.2 Conclusion

Overall it can be concluded that layers are sometimes picked manually although it was also possible to pick those automatically. Mainly the so called backorders, which are received till 16:00 are picked manually, but could theoretically be picked by one of the ALP's. The low utilization and idle time between picking waves indicate that there is room to implement lead time reduction.

## *5.2 Picking time*

In this paragraph the multivariate analysis are done to find an expression for the expected picking time of a batch within the ALP operation. The statistical process contains multiple predictor variables which explains the depended variable: picking time. For the analysis the historical data of the months April, March and June of 2015 are used. Those data contains 234 batches.

At the beginning six predictor variables are taken into account. First the amount of layers, $L$, within the batch. As a logical explanation it is expected that an increase in the amount of layers result in a higher picking time. Secondly the amount of SKU's, $S$. Also an high amount of different SKU's will result in additional picking time due to the increase in the amount of pallet handling within the automated layer picking process. The same for the amount of customers, $K$, and logically the amount of daughter pallets, $D$. Which are the third and fourth variables of the analysis. When a batch contains more customers, more daughter pallet handling needs to be done. As a result the picking time will rise. Just as previous variables, the amount of sandwich pallets, $H$, will have a positive relation with picking time because of the increase in handling. The last variable, the amount of type 2 SKU's, $T2$, is the only variable that has a negatively relation with the batch picking time. This is because of the reduction of handling per layer. The machine is able to transfer two layers at ones from the source to the daughter pallet. The analysis is started based on the regression model of Equation 1.

$$Time = a + b * L + c * S + d * D + e * K + f * H + g * T2$$

Equation 1 Default regression model

It is known that this model has two problems which could influence the model fit accuracy. First of all no variable for the amount of breakdowns is added although these regularly occur. This variable is not added due to missing information. A second problem of the known variables is the high amount of multicollinearity between the predictor variables.

From the default regression model no significant variable is found which explains the dependent variable time. For that reason the variable with the highest probability value is removed from the model and the analysis is done over. This process is repeated till all model variables are significantly. The significance level is set on 0.01. In the end, two variables remain. Namely the amount of layers and the amount of different SKU's. Only the amount of SKU's is significant. But deleting the amount of layers will result in an illogical regression formula because then the picking time only depends on the amount of SKU's. This formula can result in problems when a trip is added to a batch which already contains all the SKU's of the additional trip. According to the formula the picking time does not increase in this case. Adding trips for "free" is illogical and does not occur in reality.

For that reason a regression model only based on the amount of layers is developed. This model is expressed by Equation 2.

$$Time = a * L$$

Equation 2 Final regression model to explain the expected picking time

The adjusted R-squared of this model equals 0.93. Secondly the Breusch-Pagan test is significant which supports the multivariate assumption of homoscedasticity. The distribution of the residuals turned out distributed normally with large ends at the data distribution. The multivariate information, QQ-plot and the plot with the fitted values against the residuals can be found in Appendix L.

## 5.3 Gap analyses

In the previous chapter analysis to the expected picking time of the ALP operation is done. The simulation model that is going to be developed is based on theory rather than real practical results. For that reason it is important to perform gap analyses. With the gap analyses differences between the theoretical and actual performance can be declared. Another important reason to perform gap analyses is to find factors that can counteract the implementation of new operational processes or batch heuristics.

### 5.3.1 Machine delays

The manufacturer defines a standard machine delay of 15%. This machine delay is defined as inevitable delayed movements of the T-car or convers. But next to the prescribed manufacturer's machine delay of 15%, also operational delays, caused by human influences need to be taken into account. This influence is approximated another 5%.

### 5.3.2 Other delays

Although it is preferred that the delays within the picking should be as small as possible, there are more factors that result in additional picking time next to the specified machine delays. First factor is pallet stacking in combination with product properties. When products are stacked instable or have dimensions that create unstable positioning they are earlier tend to fall during the process. Products that fall from the pallet need to be picked up. The process can continue while fallen products are gathered and restacked on the pallet.

A second factor that creates delay is manual faults on the ALP machine. Before a pallet can be used within the picking machine, the packaging foil needs to be removed from the layers. When the operator does not have removed the foil before the pallet is needed within the machine, the process is set on hold. The process continues when the pallet is fully prepared for picking.

The third factor is manual failure at the out- or infeed of the ALP. At the infeed an operator is triggered to receive a pallet from the warehouse and deposit at the ALP by a light that turns on. When the operator is busy with other activities or do not pay attention, the requested source pallet is not inserted at the ALP on time. At the output finished pallets need to be taken away from the outfeed conveyor. If this is not done in time, pallets within the ALP congest and the operation is set on hold.

One last example of other delays is programming faults, mistakes within the software of the ALP cause inefficient picking. An example of a programming fault is, that it occurs that a daughter pallet is send to the daughter pallet buffer after receiving layers although that same pallet is needed for the following pick at the ALP platform. So the machine waits till the just send out pallet is received again.

### 5.3.3 Gap examples

To investigate the gap between theoretical and practical performance the technical service department of Kuehne + Nagel closely monitors the machine movements of the ALP. The conclusion that was drawn is more than remarkable. Table 6 shows 3 examples of batches that are monitored. In the first column the efficiency is given including idle time and breakdowns. In the second column the performance is given when all idle time is subtracted from the total picking time. It can be seen that the delay is much more than the specified 20%. The events that are found by the technical service department and cause idle time within the operation can be found in Appendix E.

**Table 6 Examples of gap analyses**

| Batch [-] | Efficiency [layers/hour] | | Difference[%] |
|---|---|---|---|
| | Incl. delay | Excl. delay | |
| **1** | 38 | 93 | 59 |
| **2** | 52 | 107 | 51 |
| **3** | 59 | 176 | 66 |

### 5.3.4 Conclusion

The gap analysis shows that there are huge differences between the specified and practical delay percentages due to operational issues. According to the technical service department those issues could be solved. It is assumed that the operation works properly when implementing new batch heuristics or introducing lead time reduction.

## *5.4 Batch performance*

In this paragraph historical data will be used to analyse the performance of already picked batches. The main goal is to find variables which positively influences the pick efficiency.

### 5.4.1 Data

Just as in previous paragraphs historical data of the months April, March and June of 2015 are used for analyses. Those data contains 234 batches. Within those batches an deviation is made between big and small variants. Big batches contain more than 100 source pallets, small batches less or equal to 100 respectively. The arbitrary value of 100 is chosen because from Figure 9 it can be seen that above this amount of source pallets per batch, the variance of the efficiency decreases enormous. This translation results in 93 small and 141 big batches.

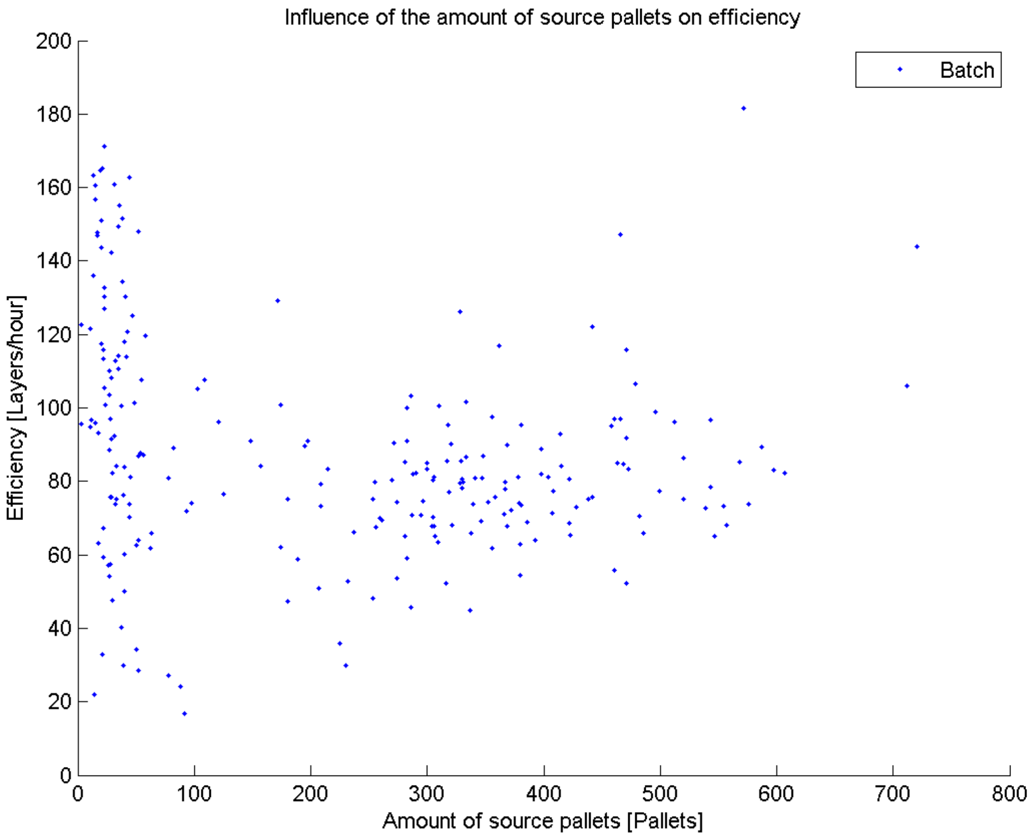


Figure 9 Influence of the amount of source pallets on efficiency

### 5.4.2 Batch size

Currently the batch size is defined as the amount of source pallets within a batch. Within the company there is a philosophy that says that the bigger the batch , the more efficient the picking will be. The idea behind this philosophy is that the bigger the batch, the more layers per SKU are picked within that batch and less broken pallets are created. So the amount of handling per layer is decreased, which directly influences the efficiency.

From Figure 9 it can be seen that relatively small batches deviate more in pick efficiency than large batches. Figure 10 supports this conclusion. The larger deviation for small batches can be explained due to the fact that disruptions have relatively more influence on smaller batches. Variance reduction can be accomplished by increasing the batch size. The figures also show that relatively small batches outperform big variants based on the mean pick efficiency. This efficiency is 96,99 layers for small and 75,75 layers per hour for big batches respectively. Figures where batch sizes defined by the amount of daughter pallets or the amount of layers are plotted against pick efficiency can be found in Appendix D. Those figures support the above drawn statements.

Thus, historical data shows that on average smaller batches outperform the bigger variants. Those conclusions suggest that another factor influences the pick efficiency per batch more than batch size. It is expected that the small batches have got more picks per source pallet because those contain for most of the part AH-orders. Naturally the deviation of big batches is smaller due to the lower sensitivity to breakdowns and external- or internal factors.

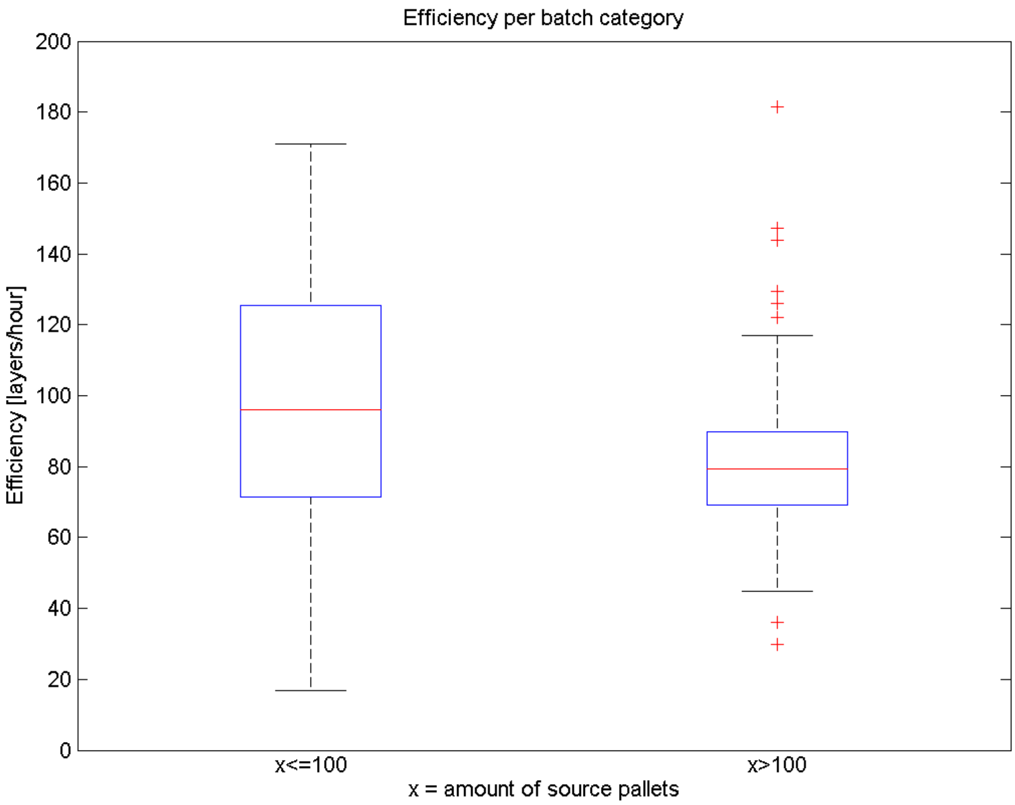


Figure 10 Efficiency based on batch category

### 5.4.3 Pick profile

In paragraph 5.4.2 it is found that batch size is a limited variable to explain batch efficiency. This variable is relatively superficial. For that reason the relation between layers, source and daughter pallets is more deeply discussed in this topic. The term pick profile is introduced. Which is defined as the amount of layers picked per source pallet. This definition is comparable to the term pick density mentioned in the literature review paragraph 3.1. It is expected that an increase in pick profile will result an increase in pick efficiency. This because the more layers per source pallet are picked, the less handling per picked layer is needed. The relation between the amount of picked layers per source pallet and the pick efficiency per batch can be found in Figure 11.

From the figure it can be concluded that the amount of layers picked per source pallet has got a positive effect on the pick efficiency of the ALP. In other words, increase in pick profile result in an increase in pick efficiency.

The batches with high pick profiles, a value of 4.5 or higher, mostly occur within small batches. Further research shows that those batches contain mainly AH- orders. Those orders are relatively similar and destined for the same kind of customer. This increases the possibility that one source pallet serves multiple customers, i.e. multiple daughter pallets. And so the possibility that an increased amount of layers needs to be picked from one source pallet. An increase in pick profile decrease the amount of pallet handling and as a result the amount of needed picking time.

To compare the pick profile with the influence of the amount of daughter pallets two more relations are introduced. The first term is called transfer profile. Transfer profile is defined as the amount of layers that needs to be transferred to one daughter pallet. This relation does not show any relation on pick efficiency. This conclusion is supported by the figures in Appendix D.

The second term is called transfer ratio. Which is defined as the ratio between the amount of daughter pallets and source pallets within a batch. The figure that illustrates the relation between transfer ratio and pick efficiency can be found in Appendix D. Transfer ratio seems to have a weak positive relation on pick efficiency. But it is believed that this is the result of the influence of the much stronger positive relation of the pick profile on pick efficiency. And so, transfer ratio cannot be used to explain the efficiency of a batch.

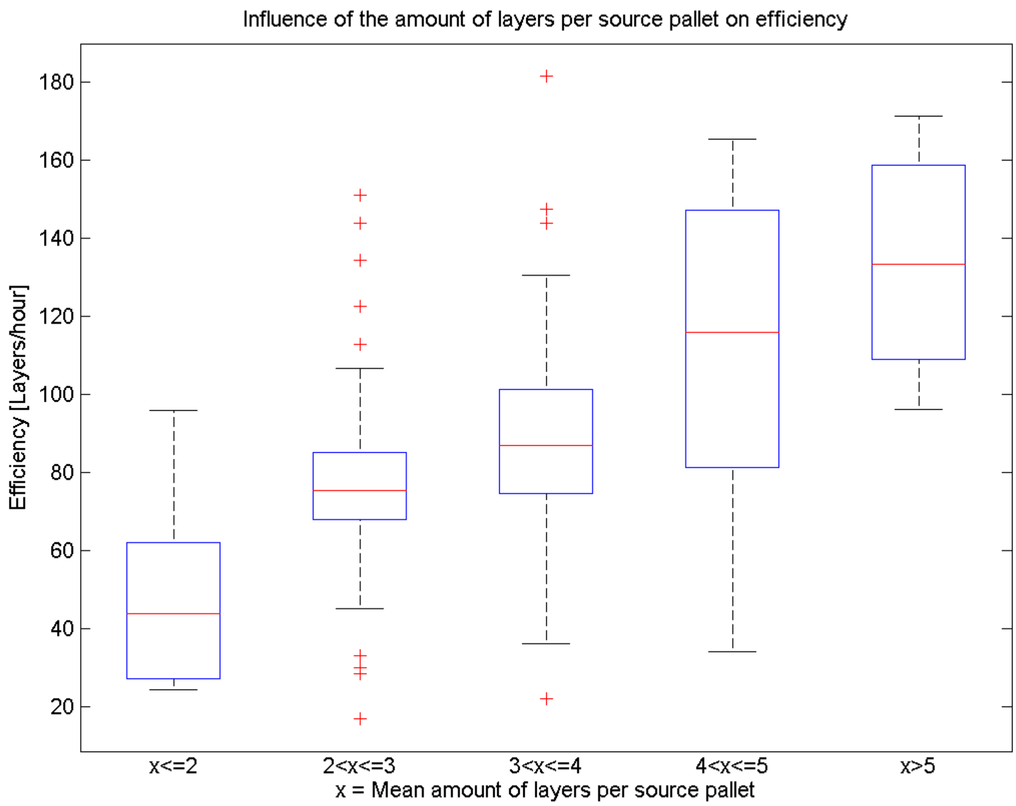


Figure 11 Effect of the amount of layers picked per source pallet on pick efficiency.

To conclude, the expectation that an increase in the pick profile leads to an increase in pick efficiency, is supported by the historical data. The effect of a decrease in handling per transferred layer on the pick efficiency can be directly seen within the performance of the ALP. The next paragraph will deepen this characteristic even more.

### 5.4.4 Synergy

In the previous paragraph it is found that the pick profile seems to be the most important parameter to explain pick efficiency so far. An increase in pick profile can be established in two different ways.

The first, and most ideal way, is the increase of order quantity per customer. With an increase in the order quantity both the source and daughter pallets stay at the picking machine for a longer period of time, and layers need to be transferred without any pallet movements. When the pick quantity reaches the maximum amount of layers that can be stored at one pallet, the upper level is reached. The automatic layer picker is not used for full pallet picking. The problem is that the warehouse operation cannot increase order quantities. What can be done is to develop order regulations in cooperation with the customer, which increases the order quantity per SKU per order.

The second way to increase the pick profile is to increase the amount of customers that are served by the same source pallet. Also then more layers are picked from one source pallet. But the only difference compared to the previous situation is that daughter pallet movements occur, since every daughter pallet serves a different customer. Pallet movements always introduce picking time. The amount of customers that are served by one source pallet can, contrarily to the customers' order quantity, be partly controlled by the operation while composing the batch.

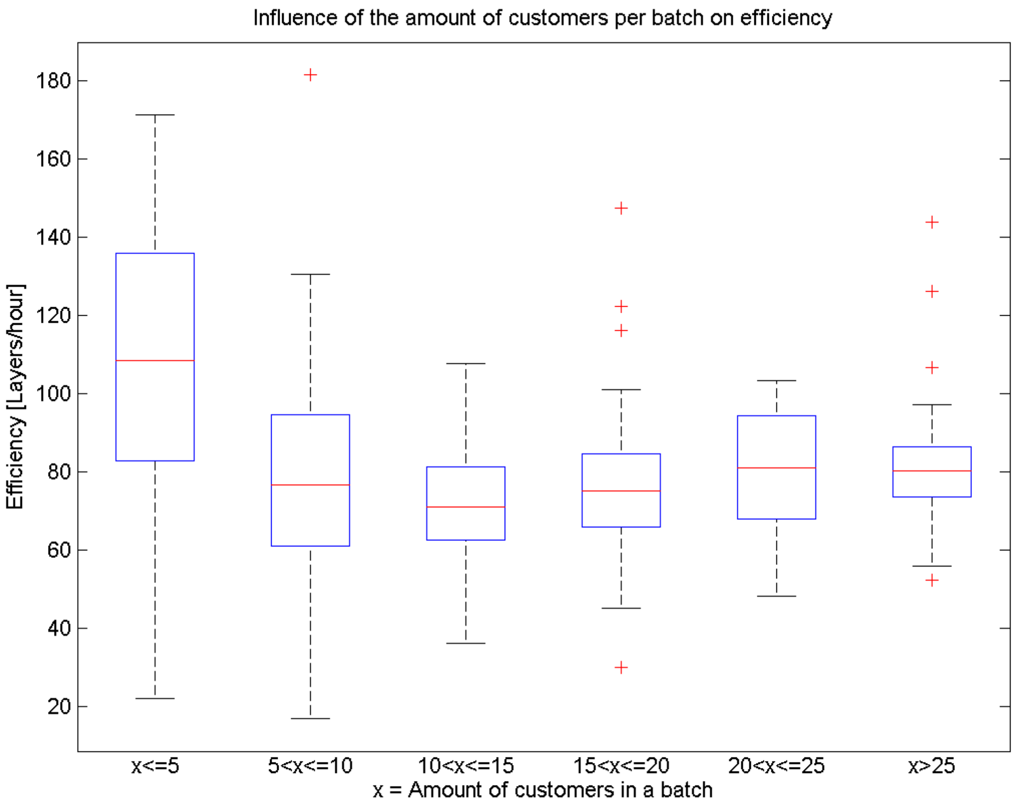


Figure 12 Influence of the amount of source pallets per customer

Adding an extra customer to a batch does not directly lead to an increase in pick performance as can be seen in figure Figure 12. The positive effect of adding an extra customer occurs when the customer ordered partly the same SKU's that are already in the batch, and ordered by the other customers in that batch. The more SKU's of the added customer are already in the batch, the larger the positive effect on pick performance will be. This is, because the pick profile will probably increase. The negative effect occurs when the new added customer does not have any SKU's ordered that are in common with the SKU's that are already in the batch. This will result in a lower mean amount of layers per SKU. And so, lower the pick profile.

The positive effect that occurs during the composition of batches is called synergy. Synergy contains two factors which decrease the amount of pallet movements within the ALP operation. First of all synergy tries to increase the pick profile as seen previously. Secondly it is preferred to decrease the amount of daughter pallet movements. Daughter pallet movements can be reduced by adding whole customers' orders to the batch and by smart sequencing. Smart sequencing can be achieved when for example a daughter pallet needs a layer from both the currently placed, and the following retrieved source pallet. Handling reduction is then achieved when the daughter pallet is not send to the daughter pallet buffer but left in the machine during the source pallet change.

### 5.4.5 Footprints

One of the customer specific requirements is footprint. The different footprint types, Chep (CHP), Euro chep (ECP), La pallet rouge chep (LPR(CHP)) and La pallet rouge euro chep (LPR(ECP)) that are used within the FMCG operation are given in Table 7. A footprint change is associated with an extra time of approximately 5 minutes. The data shows that the maximum amount of different footprints within a batch is 3. Thus, maximal 2 footprint changes can take place. Which put an additional time of 10 minutes to the original picking time.

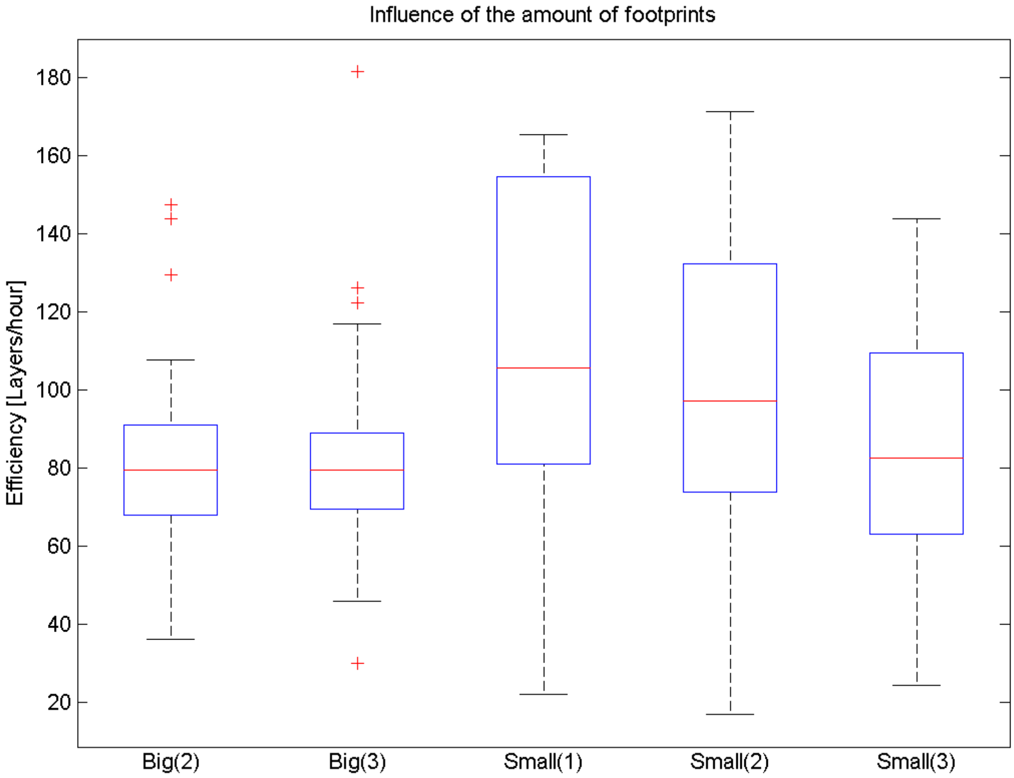


Figure 13 Influence of the amount of footprints within a batch.

Although this is not very much, Figure 13 shows differences between the picking time of batches with 1, 2 or 3 different footprints. In this figure Big() represents the defined big batches and Small()

the defined small batches respectively. The number between the brackets indicates the amount of different footprint types within the batch. The additional 10 minutes do not have the significant effect on the total picking time. More research was needed to clarify this phenomenon.

Table 7 Different pallet types

| Pallet type | Width[cm] | Length[cm] | Colour [-] |
|---|---|---|---|
| CHP | 100 | 120 | Blue |
| ECP | 80 | 120 | Blue |
| LPR(CHP) | 100 | 120 | Red |
| LPR(ECP) | 80 | 120 | Red |

Interviews with warehouse employees explain that products are stored less stable on ECP and LPR(ECP) than on the CHP variant. The reason of this instability is not the design of the pallet but it is the combination of product characteristics. One category of those instable products is tea. This product type is packed in relatively long and small boxes and has got a low weight. This combination of characteristics causes the product to fall of the pallet very easily. When a product falls of the pallet, the picking process needs to be interrupted. The process resumes when the fallen product is replaced on the pallet. The interruption is associated with additional picking time. The different pallet types with corresponding pallet dimensions constrain the possibilities of transferring a layer from a source pallet to the daughter variant. Layers on CHP pallets cannot be transferred to ECP pallets. However, the opposite is possible.

It can be concluded that not the pallet type, but product characteristics influences the picking efficiency. It could be useful to do more research to the effect of those characteristics on the ALP's performance. Maybe it is smart to pick some layers manually to prevent breakdowns.

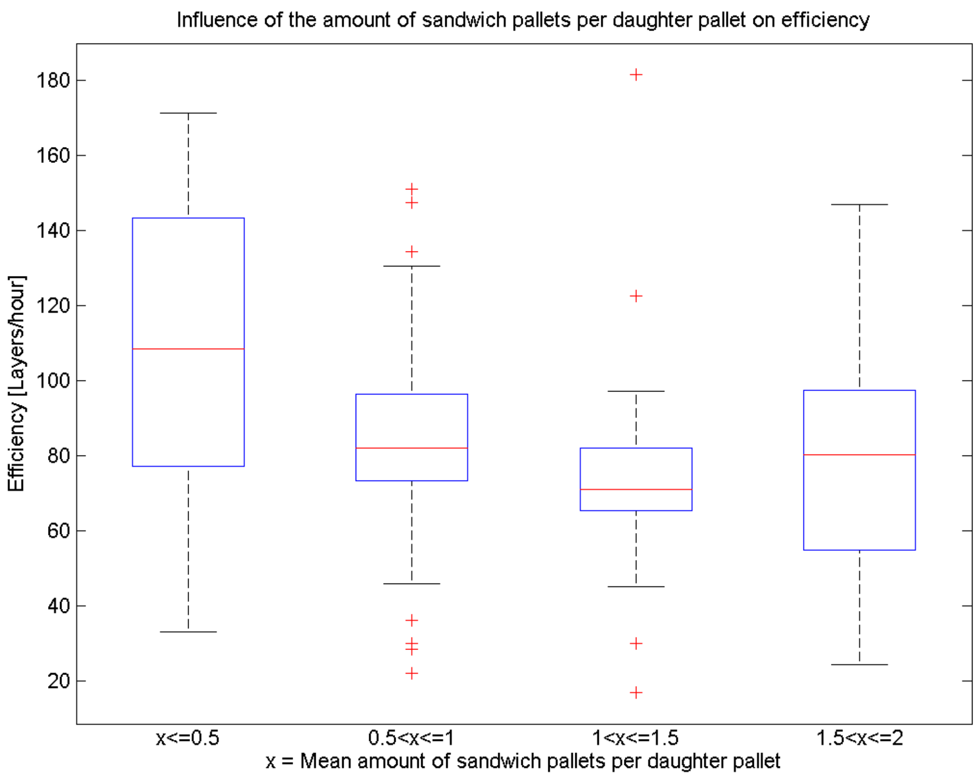

Figure 14 Influence of the amount of sandwich pallets per daughter pallet on pick efficiency

### 5.4.6 Sandwich pallets

The next variable that will be discussed is the amount of sandwich pallets that needs to get placed on a daughter pallet.  The placement of sandwich pallets has got two main disadvantages. First of all placing a sandwich pallet introduces extra picking time. Placing an extra pallet on a daughter pallets takes approximately half the time of placing a layer. Secondly, the sandwich pallet reduces the maximum amount of layers that could be placed on a daughter pallet. Therefore, more daughter pallets and are needed to pick the same amount of layers with the ALP. As a logical consequence more daughter pallets introduces more pallet movements and extra picking time. Thus, the placement of a sandwich pallet will reduce the possibility of a higher picking efficiency because extra time is introduced.  This expected negative relation is not found as can be seen in Figure 14.

### 5.4.7 Others efficiency influencers

Besides the variables like pick profile and synergy, the analysis of the batch performance also includes the products specific variables stack class, stack class sequence, crushability, weight and height. First of all, those variables do not show any significant effect on the picking efficiency. Figures of all the variables discussed in this paragraph can be found in Appendix D.

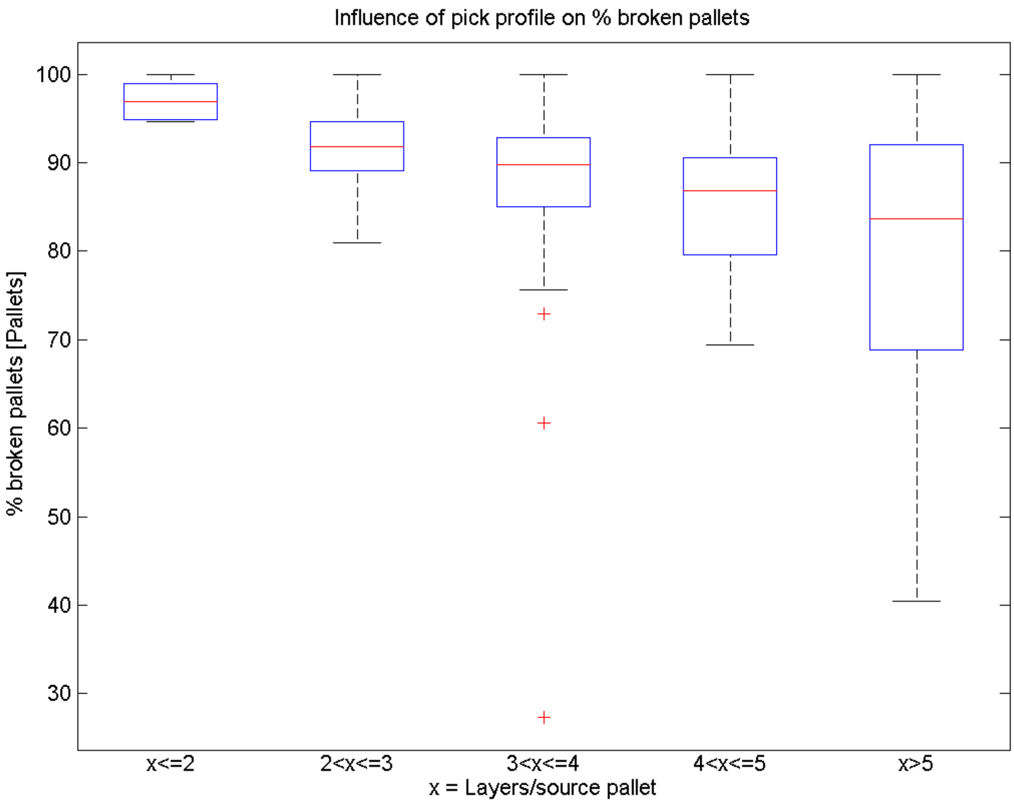


Figure 15 influence of synergy on %empty picked source pallets

### 5.4.8 Broken pallets

The last batch performance measure is the pallet handling at the outfeed of the ALP. The amount of broken pallets influences the performance in terms of costs, which is discussed in paragraph 2.2.2. From the product master data it can be seen that the mean amount of layers stored at a source pallet used for the automatic layer picking process is equal to 9.

On average, a source pallet becomes a broken pallet when a quantity between the 1 and 8 layers is picked by the ALP. When it is assumed that the probability function of the picked amount of layers is uniform distributed it is expected that 89% $\left(\frac{8}{9} * 100\%\right)$ of the incoming source pallets become a broken pallet at the outfeed of the ALP. But in fact this distribution is not uniform but depends on the pick profile of the batch. It is thought that an increase in pick profile will increase the probability of a high percentage of empty picked pallets. And thus, this will decrease the probability of a high percentage of broken pallets. This is supported with Figure 15.

As told before, introducing MOQ agreements could have a beneficial effect on the pick profile. Thus could also be beneficial for the creation of broken pallets. One of those could be the order rule that the customer can only order a multiple of a specified minimal layer quantity. For example, when the minimal order quantity is 3 layers for a specific product, and that product is stored with 9 layers on a full pallet, it is expected that 66% of the source pallets become a broken pallet. Which is a reduction of 23% for uniform distributed probability functions.

### 5.4.9 Conclusion

In this paragraph it is found that the pick profile, defined as the mean amount of layers picked from one source pallet, is the main variable that has got a positive influence on the pick performance of the ALP. To get a high pick profile the term synergy is introduced. Variables like the amount of footprints has got a negative effect on the pick performance due to the fact that those factors introduce extra picking time. The influence of these variables can only be minimized in cooperation with the customer. The expected negative influence of the amount of sandwich pallets in not found.

# 6 SCENARIO'S

In this chapter batch heuristics are developed to increase the performance of the layer picking process and decrease the order lead time. The heuristics are based on the same assumptions and same seeding algorithm as described in the next paragraph. It is possible that a heuristic contains additional assumptions. Last, a scenario is given in which process improvements can be simulated.

## *6.1 Baseline model: Current way of working*

The baseline model contains historical composed batches from the research environment described in the next chapter. The baseline model is used to compare new developed heuristics with the current situation. Before the results of those two weeks are discussed background information about the determination of the batch composition and batch allocation is given.

The batch composition of the baseline model is based on 3 picking cycles in which a distinction is made between the order types as mentioned in chapter 4. Batch composition is based on whole trips and restricted by the corresponding departure times. For clarification, the first departure time of a trip within a batch determines the maximum amount of layers that could be picked within that batch. So when picking starts at $t_{start}$ and the first trip within that batch departs at $t_{dep,i}$ then $T$ within Algorithm 2 gives the maximum amount of layers. In this function $t_f$ is the time that the picking needs to be finished before departure.

To compose the batches Kuehne + Nagel uses a KPI of 110 layers per hour for the expected pick efficiency as mentioned before. It is tried to make the batches as big as possible. Secondly, it is tried to finish the picking of 48 hour orders on one of the two ALP's before 14:00. For that reason this ALP could be used for the picking of the 24 hour variant. The steps that Kuehne + Nagel takes to compose batches are roughly compared to Algorithm 2. In practice the batch composition differs from this algorithm because composing batches is partly done based on experience and human decision making.

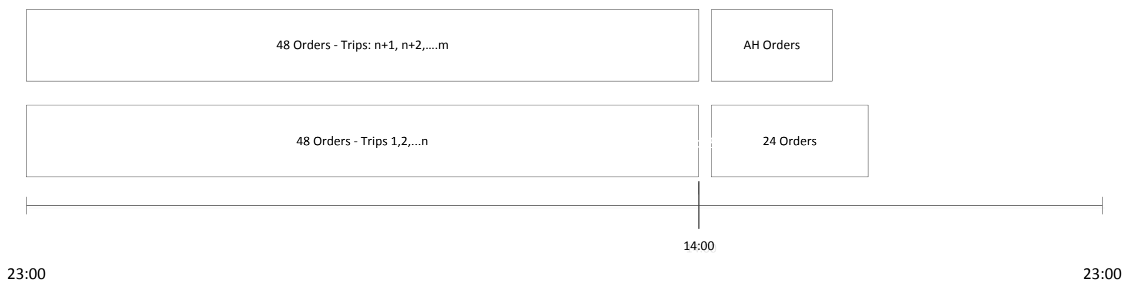


Figure 16 Schematically representation of the created batches and picking times for BM

The structure of the batch composition is the same within all three pick cycles. It is possible that an arbitrary departure time is chosen to ensure that both ALP's are used for the picking. For example, when 48 hour orders are picked by the ALP, and no arbitrary $t_{dep}$ is chosen, the batch on the first ALP will start on 23:00 on one day, and ends at the beginning of a new 48 hour pick cycle the next day. The other ALP will only be used for AH hour or 24 hour picking. Figure 16 shows an schematically example of the created batches within the baseline model.

## 6.2 *Heuristic 1: Current heuristic with theoretical performance*

The baseline model has got a major disadvantage, namely that the departure times of the trips are partly unknown or changing during the picking process. Some consequences of this disadvantage are high rack utilization at the docks, temporarily alternative trip storage and extra manual pallet handling. Also it is discussed earlier that currently not all layers are picked with the ALP although it is possible.

**Algorithm 2 Steps to compose batches**

| | | |
|---|---|---|
| Step 1 | : | Order the trips allocated to this picking cycle based on departure time. |
| Step 2 | : | Allocate the trip with the earliest departure time to the batch on the ALP 200 and remove that trip from that list. |
| Step 3 | : | Determine the maximum amount of layers for that batch with: $$T = \min[t_{dep,i}] - t_{start} - t_f$$ $t_{dep}$ is the first trip departing time within the batch, $t_{start}$ the expected start time of the batch, and $t_f$ the predefined fixed slack time. |
| Step 4 | : | Allocate the trips with the earliest departure time to the batch and remove that trip from the list. |
| Step 5 | : | Repeat step 4 as long as: $t_{ex} \leq T$. In which $t_{ex}$ is the expected picking time. Else go to step 6. |
| Step 6 | : | Repeat steps 2 -5 to compose a new batch on the other ALP till all trips are allocated to a batch or till step 5 is violated. |

The occurrence that layers, that could be picked by the ALP, are picked manually is the reason that heuristic 1 is developed. First of all Algorithm 2 is exactly followed without any deviation caused by human interference. With this heuristic new batches are created based on the known departure times of trips, the current batch composing and pick sequencing strategy. No special distinction is made between different order types, which could increase the amount of automatically picked layers.

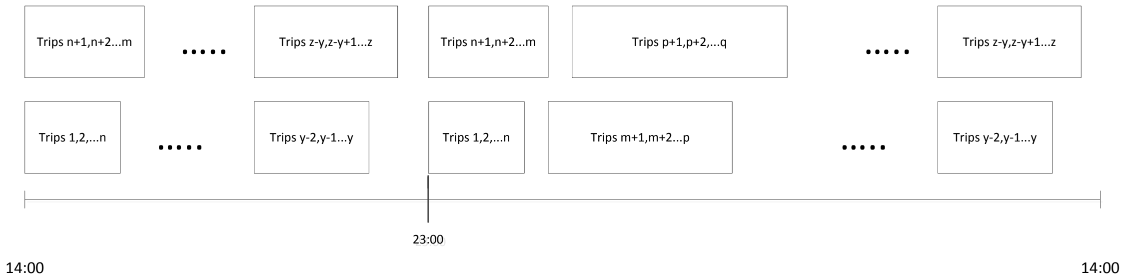


**Figure 17 Schematically representation of the created batches and picking times for heuristic 1**

Heuristic 1 shows the performance of the layer picking operation when all departure times are known in advance and when order types are combined within picking cycles. Still the picking cycles starts at 14:00 and another one at 23:00. It is expected that the amount of layers picked by the ALP increases. Thereby also the utilization of the operation, the number of batches, the number of broken pallets and the rack occupancy shall increase. Figure 17 shows an schematically example of the created batches for heuristic 1.

## 6.3 Heuristic 2: No ALP usage

The second heuristic is used to determine an upper cost level of the layer picking process and to compare the automatic layer picking process with its manual variant. This heuristic is used to show the disadvantage of picking manually. It is assumed that the picking is done just in time whereby rack occupancy has no influences on the costs. Also the number of batches and number of broken pallets do not apply for this heuristic.

It is expected that this heuristic is much more expensive than picking variants whereby the automatic layer picker is used. To calculate the costs of this heuristic the amount of layers are translated into an amount of case packs.

## 6.4 Heuristic 3: Current heuristic with lead time reduction

With the third heuristic lead time reduction is introduced. Only 24 hour and AH orders occur but still no distinction between pick cycles based on order type will be made. In this heuristic the same batch composition and pick sequencing strategy, as described in Algorithm 1 and Algorithm 2, is used. Every pick cycle starts at 14:00. The advantage of a shorter lead time is that the transport department is able to make a more accurate transport planning. It is assumed that the transport planning does change during the picking process.

It is expected that the amount of layers that is picked by the ALP is equal to or less than the amount of layers picked by the ALP with heuristic 1. This will mainly depend on the utilization of the operation. Due to the shorter lead time, the amount of batches will increase and as a logical result the average batch size decreases. It is also expected that more and shorter batches will increase the pallet handling at the infeed and outfeed of the ALP. Last, the rack occupancy will decrease because the time from start picking till departure will decrease similar to the lead time reduction. Figure 17 shows an schematically example of the created batches for heuristic 3.


**Figure 18 Schematically representation of the created batches and picking times for heuristic 3**

## 6.5 Heuristic 4: Parallel trip allocation and equal batch size

The baseline model and previous heuristics 1 and 3 result in batches of unequal size because batches are composed alternately per ALP. So the trips picked by the second ALP depart always at the same time or later, anyway never earlier, than the trips picked by the first ALP. Although those batches on the different ALP's run both at the same time. This seems very illogical in an operation where departure time is the most important variable in composing batches. That is the reason that heuristic 4 is developed. Within this heuristic not batches, but trips are allocated alternately per ALP. Thus, the batches on the two ALP´s are composed parallel. The advantage of this strategy is that the trips that departure first are always picked within a batch with the first start time. The size of the batches that run on different ALP's on the same time is kept comparable. So the batch size is restricted by the first departing trip within one of the two batches. When both batches are filled completely, new batches on both ALP's are created. The pick sequence strategy remains the same as described in Algorithm 1.

Because the batch composition is more conducted by departure time of the trips it is expected that the rack occupancy will decrease. Secondly it is expected that the number of batches will increase. Commensurate the average batch size will decrease. It is also thought that the increase in the number of batches result in more pallet handling at the in- and outfeed of the ALP. Figure 19 shows an schematically example of the created batches for heuristic 4.

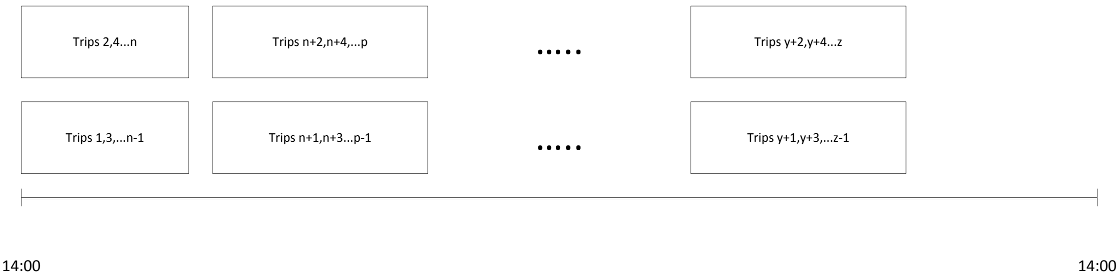


Figure 19 Schematically representation of the created batches and picking times for heuristic 4

## 6.6 Heuristic 5: Allocation based on synergy and equal batch size

Heuristic 5 is an extended version of heuristic 4. In this heuristic the batches on the two ALP's are still composed parallel. But trips are not allocated alternately per ALP. A trip is allocated to the batch whereby the resulting picking profile is the highest. The batch size is still restricted by the seed trip within one of the two batches as mentioned in paragraph 4.2. So the batch size on botch ALP's is comparable. When there is no room to add another trip to one of the two batches, the other batch is filled with trips with upcoming departure times. When both batches are filled completely, new batches on botch ALP's are created. The pick sequence strategy remains the same as described in Algorithm 1.

The advantage of synergy is explained in paragraph 5.2.4. So it is expected that the pick efficiency of the ALP operation increases. Other performance measures will be comparable to the ones of heuristic 4. Figure 20 shows an schematically example of the created batches for heuristic 5.

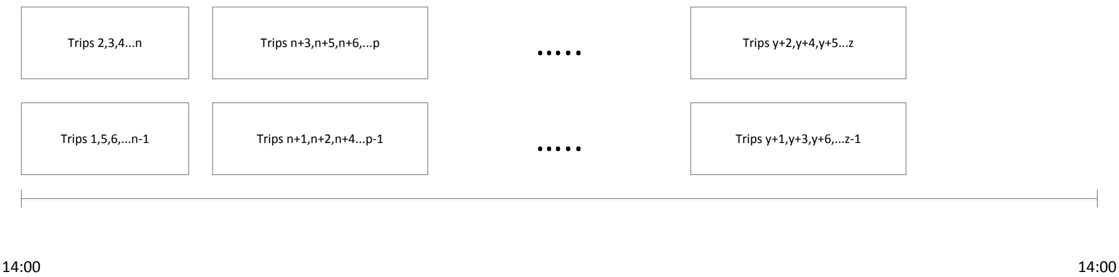


Figure 20 Schematically representation of the created batches and picking times for heuristic 5

## 6.7 Heuristic 6: Allocation based on synergy and batch specific size

The last developed heuristic, heuristic 6, is an extension of heuristic 5. In this heuristic the batches on the two ALP's are still composed parallel, and trips are allocated to the batch whereby the resulting synergy factor is the highest. But the size of the batch is determined by the first departing trip within each of the two batches separately. So the batch sizes differ per ALP. Also within this strategy one batch is filled with trips with upcoming departure times, when there is no room to add another trip to the other batch. When both batches that will be picked at the same time are completely filled with trips, new batches on both ALP's are created. The pick sequence strategy remains the same as described in Algorithm 1.

It is expected that this heuristic performs comparable to heuristic 6 on most KPI's. Difference will be found on the amount of batch size and consequentially on the amount of pallets at the in- and outfeed. Figure 21 shows an schematically example of the created batches for heuristic 6.


Figure 21 Schematically representation of the created batches and picking times for heuristic 6

## 6.8 Process improvement

In chapter 5 it is mentioned that the operational performance of the ALP is lower as specified. Even with an allowed delay of 20% the performance is not even close. Because the technical service department indicated that the issues that causes the decrease in performance can be solved, an what-if scenario is simulated. Within this scenario the batch composition is not based on the current, but on an increased pick performance. On this way the batch performance is analysed when operational improvements are made. The operational improvements are specified in paragraph 7.2.

# 7 EXPERIMENTAL SETUP

In the previous chapter the developed heuristics are discussed. A deterministic model will test the performance of these heuristics. In this chapter the consolidation of the input file for this model, the deterministic model itself, the output and research environment will be discussed.

## *7.1 Data*

The input for the model describes the pick sequence of the automatic layer picking process. This file differs per heuristic. First the batches are composed according to Algorithm 2 and the heuristic specific rules. Secondly the pick sequence is determined according to Algorithm 1. An example of the pick sequencing file can be found in Appendix F. Every row represents a collection of pick events with a unique combination of article number, amount of layers, source pallet number, daughter pallet number, placement of sandwich pallets, pick type, footprint type, relations code, stack class, stack class sequence, trip number and batch number.

The data that is used to compile the pick sequencing file is based on two historical weeks. The first week represents the picking of an average picking week. Within this week 12534 layers are ordered that could be picked with the automated picking process. The second week represents the automated picking within a busy week. The amount of layers that are ordered by customers within this week are 14636 layers. Those settings correspond with week 26 and week 16 respectively. The heuristics are tested and compared within two different research environments, which correspond with the average and busy picking week.

With the change to 24 hour lead time heuristics adaptions concerning the ordering profile are made. It is assumed that the 48 hour orders are not ordered 2, but only 1 day in advance. So, it is assumed that the 48 orders that depart for example on Wednesday, are received at Kuehne + Nagel on Tuesday instead of Monday. In fact, the amount of 24 hour orders that depart on Wednesday within the 24 hour lead time situation consists of the 24 hour and 48 hour orders that should depart on Wednesday within the old 48 hour lead time situation.

A pick week within the simulation settings contain 48 hour and 24 hour orders that depart on Tuesday till Friday and AH orders that depart from Monday till Friday. The historical picking that is done in the weekends is left out of the research environment because first of all it is tried not to use the ALP in the weekends, and secondly the available picking data is not consistent with the information provided by interviews. So, the picking starts at its earliest at Monday at 00:00 and stops not later than 23:59 on Friday.

## *7.2 Decision rule*

Within the deterministic picking model a decision rule is used to decide whether a trip can be allocated to a batch or not. This decision rule is given by Equation 3. In this formula $t_{ex}$ is the expected picking time calculated with Equation 2, $t_{dep}$ is the first trip departing time within the batch, $t_{start}$ the expected start time of the batch, and $t_f$ the predefined fixed slack time.

$$t_{ex} \leq \min\left[t_{dep,i}\right] - t_{start} - t_f$$

**Equation 3 Model decision rule**

In the scenarios in which the process improvements are analysed the weighted pick efficiency that is used to compose the batches is replaced by new expected weighted efficiencies. The corresponding regression parameter $a$, used to calculate $t_{ex}$ are calculated with Equation 4. The value $E_w$ , the weighted pick efficiency, deviates from the current pick performance of 82 layers per hour till 115 layers per hour.

$$a = \frac{3600}{E_w}$$

**Equation 4 Factor change for process improvement**

## *7.3 Deterministic picking model*

The performance of the determined pick sequence and thereby also the performance of the heuristic specific rules are found by running a developed deterministic pick model. This model is based on 19 different pallet handling events, 2 pick situations and footprint changes.

The pallet handling events can be found in Appendix C. An event may include retrieving a new source pallet, retrieving a new daughter pallet, placing a sandwich pallet, recycling the source pallet and sending pallets to the outfeed. Each event is characterized by a specific time. Due to the fact that the input file consist of a sequence of single pick events, the total pallet handling time can be calculated by summating the event times. The complete roadmap that is used within the deterministic simulation model can be found in Algorithm 3 and is modelled in Matlab.

**Algorithm 3 Roadmap of the deterministic model**

Step 1 : Run heuristic specific batch composition algorithm.

Step 2 : Run the pick sequencing algorithm, Algorithm 1.

Step 3 : Determine the stock-ID's for the required source pallets per pick based on the following rules.

- Step 3a : Check if the current pick contains the same SKU as previous pick. If no, go to step 3b. If yes, check if the amount of the previous picked layers plus the amount of layers of current pick exceed the amount of layers on the source pallet. If yes, go to step 3b. Else, the stock-ID equals the stock id of previous pick.
- Step 3b : The stock-ID of this pick equals the stock-ID of previous pick plus 1.

Step 4 : Run the deterministic simulation model.

- Step 4a : Calculate the pallet handling time, $t_{e,i}$, per pick $i$ according to the pallet handling events described in Appendix C. For example in the situation that first a sandwich pallet needs to get placed on the current placed daughter pallet, and secondly a new source and empty daughter pallet need to get retrieved, event 9 occurs. This takes 26 seconds. The 8 seconds to retrieve a new source pallet is not taken due to the occurrence of parallel events: The source pallet is retrieved during the placement of the sandwich pallet.
- Step 4b : Calculate the layer transferring time, $t_{t,i}$, per pick $i$ . Transferring Type 1 SKU's from the source pallet to the daughter pallet takes 17 seconds and Type 2 SKU's 10 seconds per layer respectively.
- Step 4c : Calculate the footprint change time, $t_{o,i}$, per pick $i$. When the footprint of the current pick differs from the footprint of previous pick, the footprint time equals 300 seconds. Else the

footprint change time equals 0 seconds.

Step 4d : Calculate the total pick time in hours:

$$t_p = \sum_{i \in I} (t_{e,i} + t_{t,i} + t_{o,i})$$

Step 5 : Calculate the amount of layers, $L$, picked within the heuristic.

Step 6 : Calculate the amount of source pallets at the infeed of the ALP:

$$I = max(stockID)$$

Step 7 : Calculate the mean efficiency in layers per hour:

$$\eta = \frac{L}{t_p * 0.8}$$

The factor 0.8 indicates the 20% delay time as explained in chapter 6.

Step 8 : Calculate the average ALP utilisation during the simulated cycle:

$$u = \frac{t_p}{5 * 24 * 2 * 0.8}$$

Step 9 : Calculate the amount of broken pallets per SKU $j$ within batch $i$. If the modules of the total amount of layers per SKU $j$ within batch $i$ and the amount of layers on a pallet of SKU $j$ equals 0, then no broken pallets are created for SKU $j$ within batch $i$. Else 1 broken pallet is created. Repeat this calculation for each specific SKU $j$ in each specific batch.

Step 10 : Calculate the rack occupancy per second during the simulation time.

Step 10a : Determine picking start time and the departure time for every trip $i$.

Step 10b : Determine for every second, $s$, the amount of trips that are stored within the racking, $R_s$ based on the picking and departure times of step 11a.

Step 10c : Determine the maximal racking occupancy:

$$R = \max[R_s]$$

Step 10d : Calculate the amount of trips that are stored at alternative locations by summating the amount of trips that need to get stored after the racking is already occupied by 81 trips. Use the figures from Appendix I and assume that trips at alternative locations depart first.

## *7.4 Performance measures*

The performances of the heuristics are measured with 9 different key performance indicators. Those KPI's are described earlier and can be can be found in paragraph 2.2.1 and will be given in absolute and relative numbers. The determinations of the savings are explained more deeply below.

### 7.4.1 Costs

In this subchapter the main factors that influences the costs of the layer pick operation are explained. The two main factors of the layer picking are the automatic and manual process. In which the automatic layer picking process can be subdivided into 3 categories: infeed, automated layer picking process and outfeed. A third main factor, that indirectly influences the costs of layers picking, is the exceedance of maximal rack occupancy at the docks.

1) The manual layer picking process contains costs of manually collecting layers from the forward picking zone in the OPH. The layers cannot be picked completely manually at ones. For that reason cost calculations need to be in terms of case packs. The picking efficiency for a picker is 330 cases/hour with an hourly wage of 23 euro. In Equation 5 the formula for the manually layer picking is given. In this formula $C$ is the total amount of case packs, $E_c$ is the pick efficiency and $w_h$ the hourly wage.

$$c_m = \frac{C}{E_c} * w_h$$

**Equation 5 Manually picking costs**

2) The costs at the infeed of the ALP depend on the amount of source pallets that needs to be retrieved. The pallets that are retrieved from the high bay are not taken into account. Data from week 41, which can be found in Appendix B, shows that on average 75% of all pallets are retrieved from the OPH. Collecting and inserting a pallet into the ALP takes on average 98 seconds,$t_i$. The corresponding costs, $c_i$, can be calculated with the hourly wage,$w_h$ and the amount of infeed pallet, $I$. This is done in Equation 6.

$$c_i = t_i * \frac{w_h}{3600} * I$$

**Equation 6 Costs of the infeed of the ALP**

3) Within the picking operation of the ALP one operator is required for each machine. Next to hourly wage, it is assumed that no extra costs are associated with this kind of layer picking. For that reason the costs of the ALP only depends on the total picking time $t_p$ and hourly wage $w_h$ as can be seen in Equation 7.

$$c_{alp} = t_p * w_h$$

**Equation 7 Costs of the automatic layer picking process**

4a) The costs of the outfeed of the ALP operation contain two parts. The first are the costs of bringing the composed daughter pallets to the racking at the docks. Because the amount of daughter pallets that needs to be brought to the racking is the same for each developed heuristic, and so the corresponding costs are also comparable, these costs are not taken into account.

4b) The second part of the costs contains the manual handling of broken pallets. These pallets need to be stored at the broken pallet area for further processing. It is calculated that the handling of broken pallets and traveling to the broken pallet area, $t_b$, takes around 84 seconds per pallet as can be found in Appendix B. Together with the amount of broken pallets, $B$ and the hourly wage, $w_h$, the costs of the second part at the ALP outfeed can be calculated as can be seen in Equation 8.

$$c_b = t_b * \frac{w_h}{3600} * B$$

**Equation 8 Costs of broken pallet handling**

5) The planning round the layer picking process directly influences the amount of finished trips stored at the racking at the docks. Logically, the longer the lead time, the longer trips are stored in the racking and the more rack locations are needed. The maximal amount of rack locations available is 81. On one rack location, one trip is stored. And a trip contains 26 pallets. When all racking locations are full, trips need to be stored at alternative locations. Alternative storage contains extra pallet handling, $t_r$, of approximately 90 seconds per pallet per trip as can be seen in Appendix B. Together with an amount of 26 pallets per trip, $P$, the hourly wage, $w_h$, and the amount of trips that needs to be stored elsewhere, $R$, the costs can be calculated. Equation 9 gives the corresponding formula.

$$c_r = \frac{w_h}{3600} * P * R * t_r$$

**Equation 9 Penalty costs for exceeding the maximal rack occupancy**

# 8 RESULTS

With the deterministic model the performance of the developed heuristics is quantified. The performance of each heuristic will be given compared to the baseline model in this chapter. Comparison is done first with reference to 8 key performance indicates which are mentioned in paragraph 2.2.1.

## 8.1 No ALP usage

Heuristic 2 is used to give an upper limit of the costs for the layer picking process. The only costs that are related to this picking strategy, taken into account within this research, are the manual picking costs. Those are based on 278806 and 330685 cases for weeks 26 and 16 respectively. The costs can be found in Table 8 and Table 9.

**Table 8 Week 26 - No ALP usage**

| | Week 26 |
|---|---|
| **Heuristic:** | 2 |
| $c_{total}$ | € 19.431,93 |
| $c_{total}/L$ | € 1,55 |

**Table 9 Week 16 - No ALP usage**

| | Week 16 |
|---|---|
| **Heuristic:** | 2 |
| $c_{total}$ | € 23.047,74 |
| $c_{total}/L$ | € 1,57 |

## 8.2 48 hour lead time

In this paragraph the baseline model and heuristic 1 within the 48 hour lead time situation will be discussed according to the key performance indicators mentioned. The costs and KPI's are listed in Table 10, Table 11, Table 12 and Table 13. A full overview of KPI's given in absolute values and in percentage can be found in Appendix G.

**Table 10 Week 26 - KPI 48 hr lead time**

| Heuristic | $R$ | $I$ | $B$ | $u$ | $L$ | $C$ | $E_w$ | $n$ |
|---|---|---|---|---|---|---|---|---|
| **0** | 98 | 2420 | 2113 | 71 | 8682 | 65848 | 120 | 9 |
| **1** | 87 | 2865 | 2394 | 87 | 11034 | 35918 | 115 | 28 |

**Table 11 Week 26 - Costs 48 hr lead time**

| Heuristic | $c_{alp}$ | $c_i$ | $c_b$ | $c_m$ | $c_r$ | $c_{total}$ | $c_{total}/L$ |
|---|---|---|---|---|---|---|---|
| **0** | € 3.266,00 | € 1.139,60 | € 1.137,46 | € 4.589,41 | € 463,45 | € 10.595,92 | € 0,85 |
| **1** | € 4002,00 | € 1349,16 | € 1288,73 | € 2503,38 | € 254,15 | € 9397,42 | € 0,75 |

It can be seen that within week 26 heuristic 1 performs better than the baseline model. Heuristic 1 turns out 10 euro cents less expensive per layer due to the increase of 19% in automatically picked layers and as a result a decrease in the amount of manual picked case packs. The same goes for week 16 where the amount of layers picked with the ALP increases with 31%, costs are reduced with 18 cents per layer although an increase in penalty costs for the exceedance of the racking occupancy.

A remarkable difference between both baseline model and heuristics 1 is the increase in the amount of batches. This is a result of an additional assumption. Heuristic 1 composes batches in sequence of trip departure. Within the baseline model the operator can leave out or add trips without violating the departure sequence. Time critical trips are picked manually instead of with the ALP which result in a decrease of the amount of batches.

Table 12 Week 16 - KPI 48hr lead time

| Heuristic | $R$ | $I$ | $B$ | $u$ | $L$ | $C$ | $E_w$ | $n$ |
|---|---|---|---|---|---|---|---|---|
| **0** | 70 | 2430 | 2065 | 68 | 8598 | 131825 | 123 | 15 |
| **1** | 100 | 3330 | 2725 | 100 | 13198 | 31774 | 125 | 29 |

Table 13 Week 16 - Costs 48hr lead time

| Heuristic | $c_{alp}$ | $c_i$ | $c_b$ | $c_m$ | $c_r$ | $c_{total}$ | $c_{total}/L$ |
|---|---|---|---|---|---|---|---|
| **0** | € 3.128,00 | € 1.144,31 | € 1.111,62 | € 9.187,80 | - | € 14.571,74 | € 0,99 |
| **1** | € 4.048,00 | € 1.380,71 | € 1.296,81 | € 5.065,65 | € 149,50 | € 11.940,66 | € 0,81 |

## 8.3 24 hour lead time

In this paragraph the four heuristics within the 24 hour lead time situation will be discussed according to the key performance indicators. The relevant costs and KPI's are listed in Table 14, Table 15, Table 16 and Table 17. A full overview of KPI's given in absolute values and in percentage can be found in Appendix G. As mentioned before, heuristic 3 is based on the current batch method, heuristic 4 uses parallel batching and both heuristics 5 and 6 use a synergy factor for the allocation of trips to batches.

Table 14 Week 26 - KPI's 24hr lead time

| Heuristic | $R$ | $I$ | $B$ | $u$ | $L$ | $E_w$ | $n$ |
|---|---|---|---|---|---|---|---|
| **3** | 57 | 3303 | 2933 | 94 | 11302 | 120 | 49 |
| **4** | 45 | 3142 | 2794 | 89 | 10397 | 117 | 60 |
| **5** | 82 | 3220 | 2864 | 92 | 10813 | 120 | 58 |
| **6** | 50 | 3283 | 2911 | 93 | 11202 | 120 | 54 |

Table 15 Week 26 - Costs 24hr lead time

| Heuristic | $c_{alp}$ | $c_i$ | $c_b$ | $c_m$ | $c_r$ | $c_{total}$ | $c_{total}/L$ |
|---|---|---|---|---|---|---|---|
| **3** | € 4324,00 | € 1555,42 | € 1578,88 | € 2037,45 | € 0,00 | € 9495,75 | € 0,76 |
| **4** | € 4094,00 | € 1479,60 | € 1504,06 | € 3536,28 | € 0,00 | € 10613,94 | € 0,85 |
| **5** | € 4232,00 | € 1516,33 | € 1541,74 | € 2876,81 | € 14,95 | € 10181,83 | € 0,81 |
| **6** | € 4278,00 | € 1546,00 | € 1567,04 | € 2254,56 | € 0,00 | € 9645,60 | € 0,77 |

First, within week 26 both heuristics 3 and 6 perform comparable in terms of costs per layer, 76 cent and 77 cents respectively. In total the costs are 150 euro lower for heuristic 3. Heuristic 4 and 5 perform less. This is because the costs are related to the amount of automatically picked layers. Identical to the change in picked layers differences in the amount of pallets that need to be processed at the in- and outfeed and manual picks occur. Thus the costs increase.

Secondly, a remarkable difference between the four heuristics is found at the maximum number of rack occupancy. Heuristic 5 exceeds the maximum number of 81 trips with 1. Third, equal batch sizes, which are used in both heuristic 4 and 5, are not beneficial for the pick performance in week 26. Contrarily, sizes which are batch specific increase the performance. Mostly because the amount of layers picked by the ALP is higher.

Also within week 16 heuristics 3 and 6 perform comparable. Both costs are reduced till 76 cents per layer. Heuristics 4 and 5 are again more expensive due to the lower amount of layers picked by the ALP. The costs of the other key performance measures are related to the change in ALP picked layers. No strange behaviour is found with other KPI's. And the conclusions drawn related to week 26 also covers week 16.

Table 16 Week 16 - KPI's 24hr lead time

| Heuristic | $R$ | $I$ | $B$ | $u$ | $L$ | $E_w$ | $n$ |
|---|---|---|---|---|---|---|---|
| 3 | 49 | 3459 | 2981 | 105 | 12819 | 116 | 68 |
| 4 | 40 | 3256 | 2818 | 102 | 11751 | 108 | 106 |
| 5 | 48 | 3293 | 2831 | 101 | 12218 | 118 | 74 |
| 6 | 50 | 3484 | 3016 | 105 | 12819 | 116 | 74 |

Table 17 Week 16 - Costs 24hr lead time

| Heuristic | $c_{alp}$ | $c_i$ | $c_b$ | $c_m$ | $c_r$ | $c_{total}$ | $c_{total}/L$ |
|---|---|---|---|---|---|---|---|
| 3 | € 4830,00 | € 1628,88 | € 1604,72 | € 3101,03 | € 0,00 | € 11164,63 | € 0,76 |
| 4 | € 4692,00 | € 1533,28 | € 1516,98 | € 5128,72 | € 0,00 | € 12870,98 | € 0,88 |
| 5 | € 4646,00 | € 1550,71 | € 1523,98 | € 3919,06 | € 0,00 | € 11654,69 | € 0,79 |
| 6 | € 4830,00 | € 1640,65 | € 1623,56 | € 3103,03 | € 0,00 | € 11195,24 | € 0,76 |

In both weeks the amount of manual picked cases is not reduced to zero. In week 26 maximal 78% of all layers are picked automatically. This number is 88% in week 16 respectively. Although earlier it is thought that synergy decreases the relative amount of broken pallets, this does not occur with heuristics 5 and 6. The percentage of broken pallets is 89% in week 26 and round 86% in week 16. When the composition of batches is based on the synergy between whole trips, the positive effects are neutralized by negative effects as discussed in paragraph 5.4.4. As a result of the neutralization of the positive synergy effect no big difference in pick efficiency is found. This conclusion is supported by Table 18. No significant differences can be found between the heuristics based on synergy.

Table 18 Pick profile per heuristic

| Heuristic: | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Week 26 | 3,59 | 3,85 | [-] | 3,42 | 3,31 | 3,36 | 3,41 |
| Week 16 | 3,54 | 3,96 | [-] | 3,71 | 3,61 | 3,71 | 3,68 |

## 8.4 Comparison

The difference in costs between the current 48 hour situation and the situation in which lead time reduction is introduced, Heuristic 1 and 3, are larger for week 26 than for week 16. In week 26 more layers are picked automatically within the 24 hour situation compared to the 48 hour variant which reduces the costs with 5 cents per layer. This is a result of a higher pick efficiency and less idle machine time. This conclusion is not as expected. It was expected that lead time reduction should decrease the pick efficiency with a negligible change in the amount of ALP picking time.

The difference between the two heuristics in week 26 is analysed more deeply. It is found that reduction of fixed cycle times could have a positive effect on the amount of automatically picked layers. A fixed start time of a new cycle could introduce idle windows. Those windows, represented by red within Figure 22 are too small to add another trip to the batch although picking time is left. This is comparable with the bin packaging problem (Johnson, Demers, Ullman, Garey, & Graham, 2006).

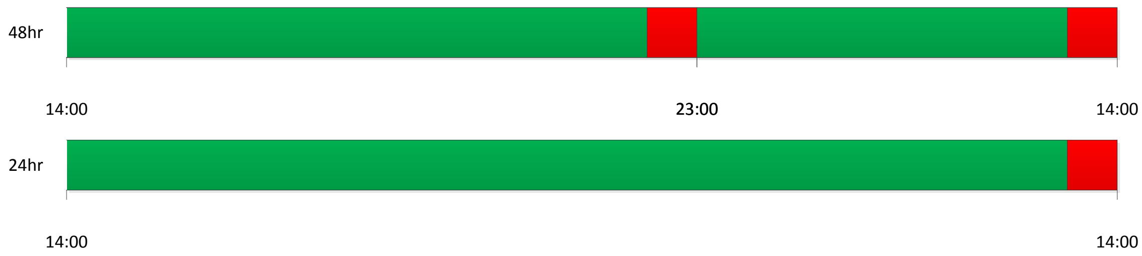


Figure 22 Effect of fixed 45cycle times

Last, it looks like the distribution of departure times of the trips during the day has a major influence on the performance of the heuristics. This hypothesis arise when looking to the rack occupancy figures of Appendix I. It is expected that the figures follow the pattern of Figure 55 in which high occupancy alternate with low occupancy. Peaks mainly arise after the start of a picking cycle. But the rack occupancy of heuristic 3 in week 26 does not follow this pattern as can be seen in Figure 50. High loads occur during the day within the second half of the week.

## 8.5 *Process improvement*

In this paragraph the batch performance in terms of costs in analysed for the two best heuristics within the 24 hour situation, heuristic 3 and 6. The relevant cost functions for both scenarios can be found in Figure 23. A full overview of the KPI's in absolute values and in percentage can be found in Appendix M.

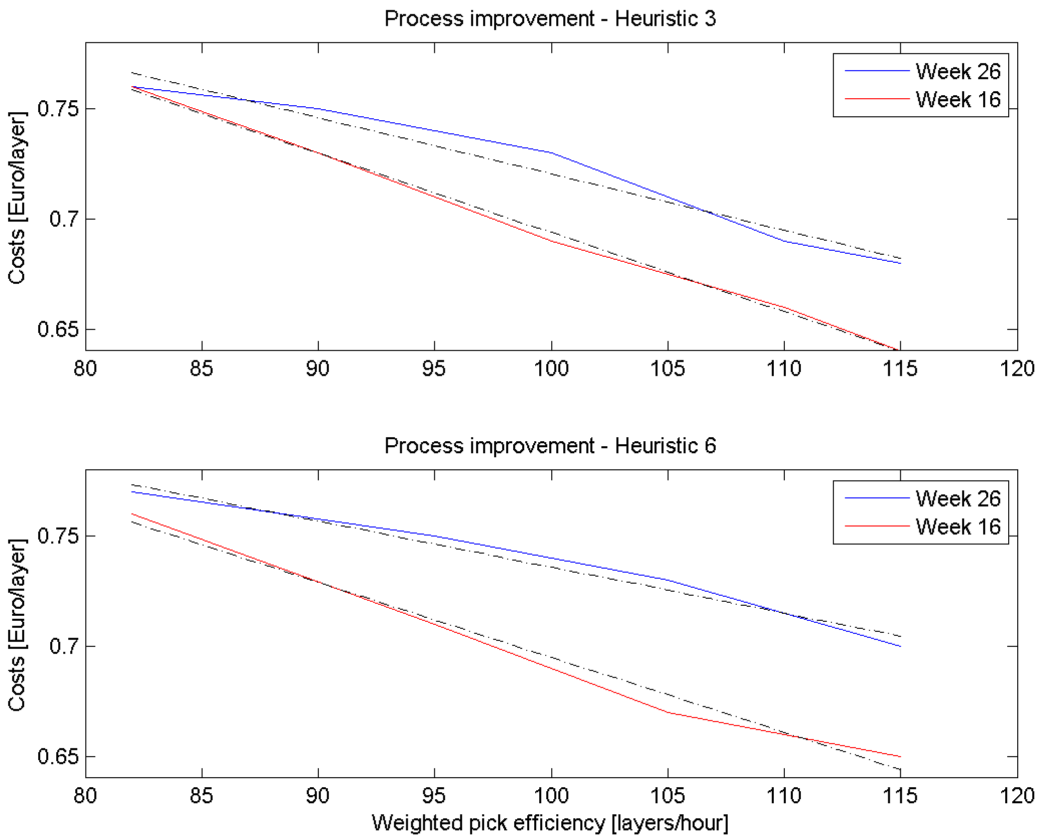


Figure 23 Costs reduction as a result of process improvement

Improving the operational process will result in a batch planning which is based on an increased weighted pick efficiency, $E_w$. As direct result the costs will decrease. Again this positive advantage is related to the decrease in manual picked cases and thereby the increase in the amount of automatically picked layers. With an weighted pick efficiency of 115, 95% of the layers can be picked with the ALP. From the figure it can be seen that the decrease in costs per increased weighted pick efficiency is higher for week 16. Thus, more operational benefits can be found in weeks with a high picking load. On average, heuristic 3 decreases with 0.0031 cents when the weighted pick efficiency is increased with 1 layer per hour. This number is 0.0027 for heuristic 6. With an average difference of 13%, operational improvements are more effective on heuristic 3.

A second advantage of process improvement is the reduction of batches . A reduction of the amount of single batches reduces the operational complexity. Not only the planning complexity, but also the pallet handling within the OPH becomes less time critical due to the elimination of batch specific deadlines.

Notable is the increase in pick efficiency when process improvements are applied on week 16. Where the pick efficiency within week 26 remains almost constant, it is increased till 130 layers per hour for the busy week. This increase could not be related to any increase in for example the picking profile. For that reason it is thought that other variable like the mentioned distribution of departure times of trips during the day has an significant influence on this occurrence. An increase in pick efficiency will result in an increase in layer picking with the ALP. And thus, reduce the costs even more.

# 9 CONCLUSIONS AND RECOMMENDATIONS

In this chapter the conclusions that can be drawn from the research are discussed. The conclusion are presented per research topic. Secondly recommendations will be given towards Kuehne+Nagel Veghel. The recommendations clarify points of attentions when the 24 hour lead time situation is operational introduced. Last the limitations of the research will be discussed. The limitations are linked to the further research suggestions.

## *9.1 Conclusions*

### 9.1.1 Current performance

First of all the actual performance, which is measured on site, turned out much lower than the used KPI. In fact the average batch efficiency is 87 layers per hour. The corresponding weighted pick efficiency is 82 layers per hour instead of 110.

Secondly it turned out that the ALP operation is utilised on average 66% of the time during an average busy week. A relatively low utilisation can indicate a good performance when all layers that can be picked by this operation are picked automatically. However it turned out that on average 18% of the layers are picked manually. It was thought that those layers cannot be picked automatically due to the fact that those layers are backorders. However in the research it is shown that, based on the utilisation of the ALP operation during the day, all ALP allowed layers could be picked automatically.

Pallet movements within the automated layer picker mainly determines the efficiency of the batch. To reduce those pallet movements the term synergy is developed. First of all synergy is met by increasing the pick profile. This is the most important factor that influences those pallet movements. The other factor describes smart batching. By smart batching the amount of daughter pallet movements is reduced.

### 9.1.2 Results

First it can be concluded that it is beneficial to pick layers with the ALP instead of manually. The costs are reduced with round the 80 cents per layer within the 24 hour situation.

Secondly, the simulation model is compared with the baseline model within the 48 hour situation. Based on the current layer picking performance the amount of layers picked automatically could theoretically be increased to 73% or 83% depending on the operational situation. With heuristic 1, that does not distinction between order types within the same picking cycle, the costs per layer could be reduced with 10 cents in week 26 and with 29 cents in week 16. Mostly due to increased amount of automatically picked layers.

Thirdly, four different batch heuristics are compared for the 24 hour lead time situation. It can be concluded that the heuristic that is based on the currently used set of batch rules and the heuristic in which a synergy factor in combination with variable batch sizes perform comparable. Heuristics in which the batch size is variable outperform heuristics that compose batches with fixed batch sizes. The difference between the costs is again caused by the amount of automatically picked layers, and thereby the amount of manual case picks.

Compared to heuristic 1 the 24 hour situation is more expensive. Within week 26 the costs per layer are 76 cents. The costs per layer are the same in week 16. In this week the cost to accomplish lead time reduction reduces with 5 cents.

The ALP operation does perform below specified. The company's technical service department implies that the operational issues that causes the low performance could be solved. For that reason the layer pick operation is analysed in which operational improvements are accomplished. It is found that the amount of automatically picked layer could be raised till 95%. The costs are then reduced till 68 and 64 cents for the weeks 26 and 16 respectively. This is accomplished with an weighted pick efficiency of 115 layers per hour and applied on heuristic 3. Naturally extra improvements could result in a higher percentage of automated picked layers and lower costs per layer. The costs when improvements are applied on heuristic 6 are a few cents higher.

### 9.1.3 Research question

It can be concluded that the layer pick operation can handle the future trend of handling only 24 hour lead time orders and same day deliveries. In fact, the amount of layers picked by the ALP can be increased compared to the current situation due to a more accurate transport planning and the reduction of picking cycles. The heuristic that performs best in this new situation is based on the simple batching method in which it is just tried to make the batches as big as possible.

## *9.2 Recommendation*

This paragraph explains points of attention that are caused by the implementation of the 24 hour situation and corresponding preferred batch heuristic. First of all it is concluded that other factors have influence on the performance of the heuristics which are not fully simulated in this research. One of those factors is the distribution of departure times of trips during the day. It is thought that this factor can influence the performance significantly. Therefore a more detailed dynamic simulation needs to be done before implementing the lead time reduction.

Secondly operational changes need to be made. Without improving the operation the implementation of lead time reduction could be disadvantageous:

- The reduction of lead time requires tight scheduling with strict deadlines per process. Exceeding specified event times can have a major impact on the overall pick planning due to the more tight sequencing of pick events. Cooperation between internal departments and external customers is required to improve this process.
- Another important operational issue is the improvement of the automated layer picking process. As described in chapter 6 and shown with the research from the technical service department revealed 12 issues. The simulations showed that those operations improvements could be extremely beneficial in terms of costs reduction.

## *9.3 Limitations and future research*

This paragraph indicates limitations that arise due to assumptions or the lack of information. Also areas for future research will be mentioned. Those areas are partly a continuation of the limitations of the research.

First of all a static simulation is used to compare the heuristics. A dynamic simulation which uses for example stochastic order intake, batch start times, failure times and trip departure could increase the accuracy of the conclusions. Also the effect of the distribution of departure times of trips during the day could be found as seen in the previous chapter.

The costs of THT problems are not taken into account within the comparison of heuristics. It is possible that the amount of batches, or the batch composition, increases the THT problem, and thereby on costs. As told before, this problem is not taken into account due to the increase complexity of the research. Future research, on the effect of batch size and batch composition on the occurrence of THT problems, could give more insight in the effect of batch heuristics on operational costs.

In the research no effect of the use of a synergy factor within the batch composition process on the performance of the automatic layer picking process is found. However, the synergy term is used on trip level, all orders in one trip must be assigned to the same batch. Future research is required to find the effect of the use of synergy on order level. Thus, allocate single customer orders instead of assigning complete trips to batches to increase the synergy level and as a result also increase the pick performance.

Another area for future research is the effect of introducing minimal order quantities based on volume instead of costs on the pick operation. Agreements in which MOQ's are defined in terms of order volume could reduce the amount of manual handling within the operation. A second area of future research, is the possibility to introduce dynamic or customer specific delivery times to obtain peak shaving within the workload of the warehouse.

Finally, future research can be done to find the effect of product characteristic on pick performance. Currently it is already concluded that some products are stacked unstable on the pallets, whereby they fall and create delays. It could be beneficial to expand the existing set of SKU specific batch or pick rules.

## *9.4 Academic relevance*

The literature review showed that the amount of research done to automated layer picking was minimal. This project contributes to the literature because the thesis shows that lead time reduction can be accomplished within partly automated warehouse systems without the introduction of complicated batching decision rules. Furthermore, the research presents points for further research in which the operational performance within the warehouses can be increased even more.

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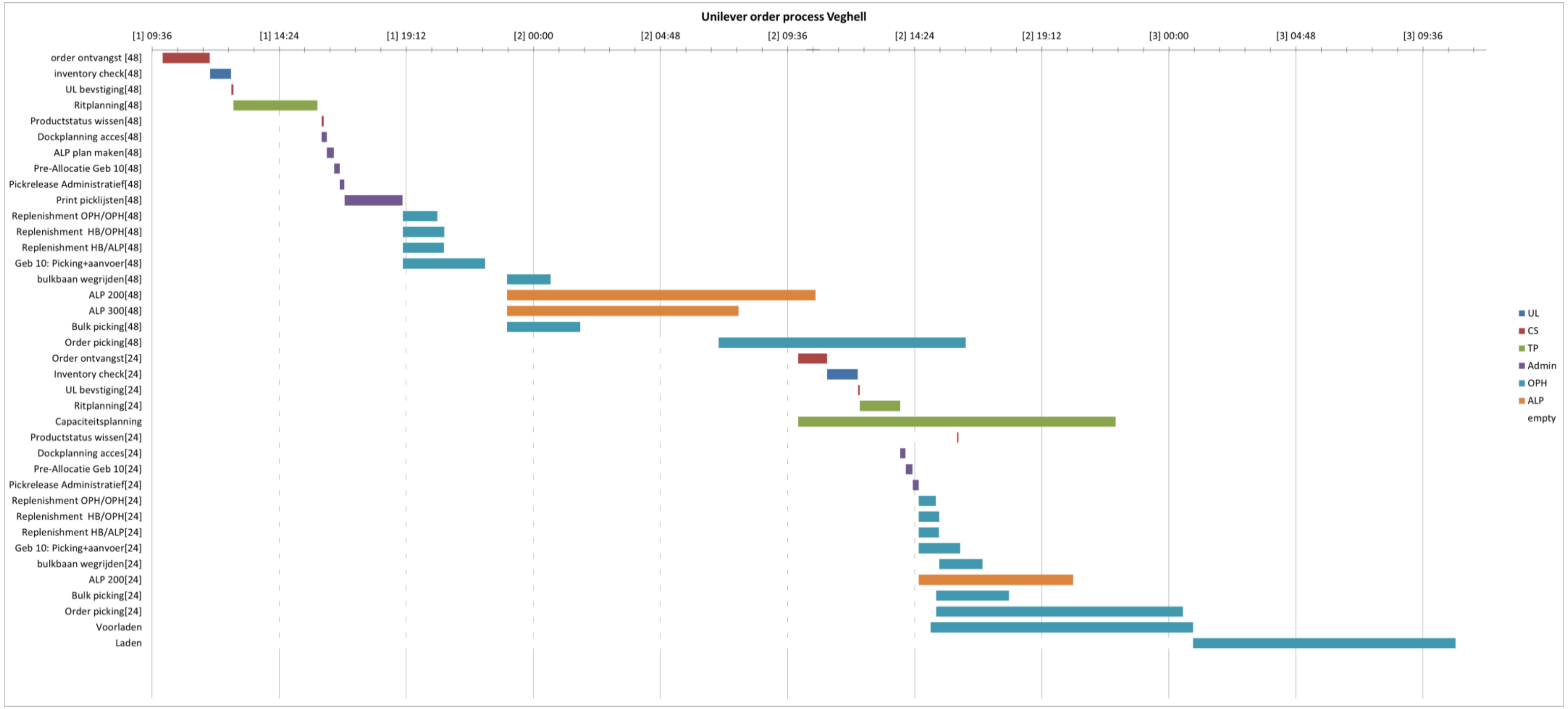
# APPENDIX A: Unilever order process Veghel



# APPENDIX B: Handling time at the ALP's in/outfeed

Table 19 Measurements of pallet handling at the infeed of the ALP

| Measurement | Amount[pallets] | Time [min] | Time per pallet[sec] | Costs per pallet[euro] |
|---|---|---|---|---|
| **1** | 6 | 08:48 | 88,00 | € 0,56 |
| **2** | 2 | 03:52 | 116,00 | € 0,74 |
| **3** | 5 | 07:50 | 94,00 | € 0,60 |
| **4** | 8 | 14:20 | 107,50 | € 0,69 |
| **5** | 1 | 01:00 | 60,00 | € 0,38 |
| **6** | 1 | 02:20 | 140,00 | € 0,89 |
| **7** | 2 | 03:30 | 105,00 | € 0,67 |
| **8** | 3 | 06:00 | 120,00 | € 0,77 |
| **9** | 2 | 03:15 | 97,50 | € 0,62 |
| **10** | 6 | 06:00 | 60,00 | € 0,38 |
| **11** | 3 | 05:10 | 103,33 | € 0,66 |
| **12** | 2 | 03:25 | 102,50 | € 0,65 |
| **13** | 4 | 05:05 | 76,25 | € 0,49 |
| **14** | 3 | 04:45 | 95,00 | € 0,61 |
| **15** | 2 | 03:45 | 112,50 | € 0,72 |
| **16** | 2 | 03:14 | 97,00 | € 0,62 |
| **Average:** | 6 | 0:05:09 | 98,41 | € 0,63 |

Table 20 Measurements of pallet handling at the outfeed of the ALP

| Measurement | Single pallet handling [sec] | Dropping pallets[sec] | Amount [pallets] | Time per pallet[sec] |
|---|---|---|---|---|
| **1** | 27 | 130 | 3 | 70,33 |
| **2** | 19 | 237 | 4 | 78,25 |
| **3** | 27 | 122 | 2 | 88 |
| **4** | 18 | 60 | 1 | 78 |
| **5** | 18 | 103 | 2 | 69,5 |
| **6** | 29 | 135 | 2 | 96,5 |
| **7** | 23 | 105 | 2 | 75,5 |
| **8** | 26 | 135 | 2 | 93,5 |
| **9** | 22 | 72 | 1 | 94 |
| **10** | 19 | 80 | 1 | 99 |
| **Average:** | 22,8 | 117,9 | 2 | 84,25 |

Table 21 Percentage HB flow at the infeed of the ALP

| Day: | 1 | 2 | 3 | 4 | 5 | Total: |
|---|---|---|---|---|---|---|
| **OPH** | 588 | 611 | 534 | 476 | 530 | 2739 |
| **HB** | 174 | 275 | 159 | 161 | 149 | 918 |
| **%OPH** | 77% | 69% | 77% | 75% | 78% | 75% |

# APPENDIX C: Event times

Table 22 Defined event times in seconds

| | Source | DPU | | | | | Delay | | |
|---|---|---|---|---|---|---|---|---|---|
| **No** | **New** | **Sandwich** | **Out** | **Empty** | **Filled** | **Sub-total** | **Recycle** | **Task** | **Total** |
| **1** | - | 10 | - | - | - | 10 | - | - | 10 |
| **2** | - | 10 | 7 | 9 | - | 26 | - | - | 26 |
| **3** | - | 10 | 7 | - | 9 | 26 | - | - | 26 |
| **4** | - | 10 | 7 | - | - | 17 | - | - | 17 |
| **5** | - | - | 7 | 9 | - | 16 | - | - | 16 |
| **6** | - | - | 7 | - | 9 | 16 | - | - | 16 |
| **7** | - | - | 7 | - | - | 7 | - | - | 7 |
| **8** | 8 | 10 | - | - | - | 10 | - | - | 10 |
| **9** | 8 | 10 | 7 | 9 | - | 26 | - | - | 26 |
| **10** | 8 | 10 | 7 | - | 9 | 26 | - | - | 26 |
| **11** | 8 | 10 | 7 | - | - | 17 | - | - | 17 |
| **12** | 8 | - | 7 | 9 | - | 16 | 9 | 4 | 29 |
| **13** | 8 | - | 7 | - | 9 | 16 | 9 | 4 | 29 |
| **14** | 8 | - | 7 | - | - | 7 | 9 | 4 | 20 |
| **15** | 8 | - | 7 | - | - | 7 | - | 4 | 11 |
| **16** | 8 | - | 7 | 9 | - | 16 | - | 4 | 20 |
| **17** | 8 | - | 7 | - | 9 | 16 | - | 4 | 20 |
| **18** | 8 | - | - | - | - | 0 | - | - | 8 |
| **19** | 8 | - | - | - | - | 0 | 9 | - | 17 |

# APPENDIX D: Efficiency figures

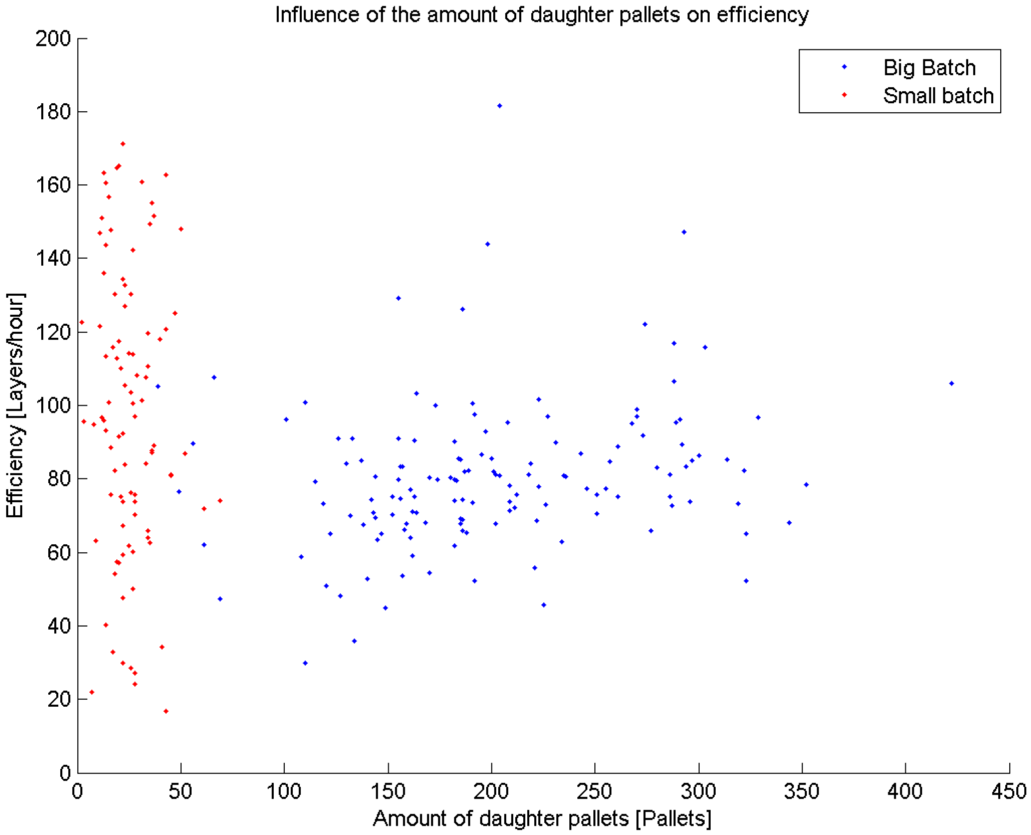



Figure 24 Influence of the amount of daughter pallets on efficiency

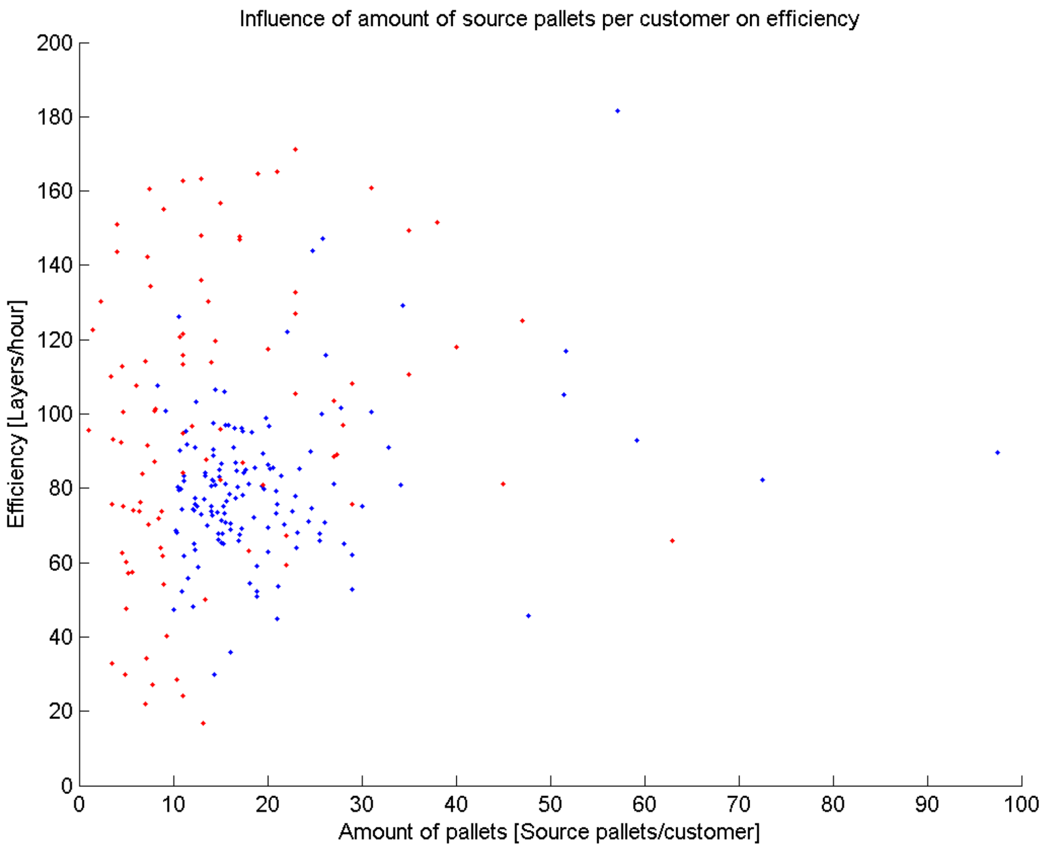



Figure 25 Influence of the amount of source pallets per customer on efficiency

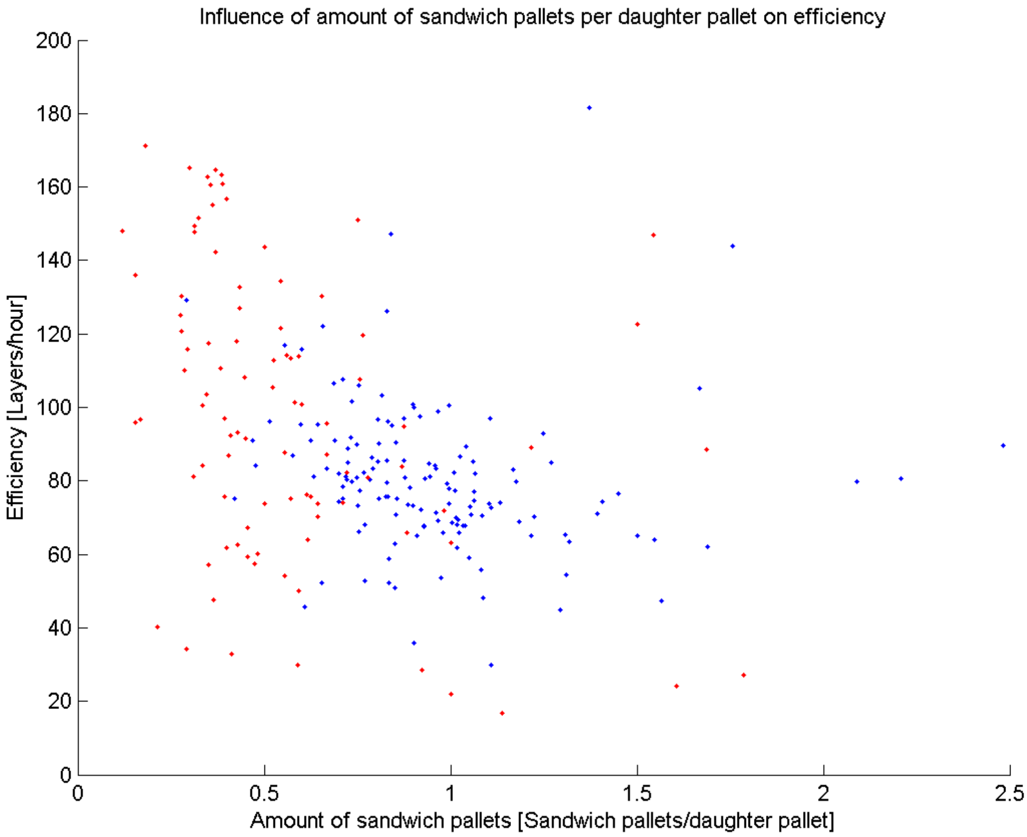



Figure 26 Influence of the amount of sandwich pallets per daughter pellet on efficiency

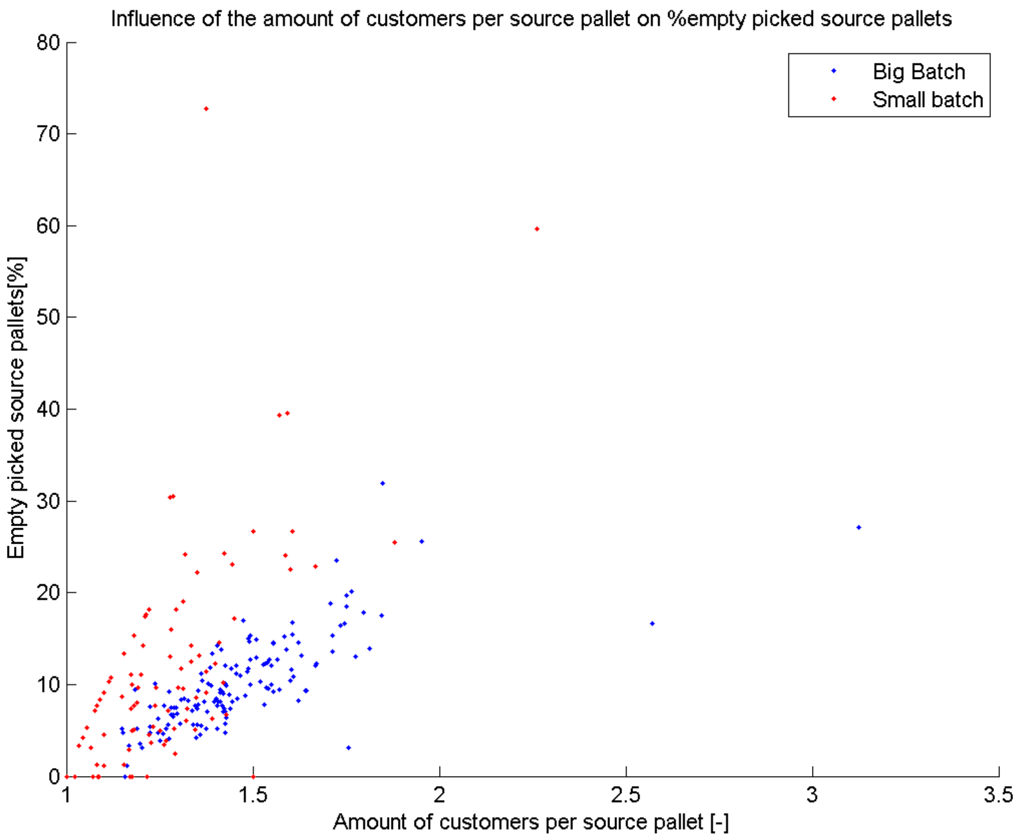



Figure 27 Influence of the amount of customers/ source pallet on % empty picked source pallets

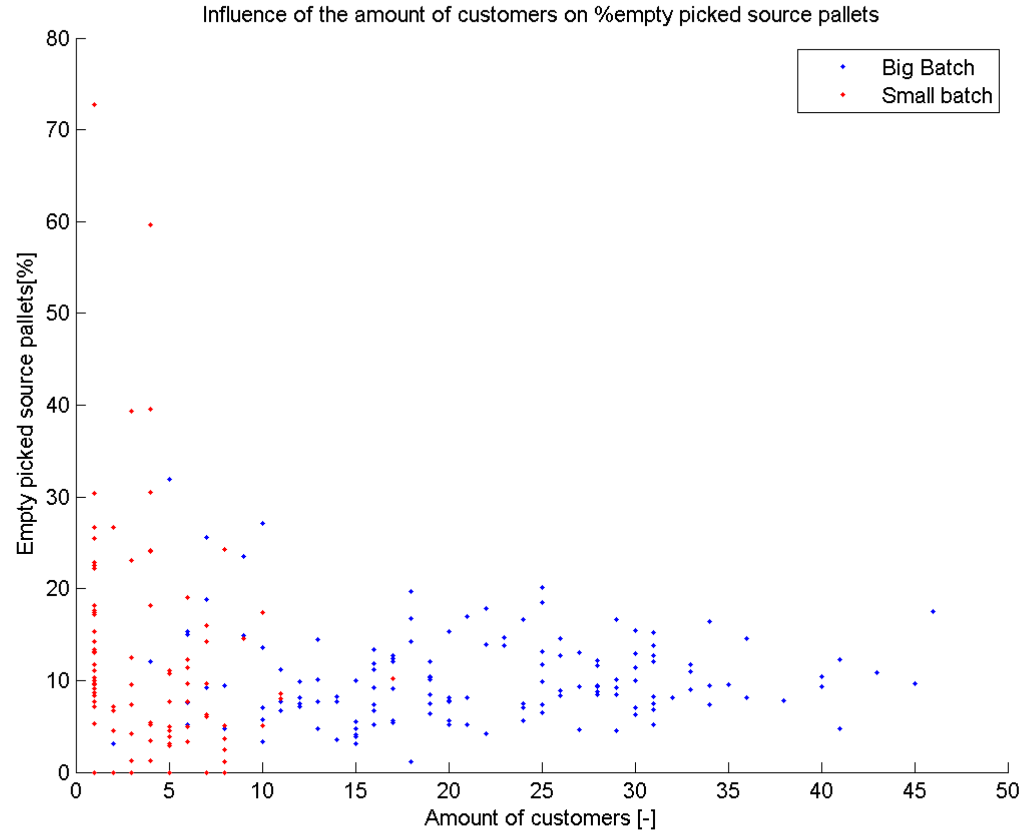



Figure 28 Influence of the amount of customers on % empty picked source pallets

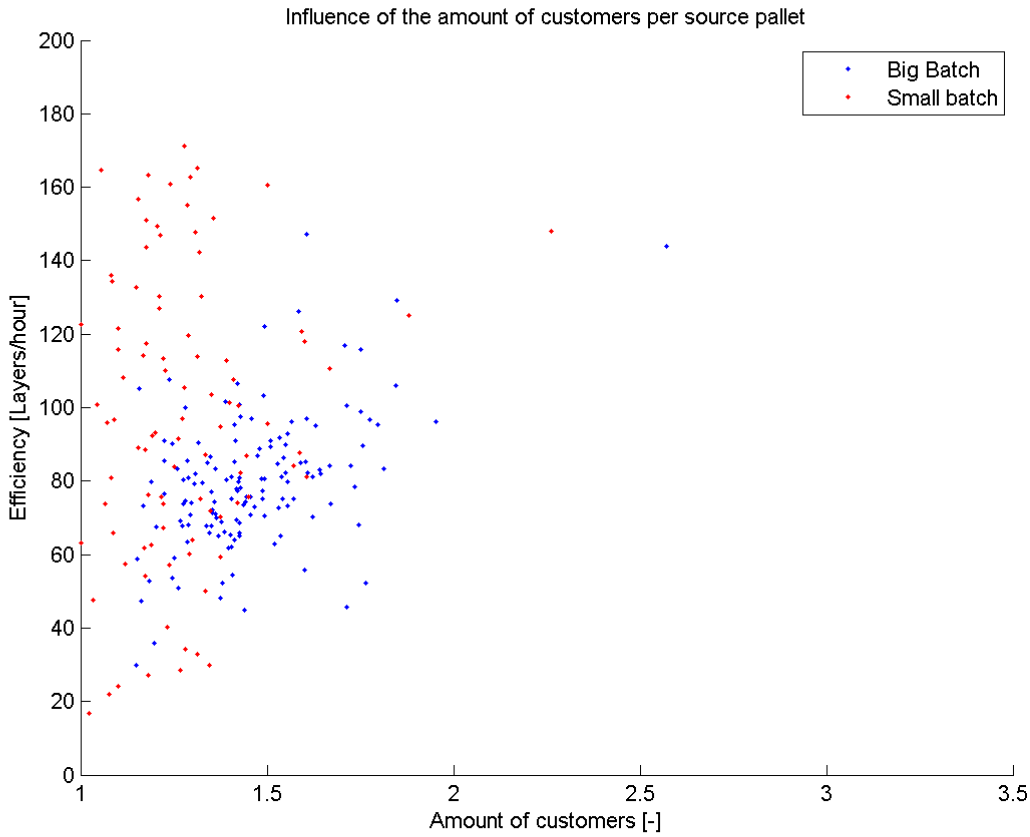



Figure 29 Influence of the amount of customers per source pallet

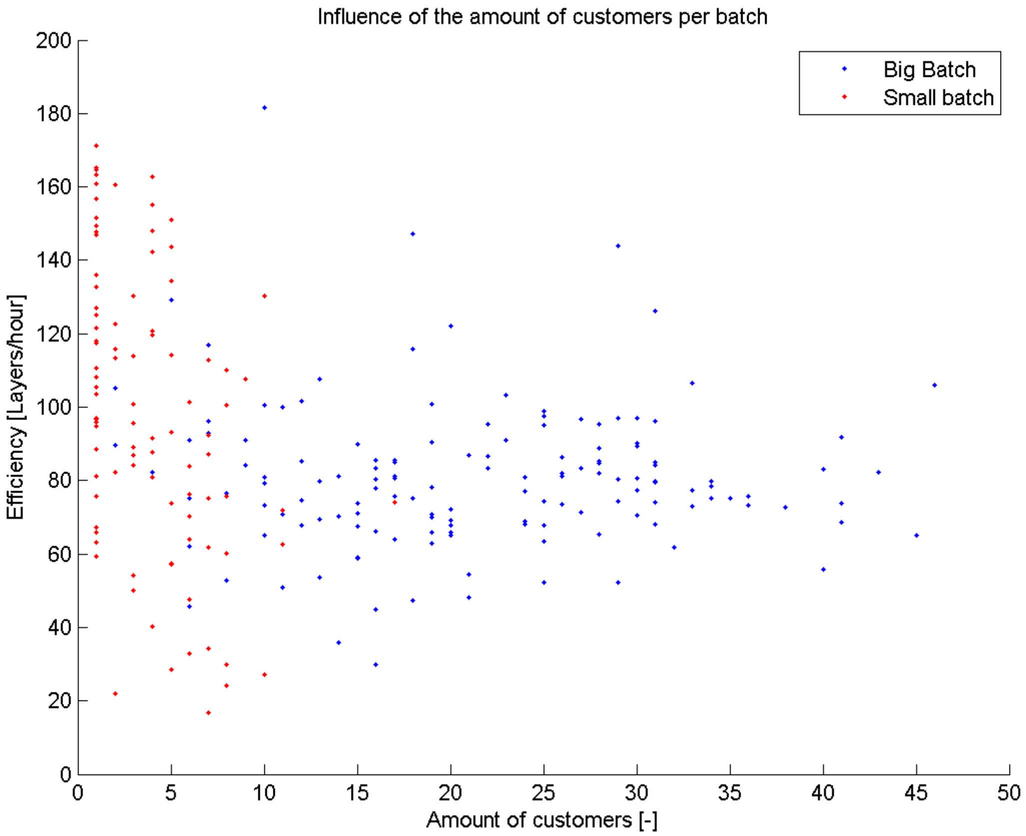



Figure 30 Influence of the amount of customers per batch on efficiency

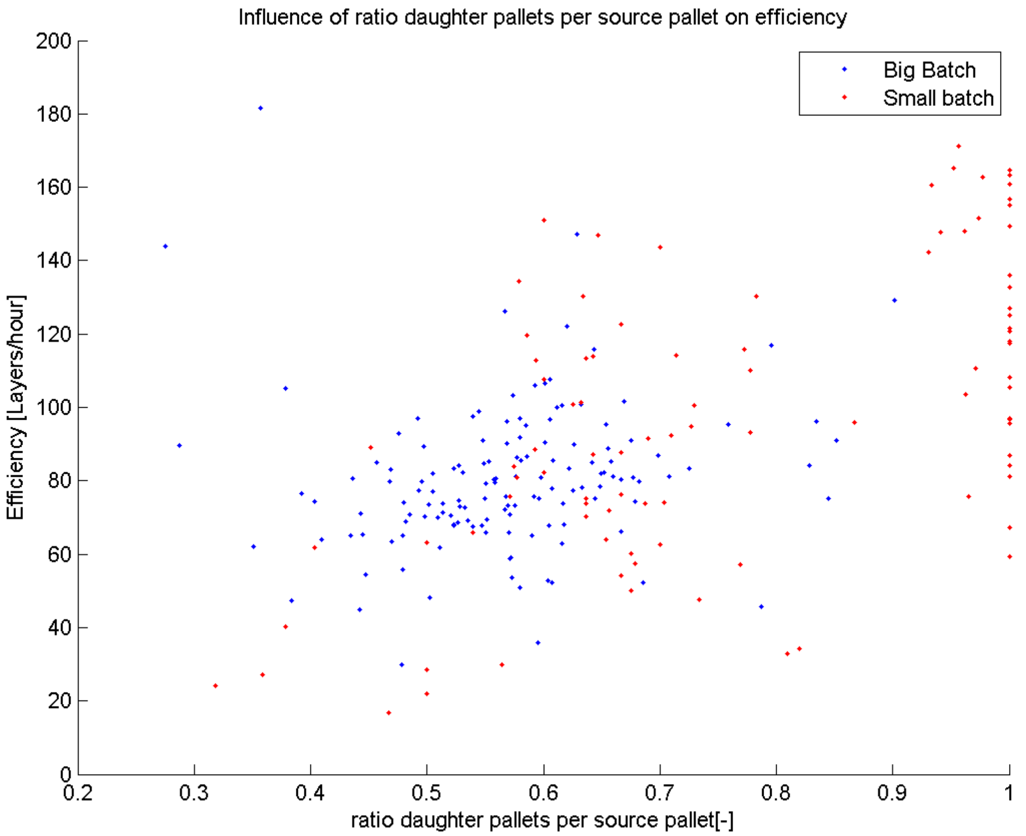



Figure 31 Influence of ratio daughter pallets per source pallet on efficiency

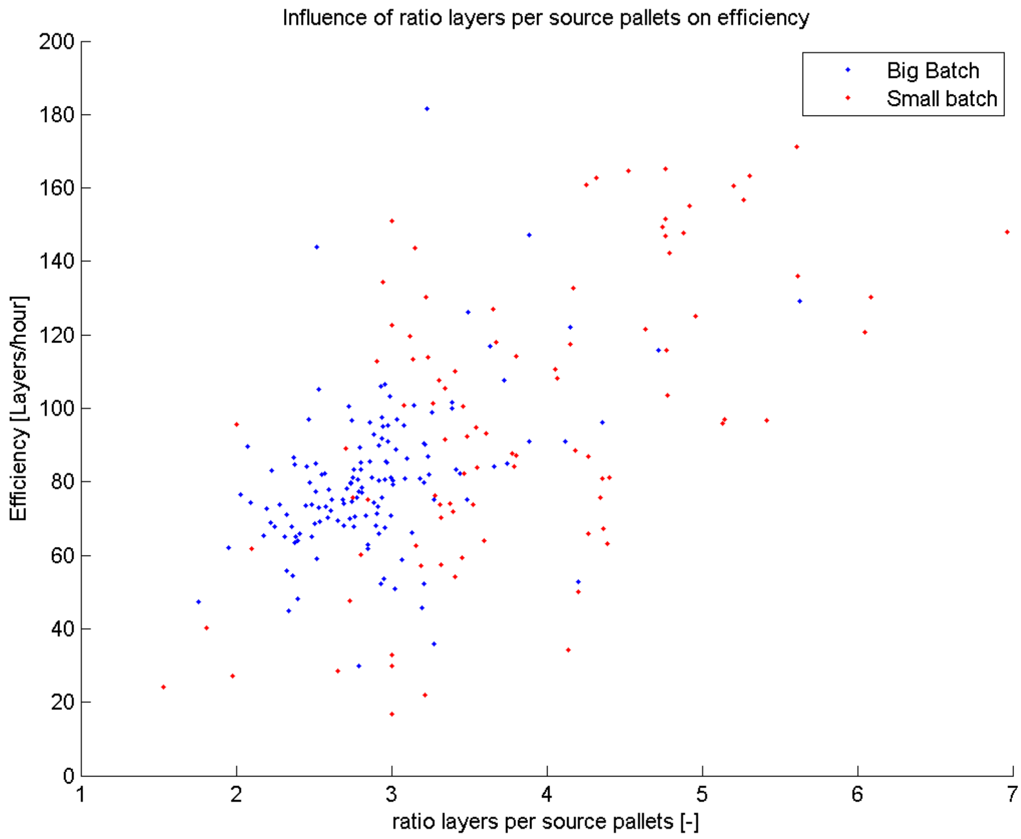



**Figure 32 Influence of the ratio layer per source pallet on efficiency**

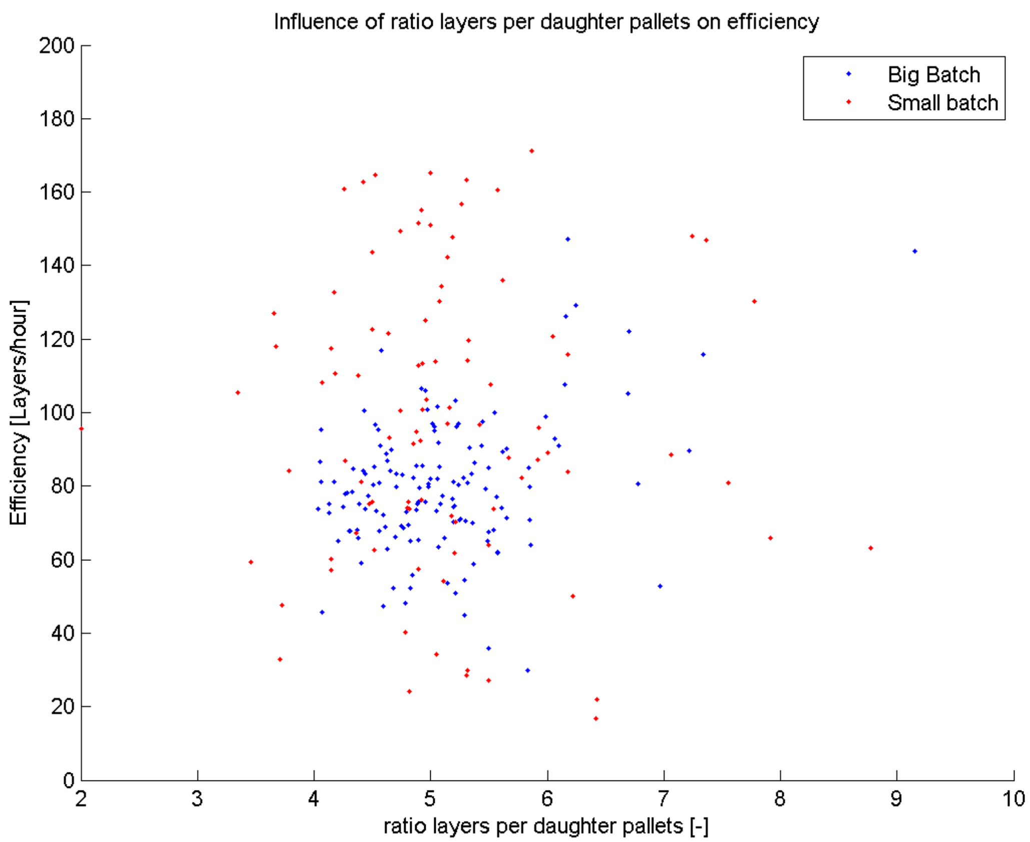



**Figure 33 Influence of the ratio layers per daughter pallet on efficiency**

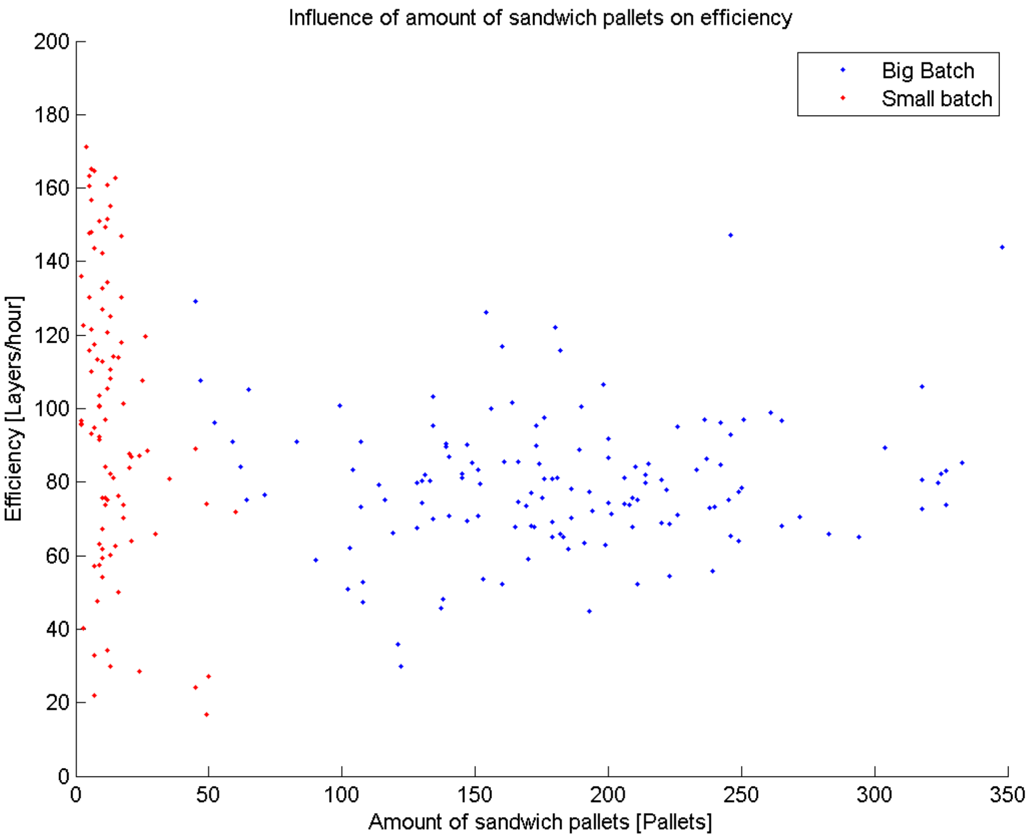



Figure 34 Influence of the amount of sandwich pallets per batch on efficiency

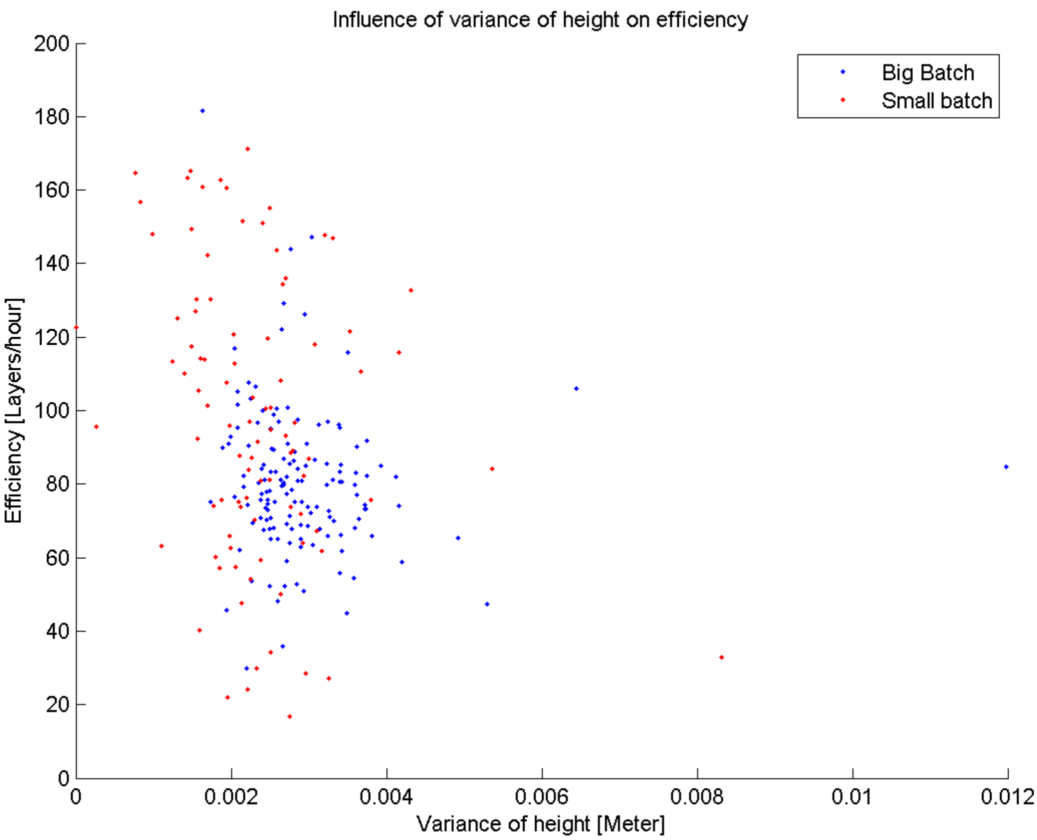



Figure 35 Influence of variance of product height on efficiency

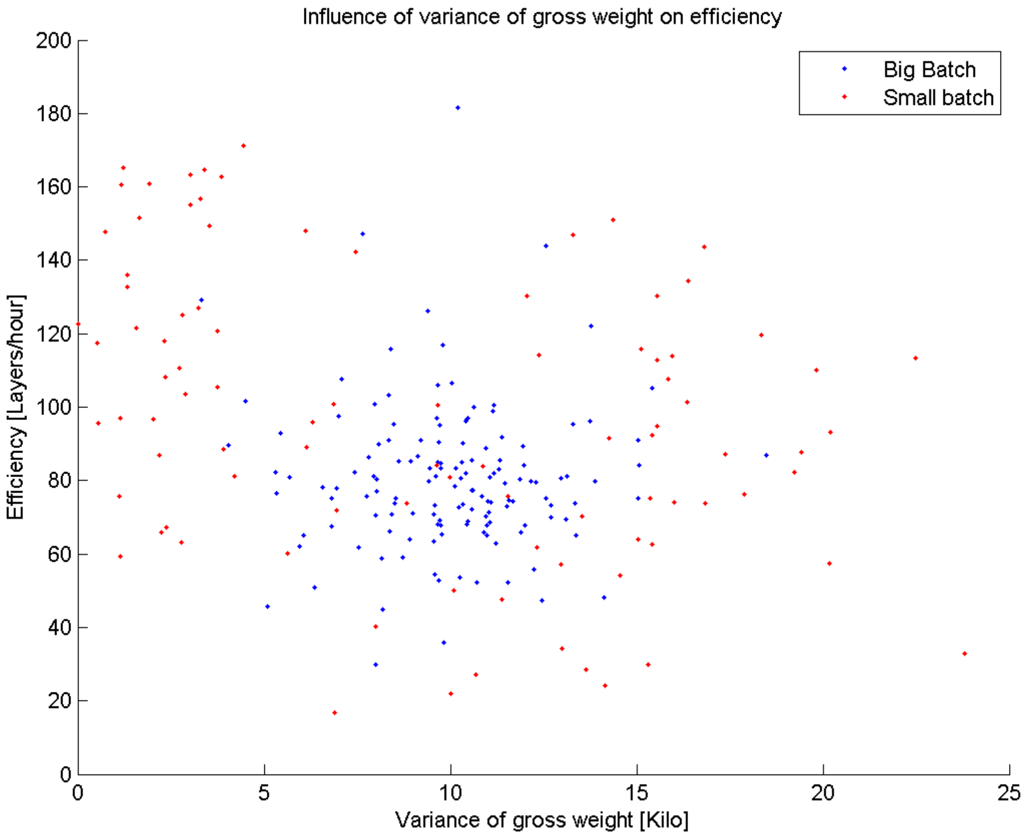



Figure 36 Influence of the variance of mean gross weight per batch on efficiency

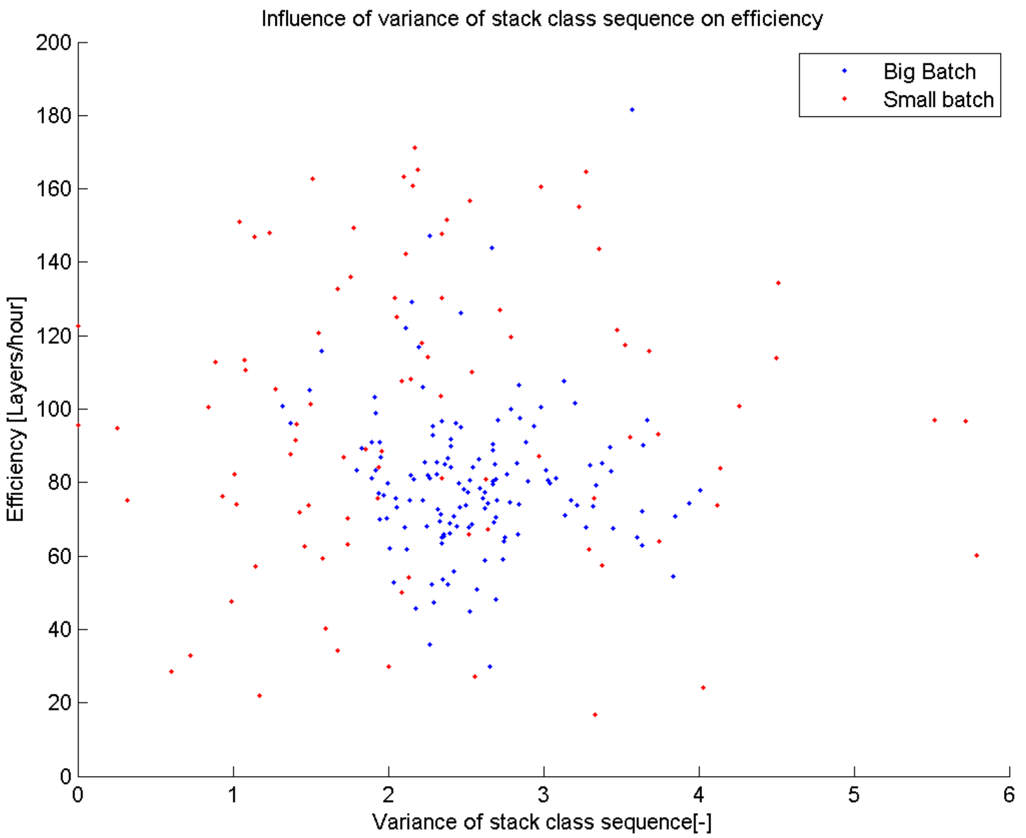



Figure 37 Influence of the variance of the stack class sequence on efficiency

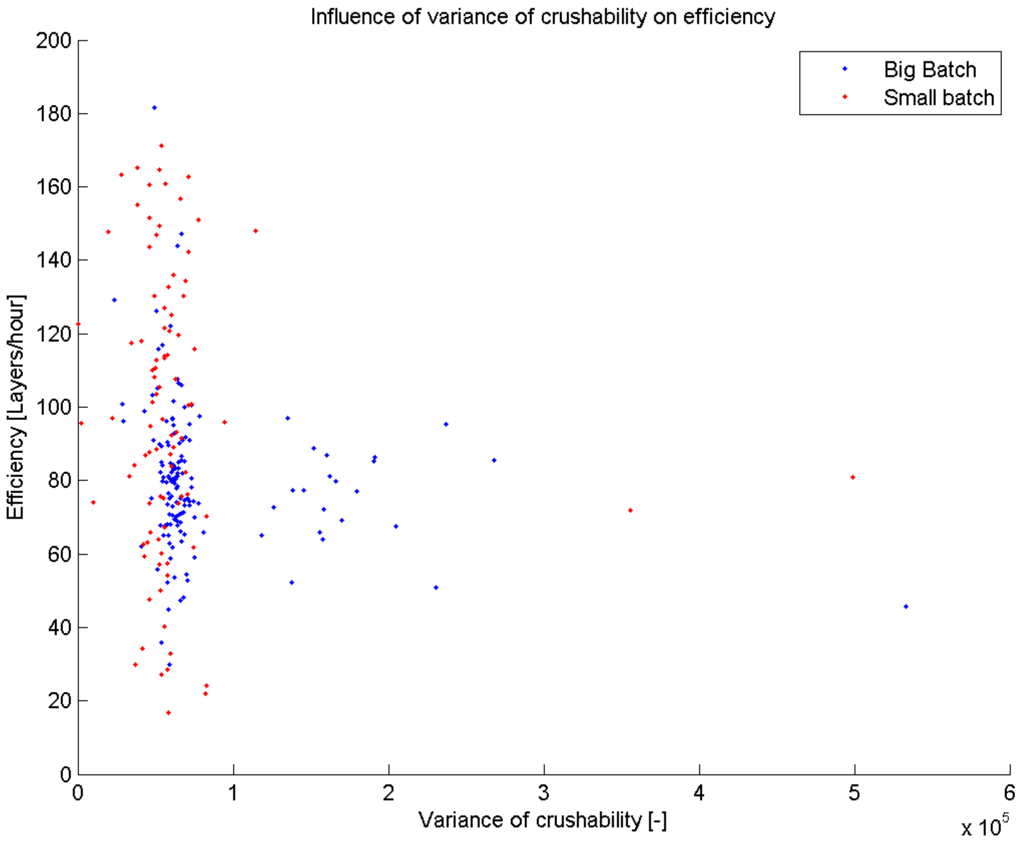



Figure 38 Influence of the variance of crushability on efficiency

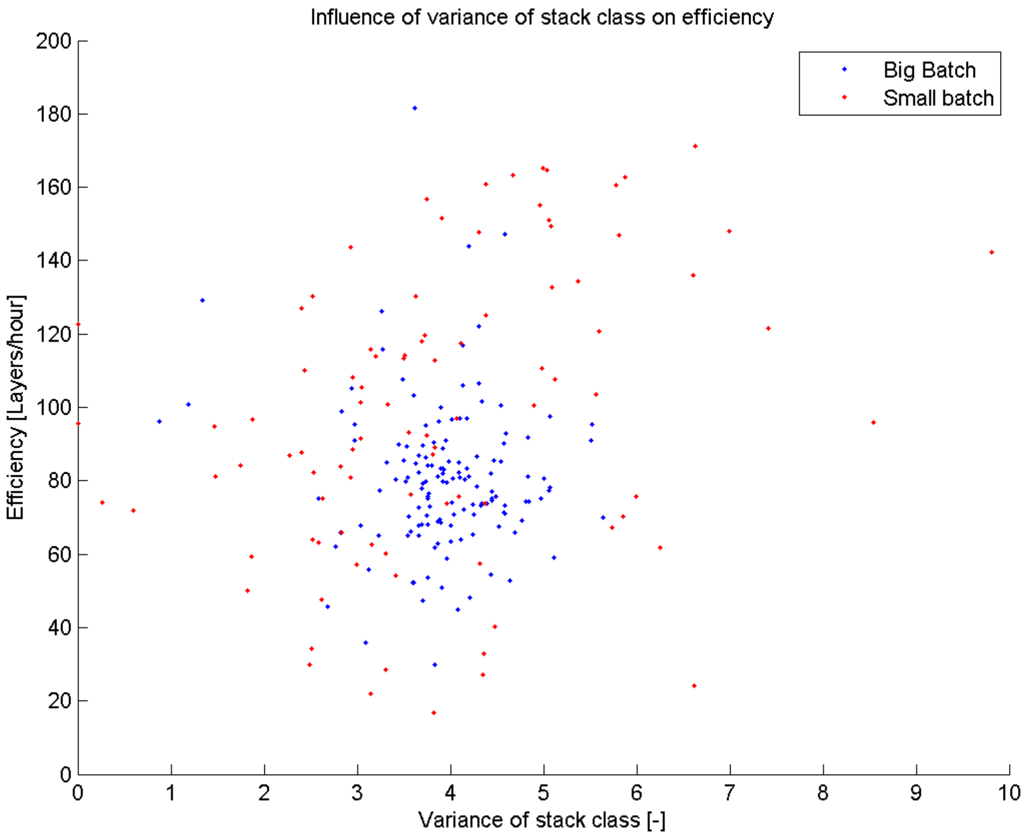



Figure 39 Influence of variance of stack class on efficiency

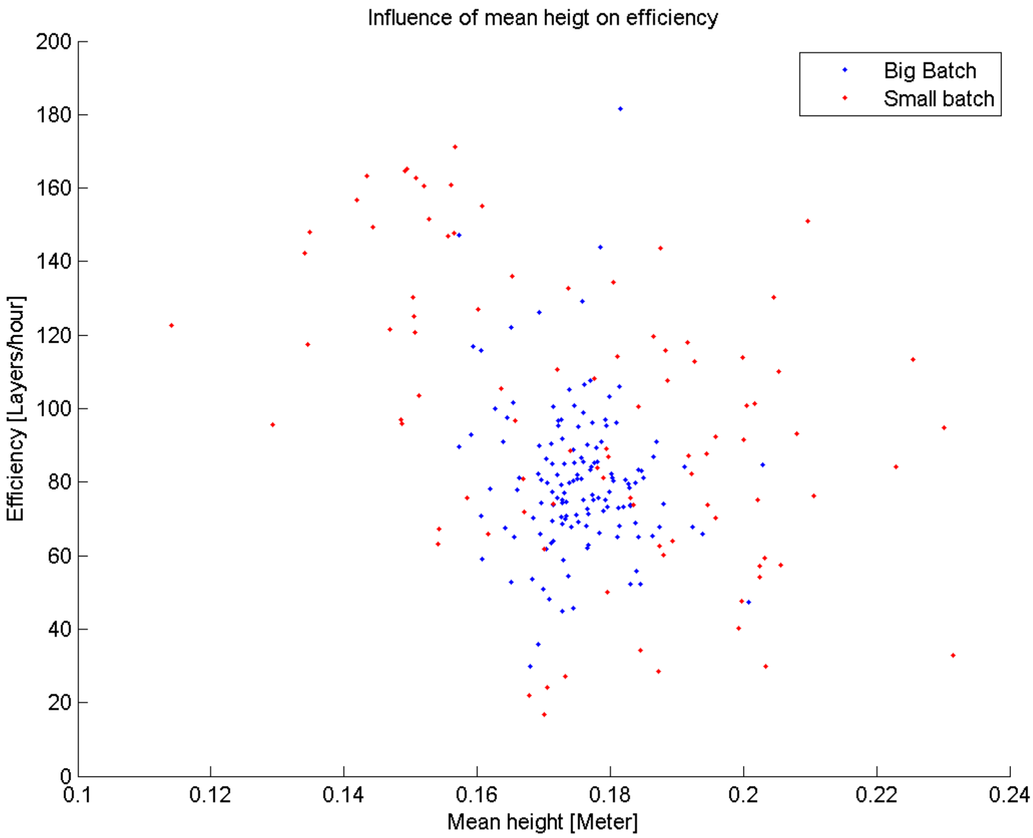



**Figure 40 Influence of mean product height on efficiency**

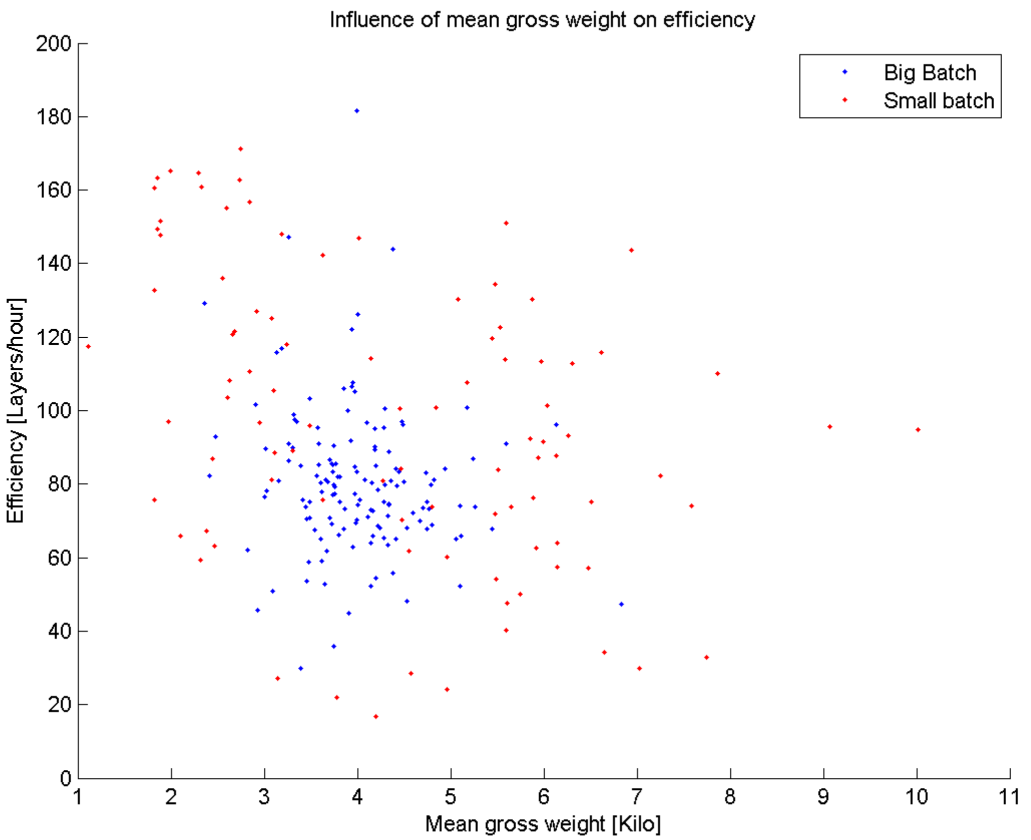



**Figure 41 Influence of the mean gross weight on efficiency**

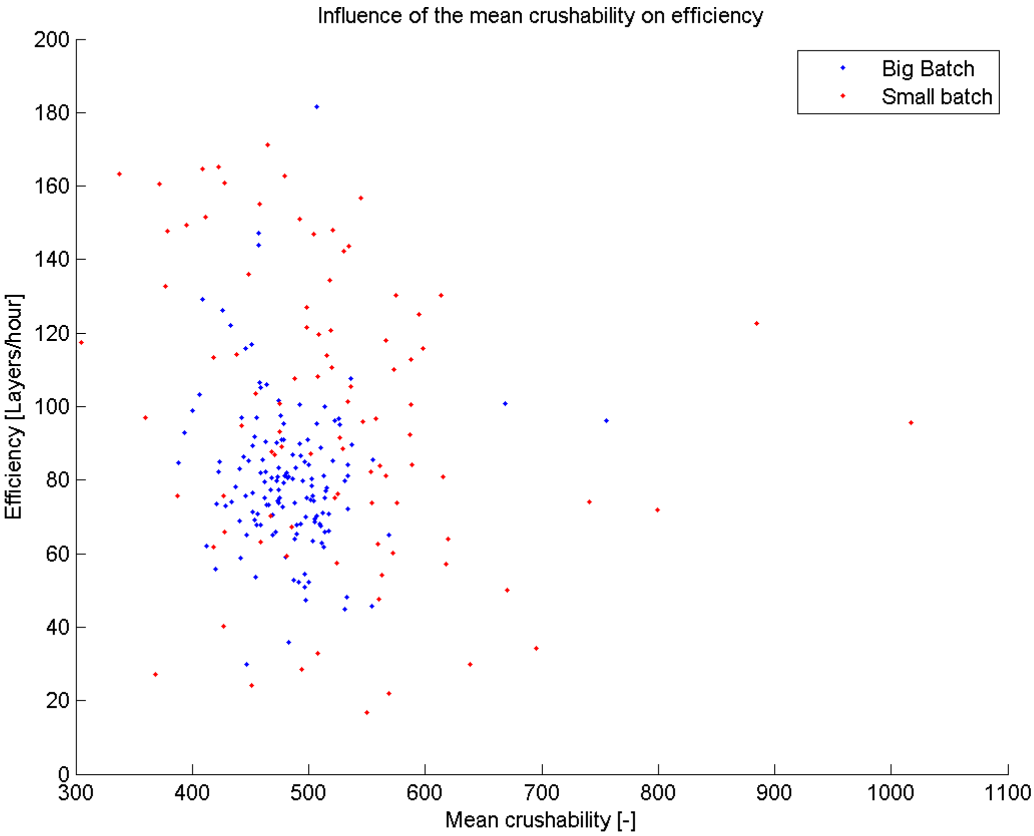



Figure 42 Influence of the mean crushability per batch on efficiency

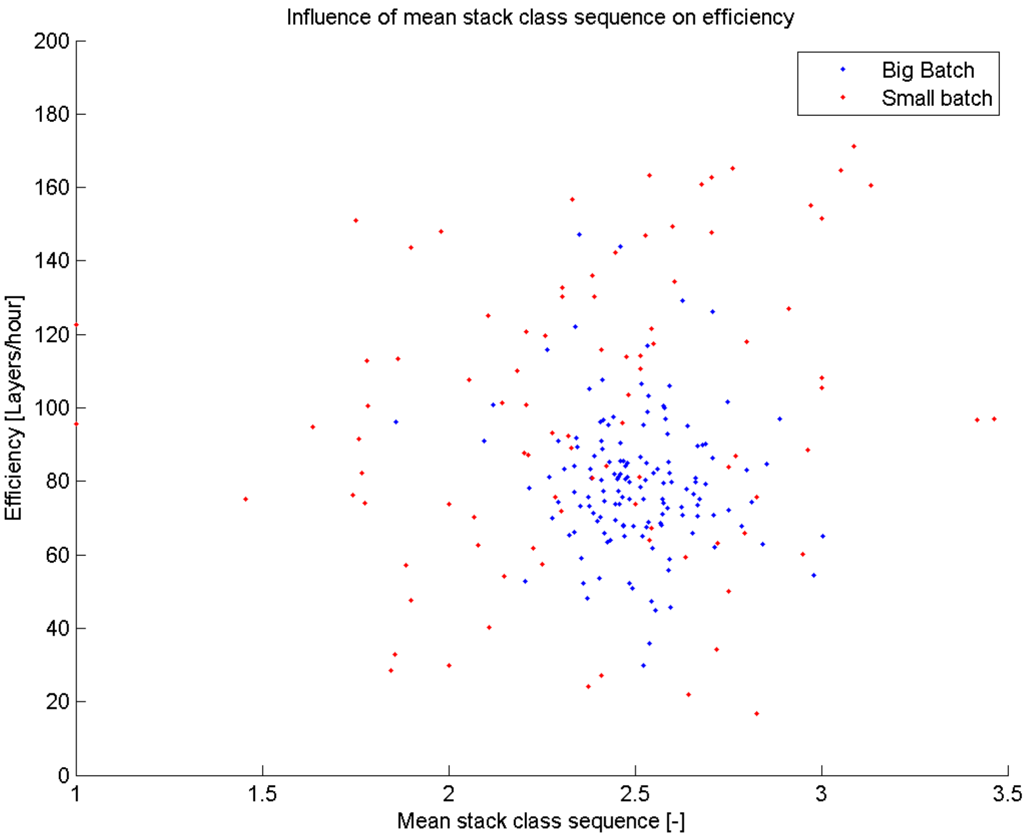



Figure 43 Influence of the mean stack class sequence per batch on efficiency

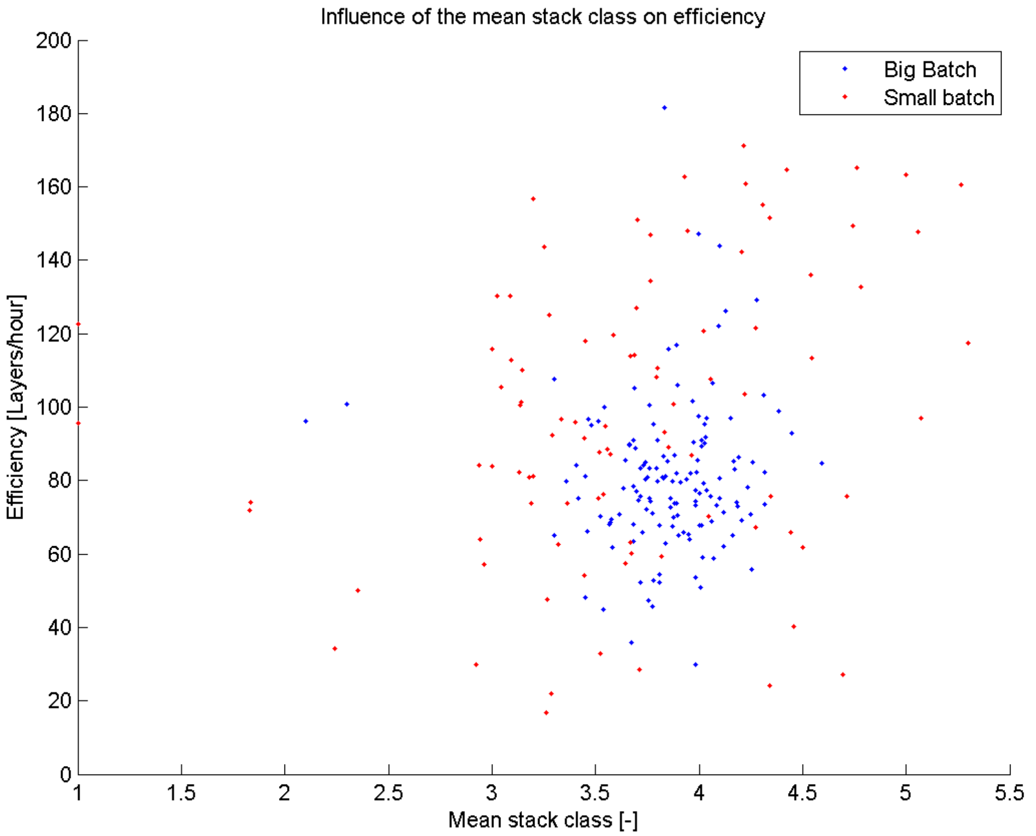



Figure 44 Influence of the mean stack class per batch on efficiency

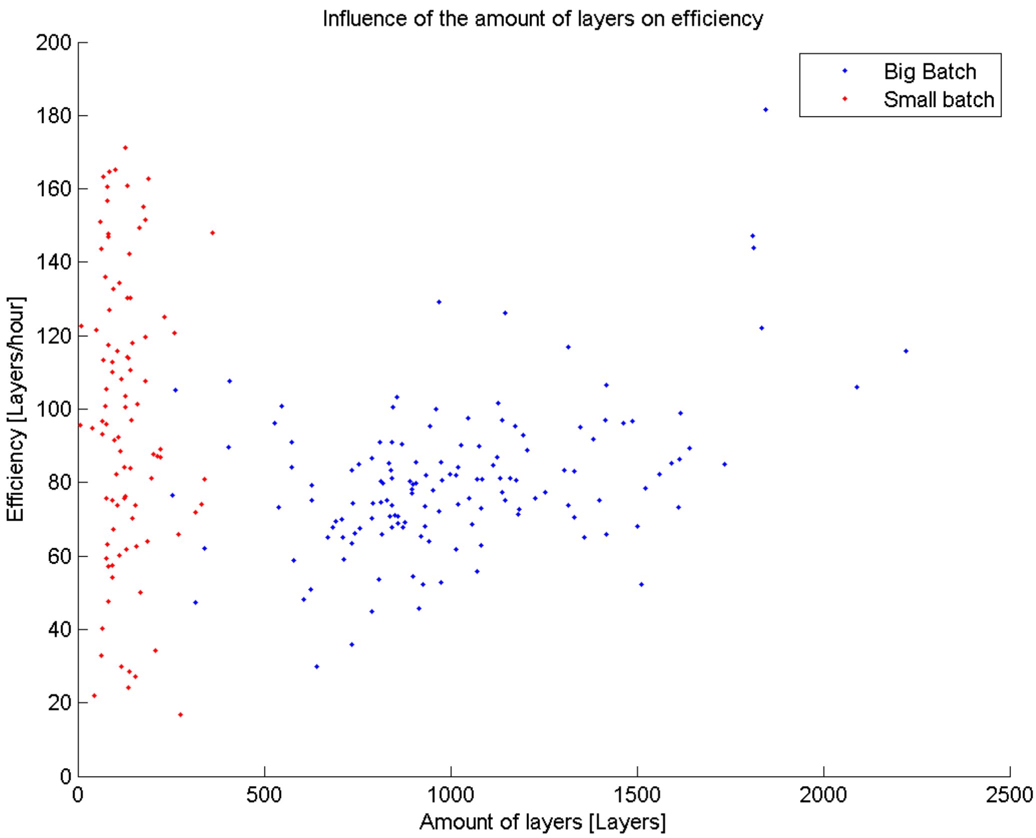



Figure 45 Influence of the amount of layers per batch on efficiency

# APPENDIX E: Example of delays within the ALP operation

Table 23 Example of delays within physical picking of the ALP

| Cause description | Number of occurred times | Total time | Mean time per occurrence |
|---|---|---|---|
| **Pressure build-up within the vacuum** | 8 | 0:01:45 | 0:00:13 |
| **ALP head stops without a reason** | 2 | 0:00:56 | 0:00:28 |
| **Slip-sheet not removed** | 1 | 0:00:30 | 0:00:30 |
| **No source pallet available** | 8 | 0:04:42 | 0:00:35 |
| **No daughter pallet available situation 1** | 4 | 0:01:30 | 0:00:22 |
| **No daughter pallet available situation 2** | 1 | 0:00:40 | 0:00:40 |
| **Daughter pallet is send out and retrieved again** | 4 | 0:07:25 | 0:01:51 |
| **Damaged pallet** | 1 | 0:07:18 | 0:07:18 |
| **Source pallet send to the outfeed without a pick** | 1 | 0:00:26 | 0:00:00 |
| **Footprint change** | 1 | 0:01:44 | 0:01:44 |
| **Congestion at the outfeed** | 3 | 0:04:02 | 0:01:21 |
| **Unknown delay** | 4 | 0:12:43 | 0:03:11 |
| | 40 | 0:45:58 | 0:01:09 |
| The events described within this table occurred within a time window of 1:29 hour. Within this time window 77 layers are picked which resulted in a pick performance of 52 layers per hour. | | | |

# APPENDIX F: Example of a pick sequencing file

Table 24 Example of a simplified pick sequencing file

| Article number | Amount of Layers | Source pallet number* | Daughter pallet number | Sandwich pallets | Pick Type | Footprint type | Relation code | Stack class | Stack class seq. | Departure date | Trip Number | Batch number |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 871410025608400 | 7 | 34 | 17030547 | 0 | 1 | 1 | 10101932 | 2 | 2 | 14-4-2015 | 2901 | 4 |
| 871811495192801 | 6 | 35 | 17029449 | 1 | 1 | 1 | 683567 | 2 | 2 | 14-4-2015 | 2023 | 4 |
| 871256657486504 | 4 | 36 | 17022663 | 0 | 2 | 1 | 10398431 | 3 | 2 | 14-4-2015 | 2028 | 4 |
| 871084720762400 | 1 | 37 | 17022682 | 0 | 2 | 1 | 762 | 5 | 1 | 14-4-2015 | 2028 | 4 |
| 871210016254101 | 10 | 38 | 17028038 | 1 | 2 | 1 | 816 | 5 | 1 | 13-4-2015 | 1215 | 5 |
| 871210016337101 | 6 | 39 | 17028039 | 0 | 2 | 1 | 683567 | 5 | 2 | 13-4-2015 | 1215 | 5 |
| 871210016337101 | 3 | 39 | 17028040 | 0 | 2 | 1 | 10000455 | 5 | 2 | 13-4-2015 | 1215 | 5 |

*Source pallet number = Stock-ID

# APPENDIX G: Performance measured in relative values

Table 25 Performance measures of the average week in absolute values

| Situation: | 48 Lead time | | No ALP | 24 hour lead time | | | |
|---|---|---|---|---|---|---|---|
| Heuristic: | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| $\tau$ | 49,30 | 48,75 | [-] | 25,50 | 25,50 | 25,50 | 25,50 |
| $A_t$ | 98 | 87 | [-] | 57 | 45 | 82 | 50 |
| $A_i$ | 2420 | 2865 | | 3303 | 3142 | 3220 | 3283 |
| $A_b$ | 2113 | 2394 | [-] | 2933 | 2794 | 2864 | 2911 |
| $t_p$ | 71 | 87 | [-] | 94 | 89 | 92 | 93 |
| $A_{alp}$ | 8682 | 11034 | [-] | 11302 | 10397 | 10813 | 11202 |
| $\eta$ | 120 | 115 | [-] | 120 | 117 | 120 | 120 |
| $n$ | 9 | 28 | [-] | 49 | 60 | 58 | 54 |
| $A_m$ | 65848 | 35918 | 278806 | 29233 | 50738 | 41276 | 32348 |

Table 26 Performance measures of the busy week in absolute values

| Situation: | 48 Lead time | | No ALP | 24 hour lead time | | | |
|---|---|---|---|---|---|---|---|
| Heuristic: | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| $\tau$ | 49,8 | 48,5 | [-] | 25,33 | 25,33 | 25,33 | 25,33 |
| $A_t$ | 70 | 100 | [-] | 49 | 40 | 48 | 50 |
| $A_i$ | 2430 | 3330 | | 3459 | 3256 | 3293 | 3484 |
| $A_b$ | 2065 | 2725 | [-] | 2981 | 2818 | 2831 | 3016 |
| $t_p$ | 68 | 100 | [-] | 105 | 102 | 101 | 105 |
| $A_{alp}$ | 8598 | 13198 | 0 | 12819 | 11751 | 12218 | 12819 |
| $\eta$ | 123 | 125 | [-] | 116 | 108 | 118 | 116 |
| $n$ | 15 | 29 | [-] | 68 | 106 | 74 | 74 |
| $A_m$ | 131825 | 31774 | 330685 | 44493 | 73586 | 56230 | 44493 |

Table 27 Performance measures of the average week in relative values

| Situation: | 48 Lead time | | No ALP | 24 hour lead time | | | |
|---|---|---|---|---|---|---|---|
| Heuristic: | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| $\tau$ | 103% | 102% | | 53% | 53% | 53% | 53% |
| $A_t$ | 121% | 107% | | 70% | 56% | 101% | 62% |
| $A_i$ | 100% | 118% | | 136% | 130% | 133% | 136% |
| $A_b$ | 87% | 84% | | 89% | 89% | 89% | 89% |
| $t_p$ | 59% | 73% | | 78% | 74% | 77% | 78% |
| $A_{alp}$ | 69% | 88% | | 90% | 83% | 86% | 89% |
| $\eta$ | 109% | 105% | | 109% | 106% | 109% | 109% |
| $n$ | 100% | 311% | | 544% | 667% | 644% | 600% |

Table 28 Performance measures of the busy week in relative values

| Situation: | 48 Lead time | | No ALP | 24 hour lead time | | | |
|---|---|---|---|---|---|---|---|
| Heuristic: | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| $\tau$ | 104% | 208% | | 53% | 53% | 53% | 53% |
| $A_t$ | 86% | 123% | | 60% | 49% | 59% | 62% |
| $A_i$ | 100% | 137% | | 142% | 134% | 136% | 143% |
| $A_b$ | 85% | 4% | | 86% | 87% | 86% | 87% |
| $t_p$ | 57% | 83% | | 88% | 85% | 84% | 88% |
| $A_{alp}$ | 59% | 90% | | 87% | 80% | 83% | 87% |
| $\eta$ | 112% | 114% | | 105% | 98% | 107% | 105% |
| $n$ | 100% | 193% | | 453% | 707% | 493% | 493% |

# APPENDIX I: Rack occupancy during the week

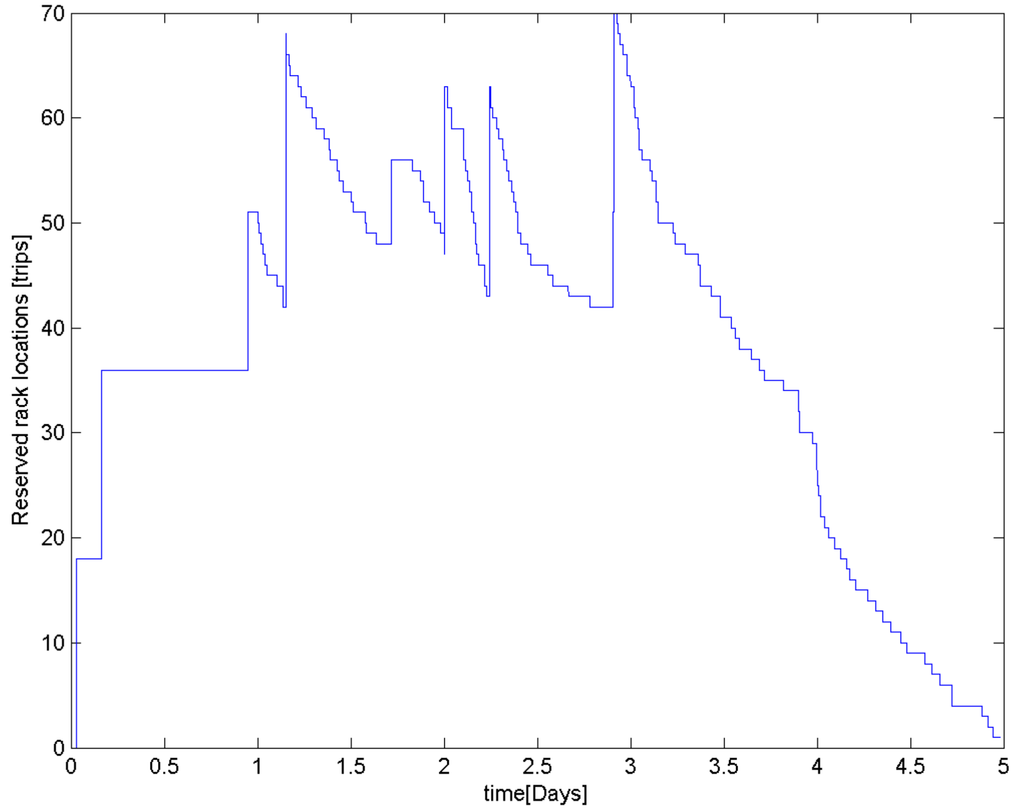



Figure 46 Reserved rack locations baseline model week 16

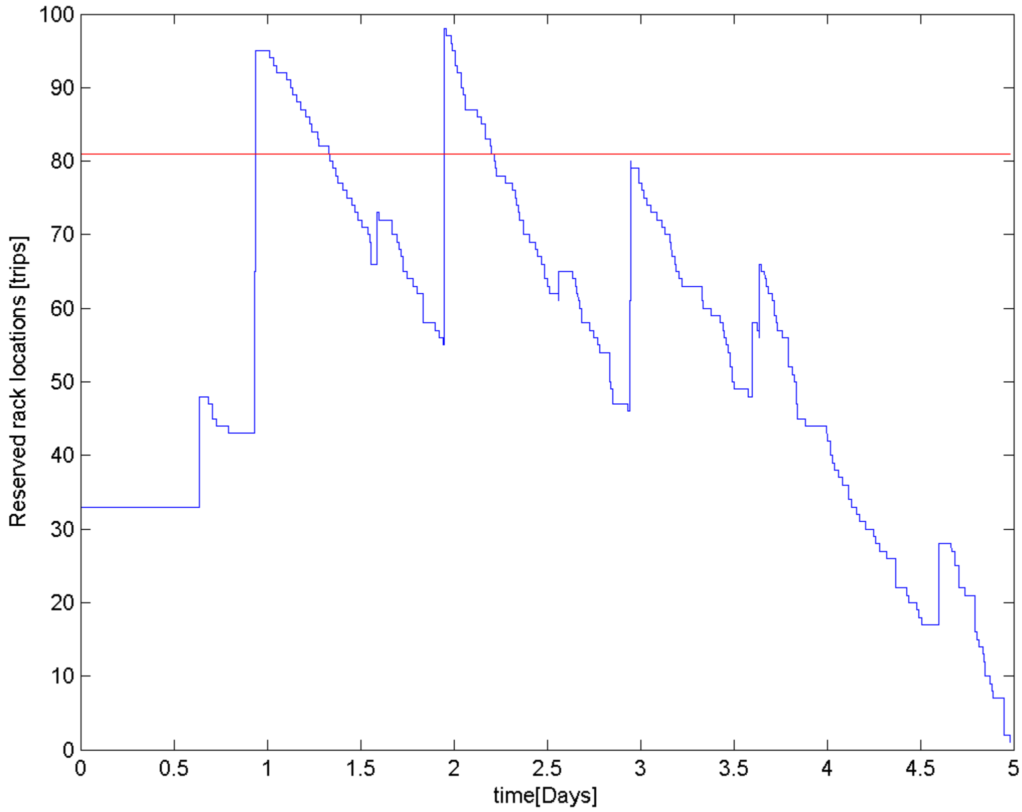



Figure 47 Reserved rack locations baseline model week 26

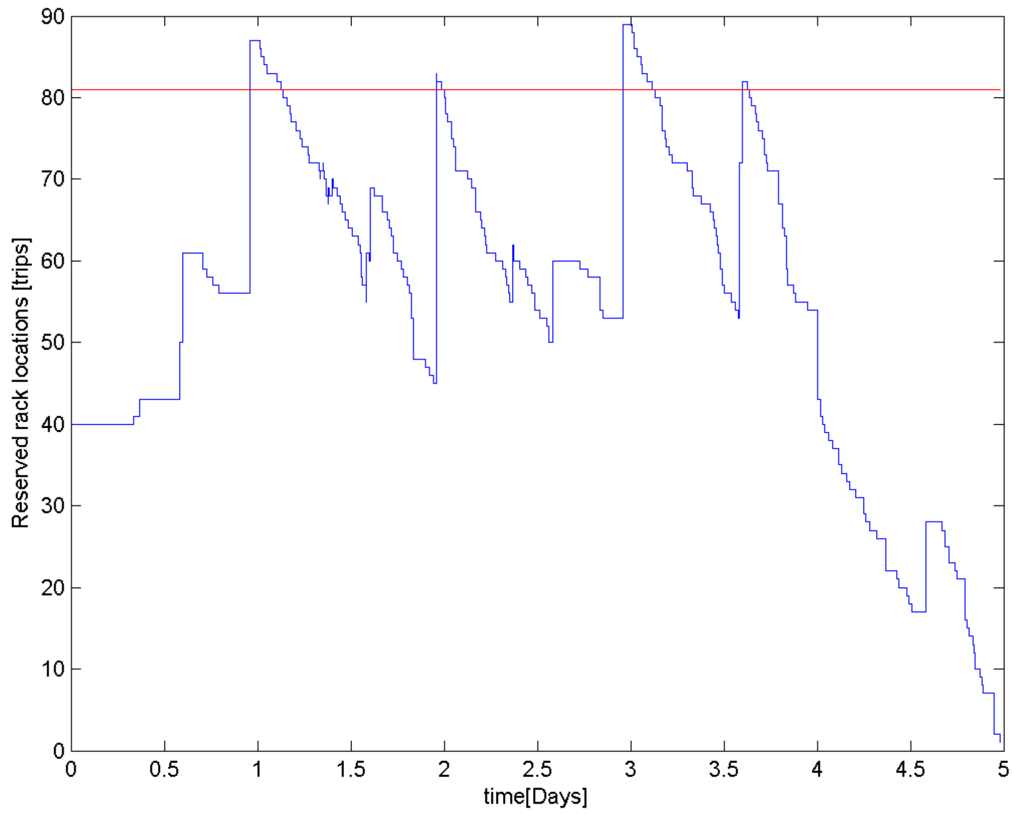



**Figure 48 Reserved rack locations heuristic 1 week 26**

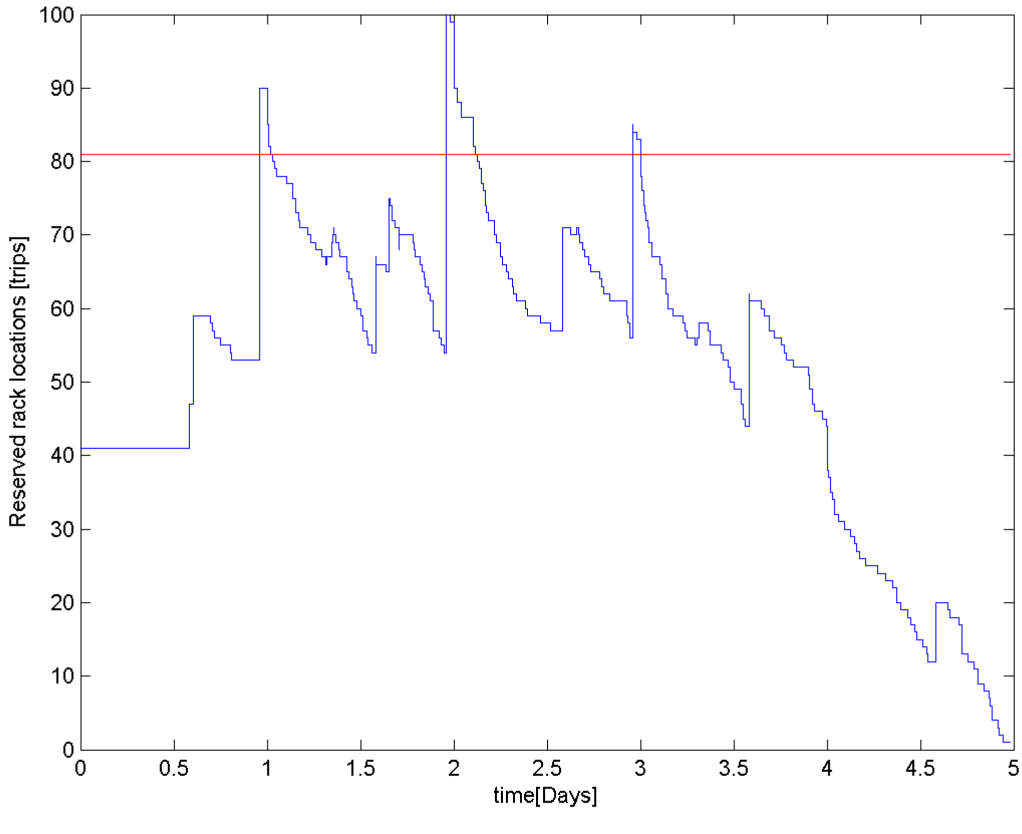



**Figure 49 Reserved rack locations heuristic 1 week 16**

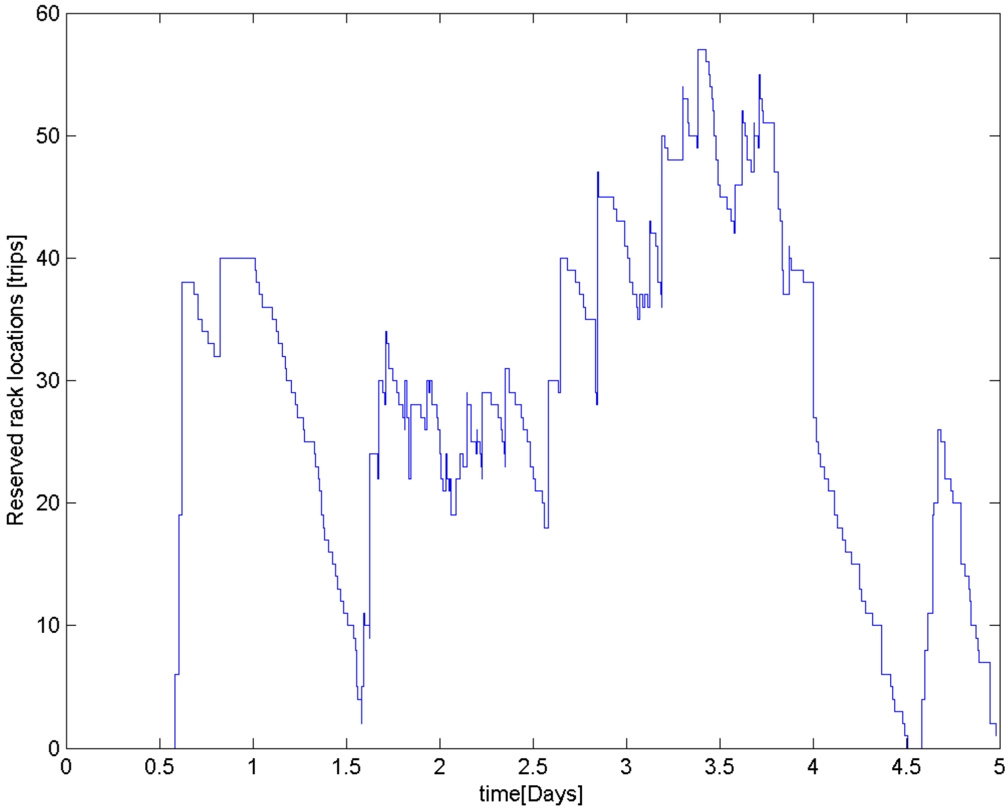



Figure 50 Reserved rack locations heuristic 3 week 26

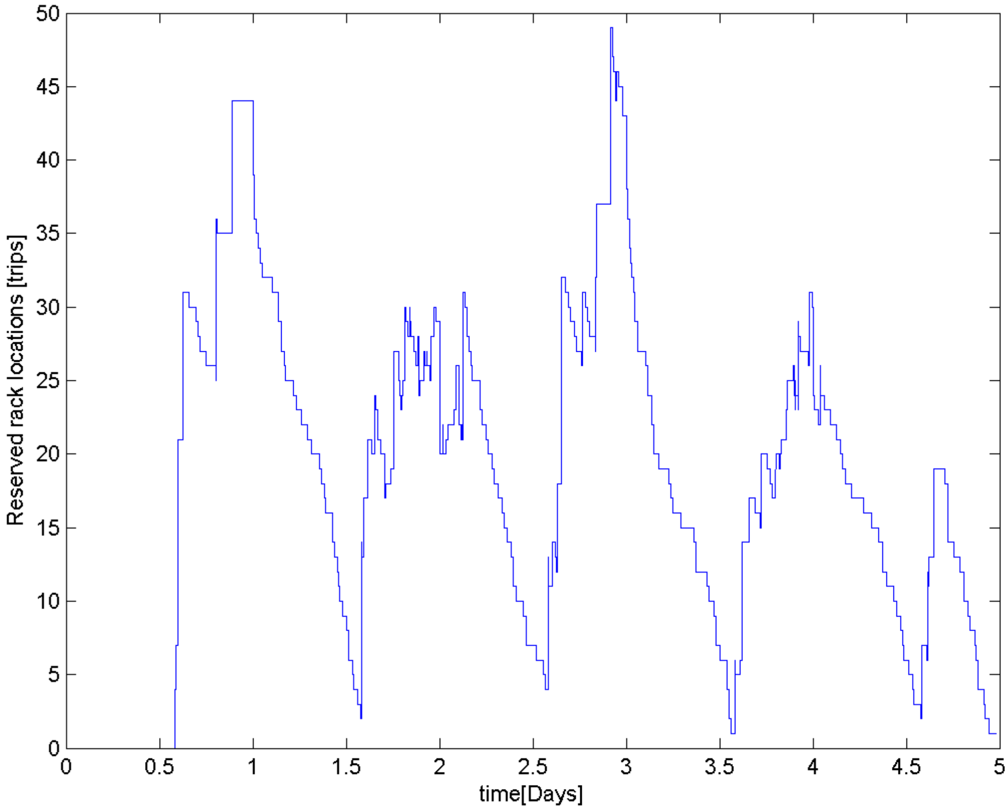



Figure 51 Reserved rack locations heuristic 3 week 16

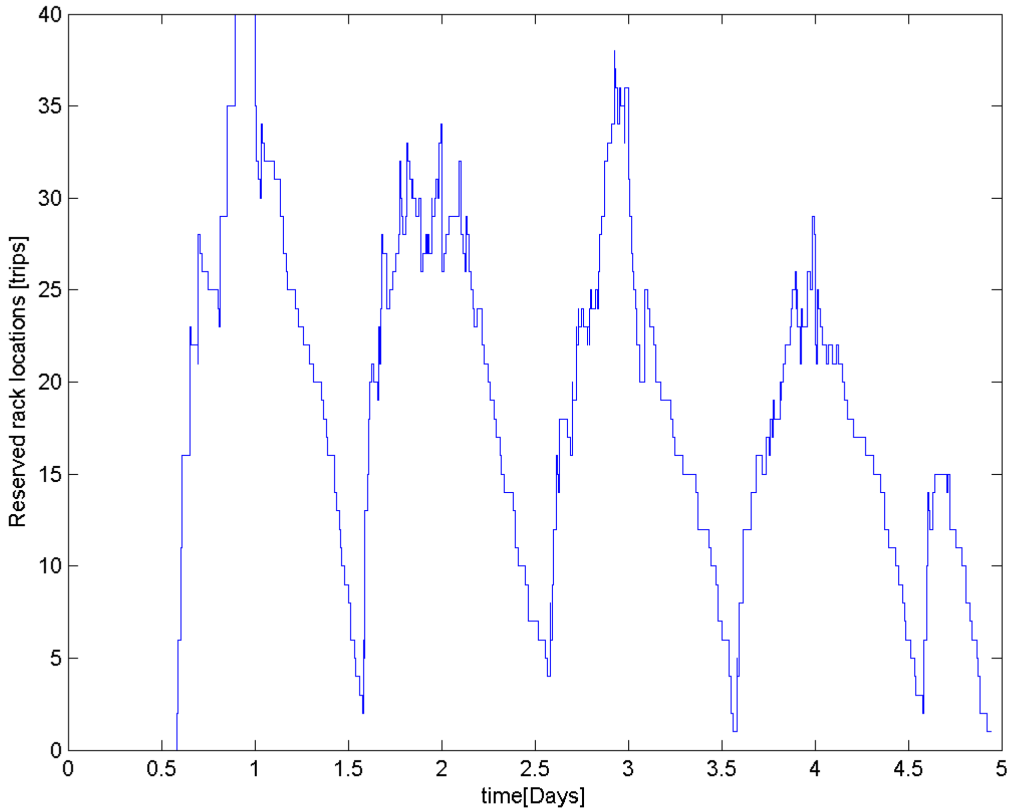



Figure 52 Reserved rack locations heuristic 4 week 16

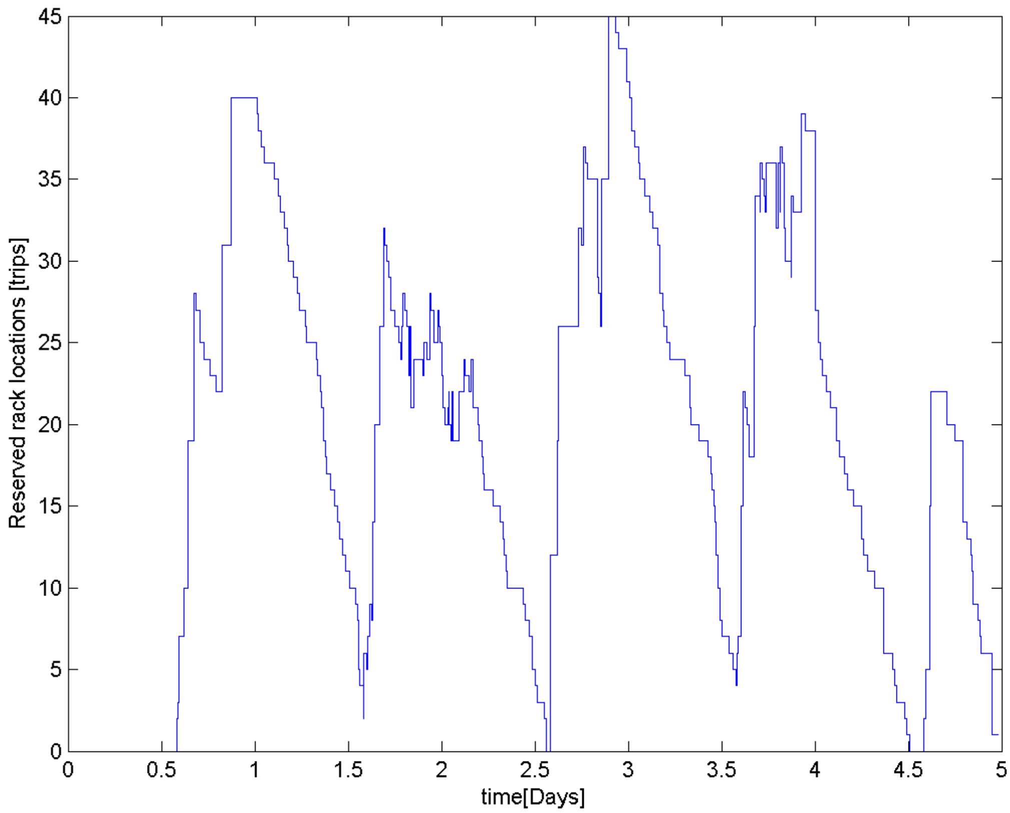



Figure 53 Reserved rack locations heuristic 4 week 26

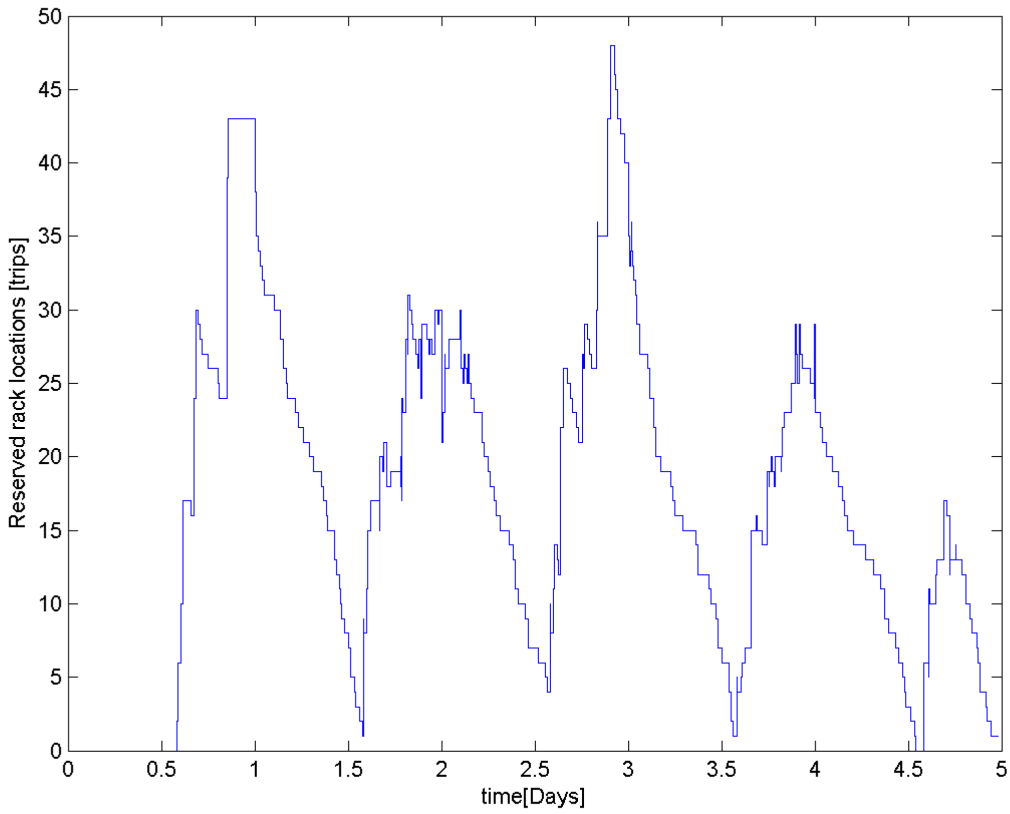



Figure 54 Reserved rack locations heuristic 5 week 16

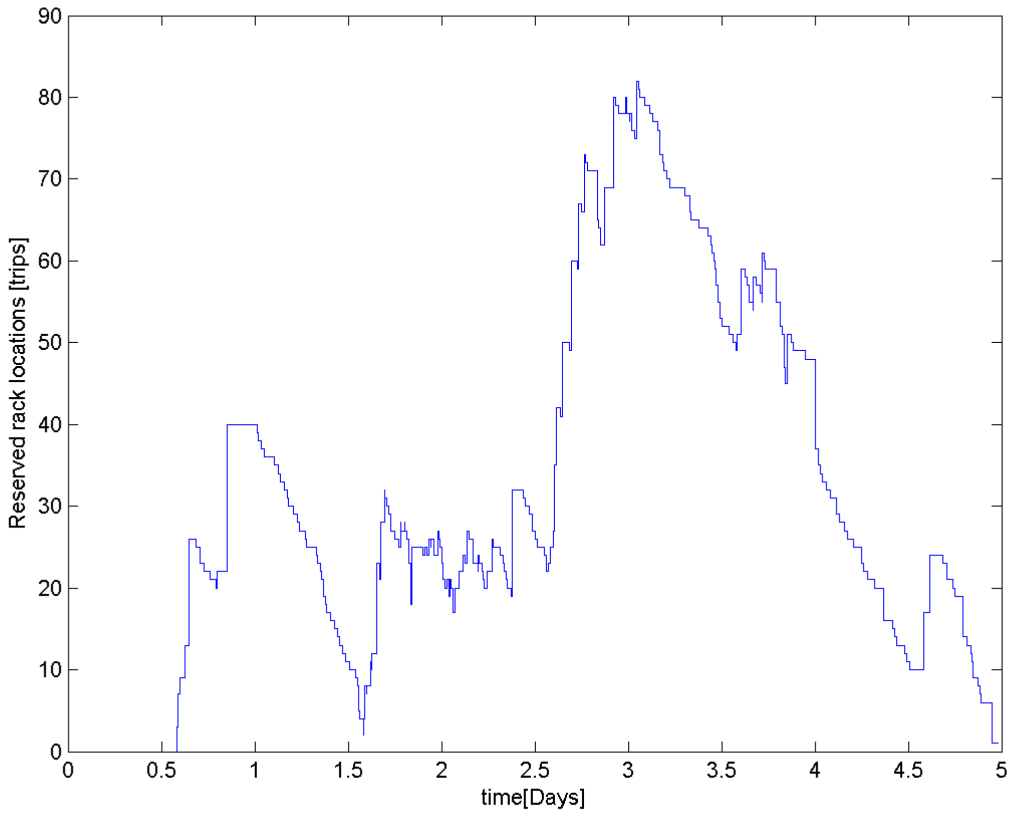



Figure 55 Reserved rack locations heuristic 5 week 26

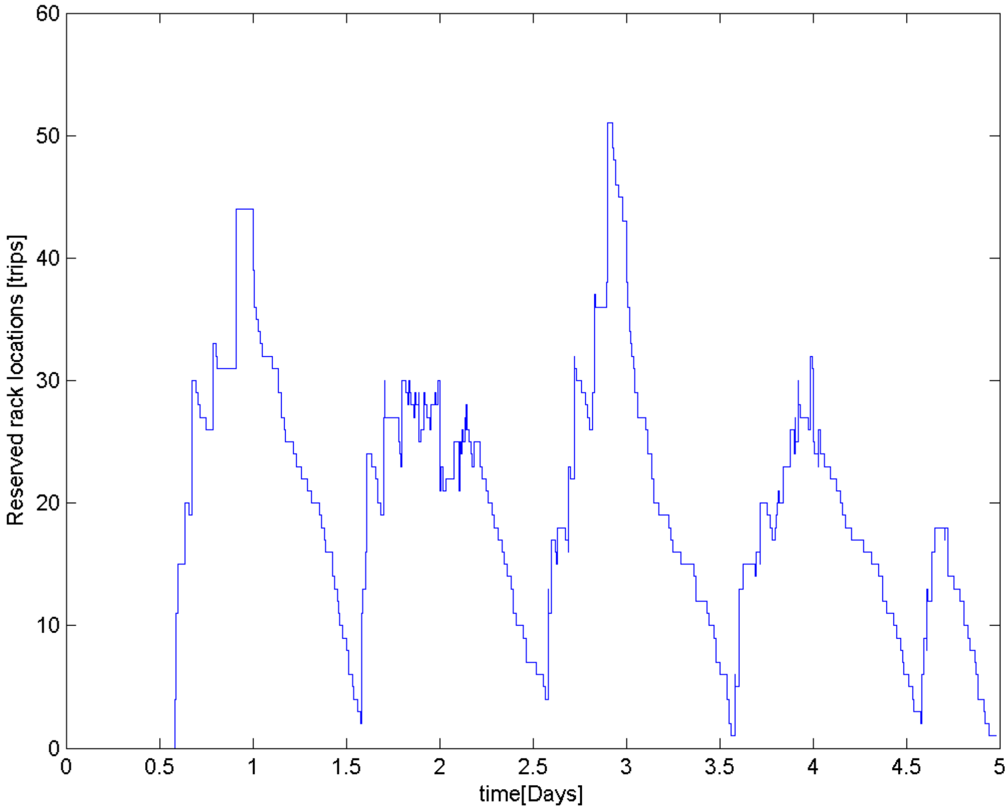



Figure 56 Reserved rack locations heuristic 6 week 16

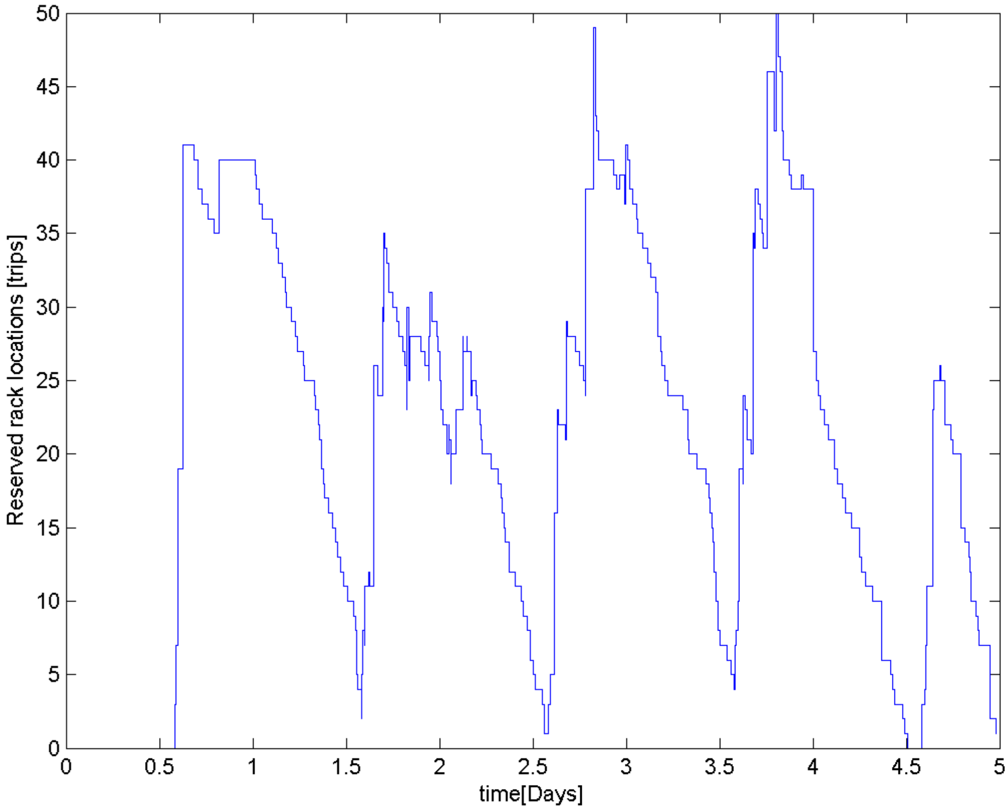



Figure 57 Reserved rack locations heuristic 6 week 26

# APPENDIX J: Automatic layer picker

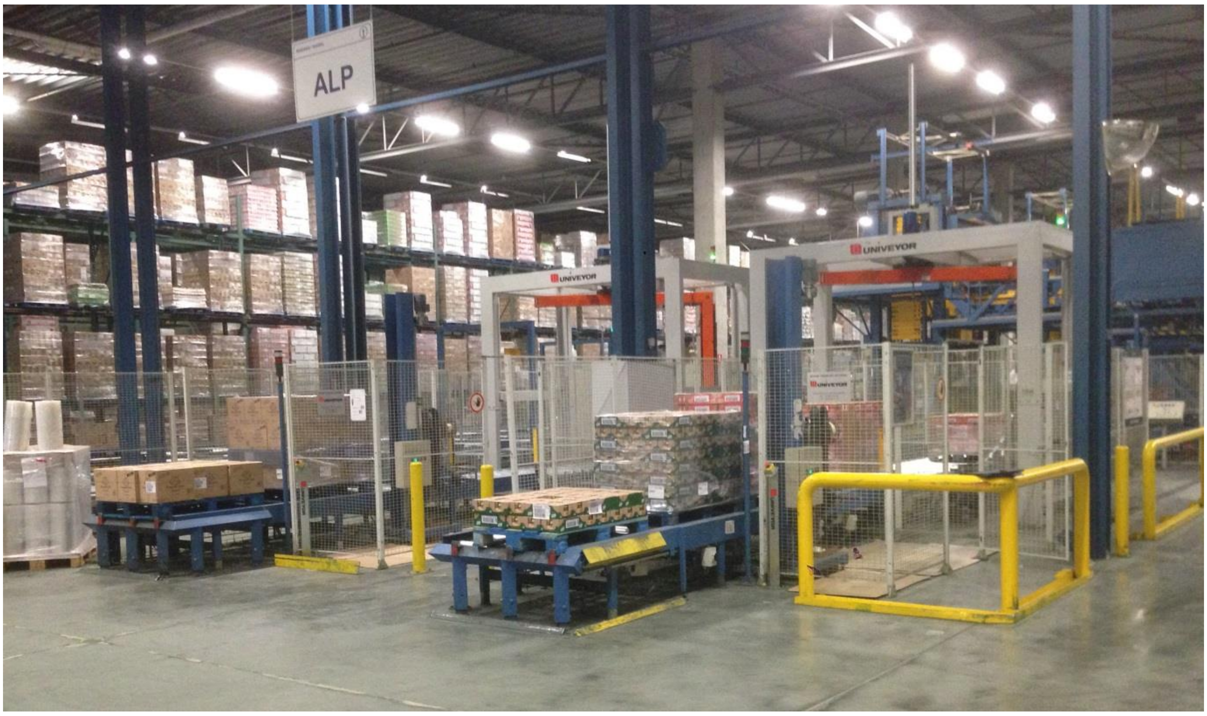



Figure 58 Outfeed of the ALP


Figure 59 ALP operation

Figure 60 Front of the ALP operation


Figure 61 Buffer area of the ALP

# APPENDIX K: Rack occupancy by process improvements

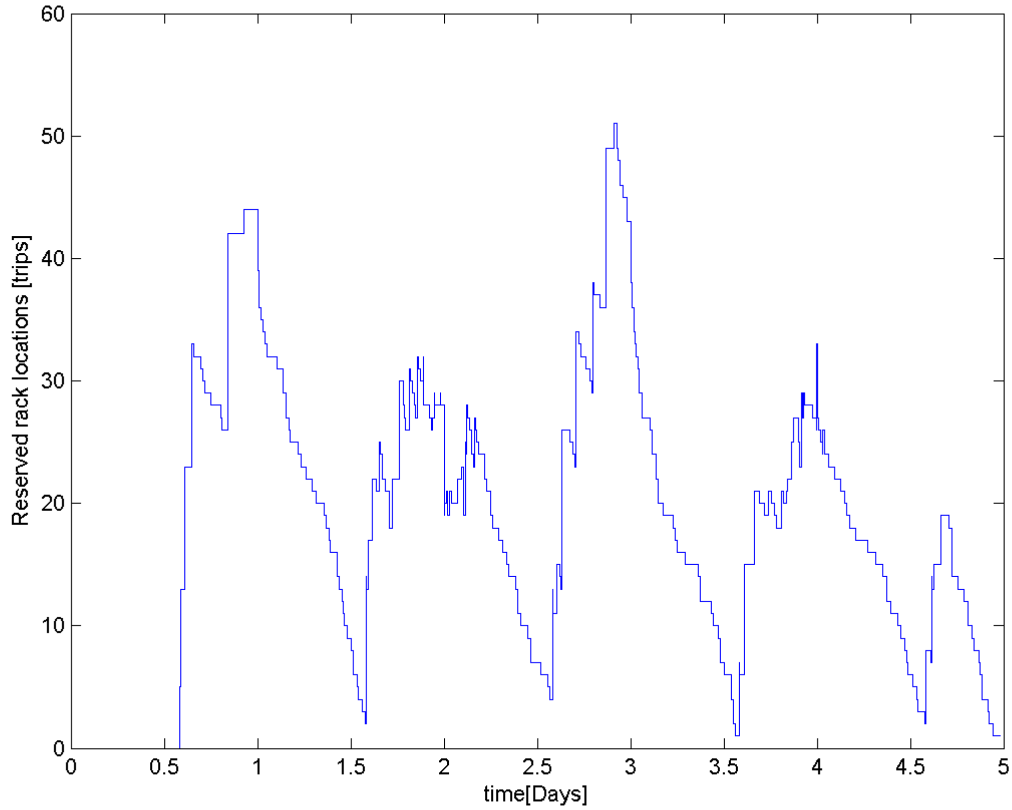



Figure 62 Reserved rack locations week 16 - 90 layers per hour - Heuristic 3

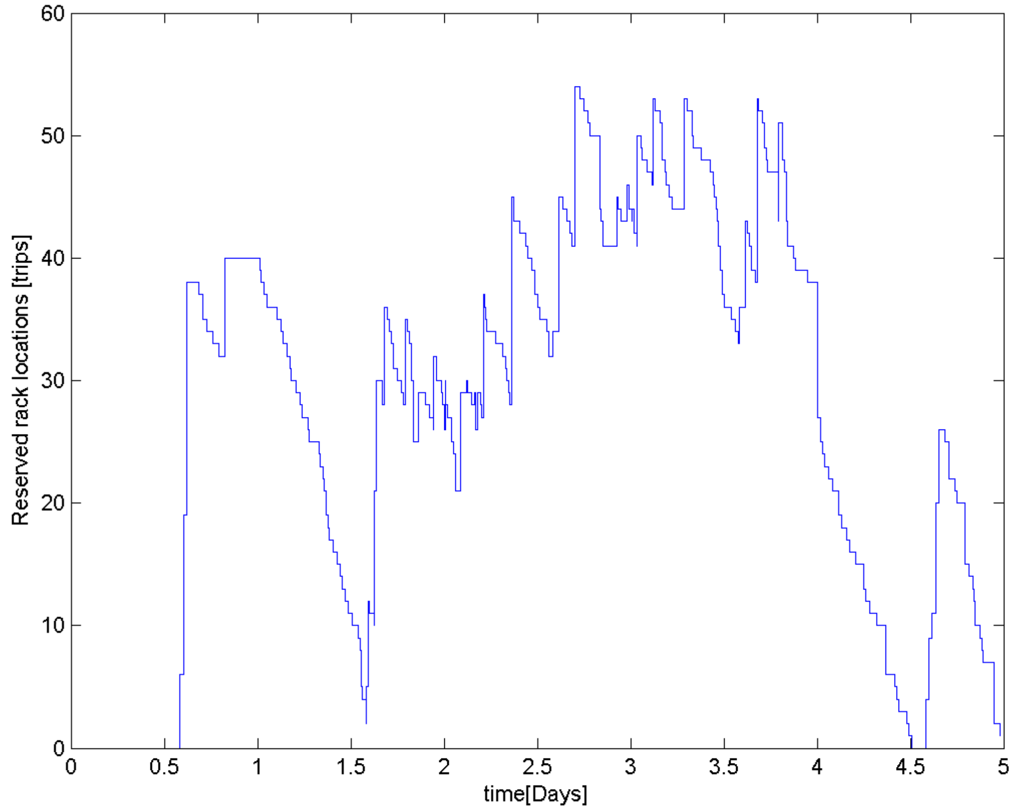



Figure 63 Reserved rack locations week 26 - 90 layers per hour - Heuristic 3

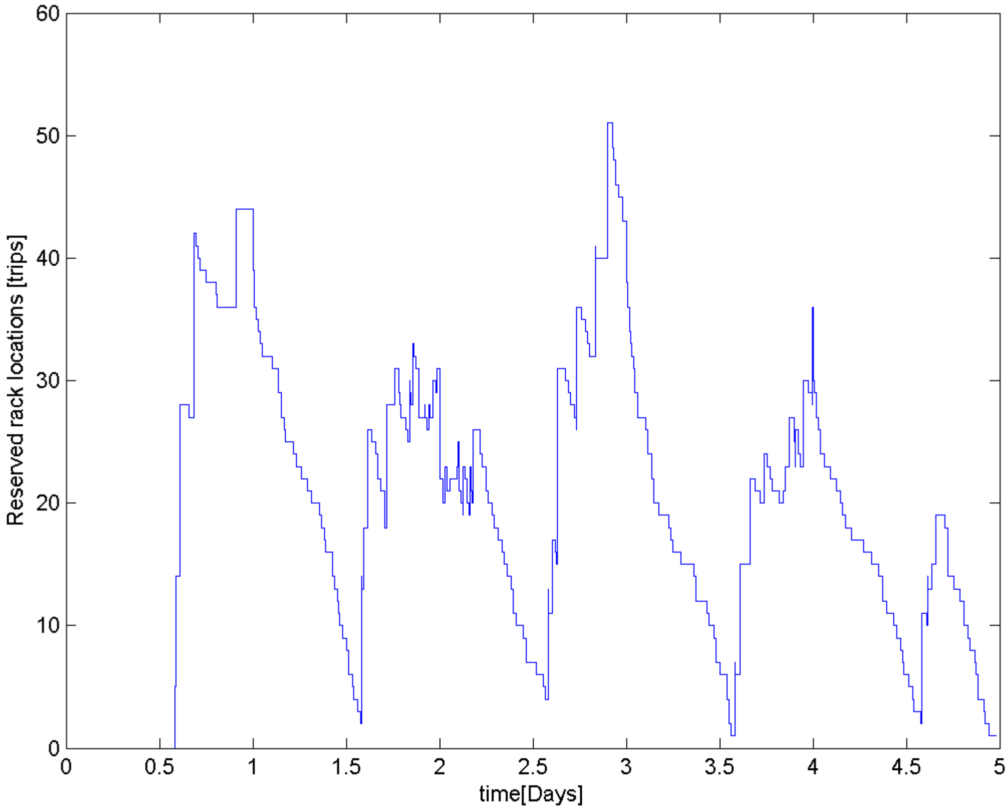



Figure 64 Reserved rack locations week 16 - 100 layers per hour - Heuristic 3

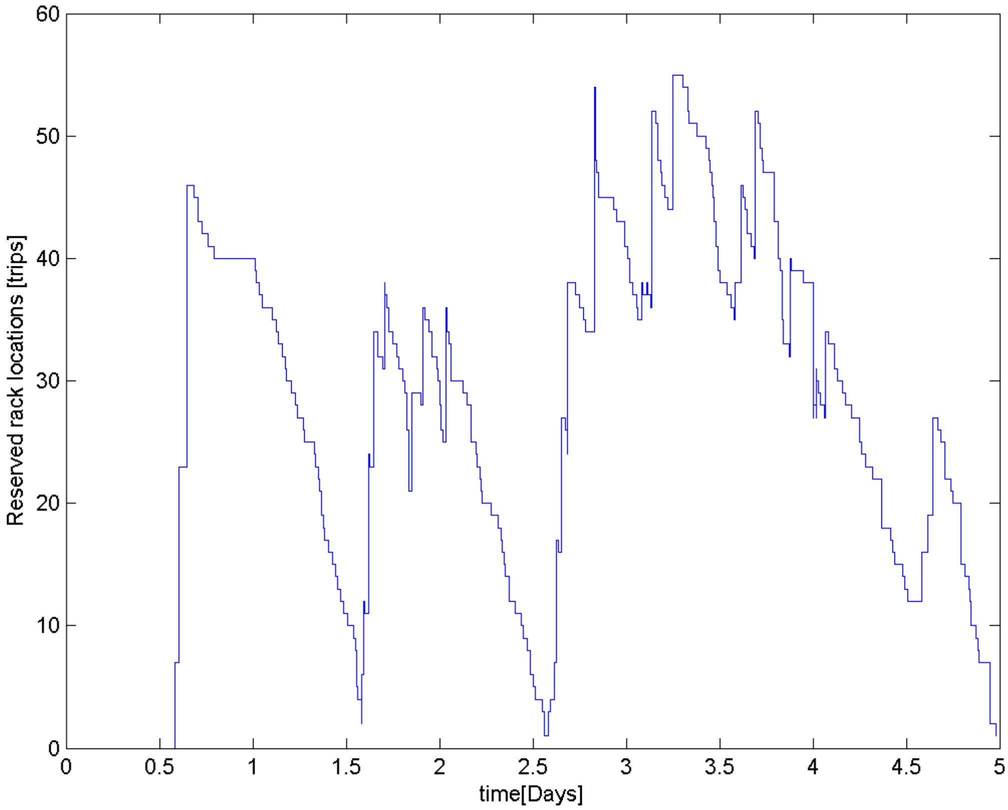



Figure 65 Reserved rack locations week 26 - 100layers per hour - Heuristic 3

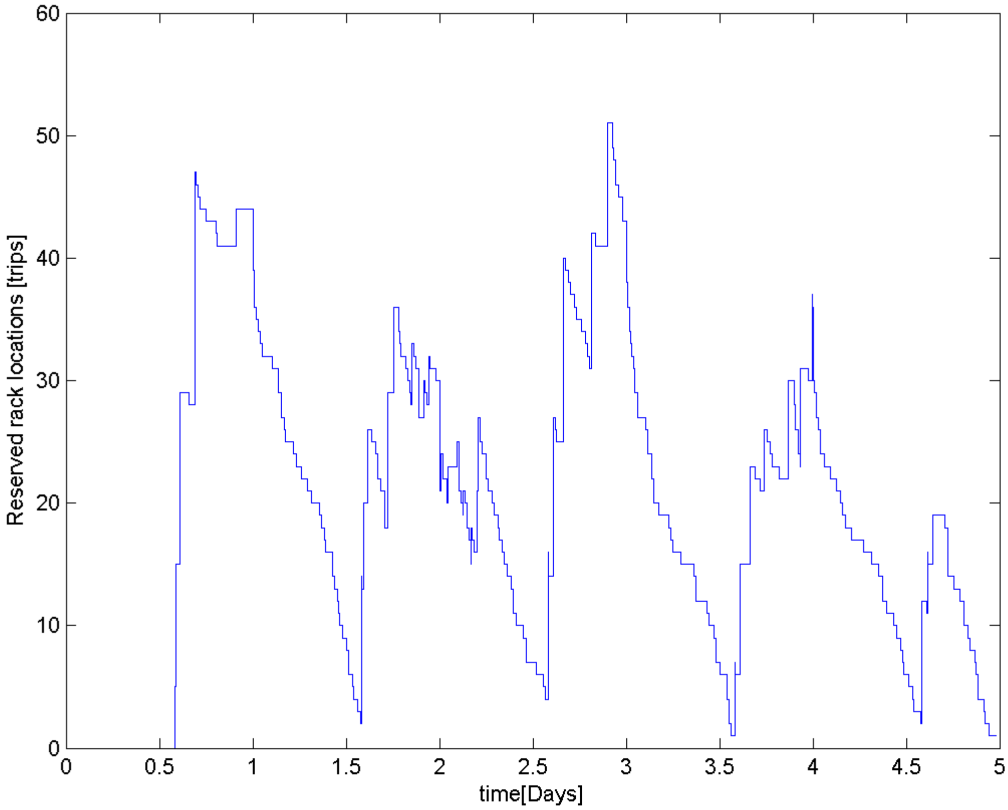



Figure 66 Reserved rack locations week 16 - 110 layers per hour - Heuristic 3

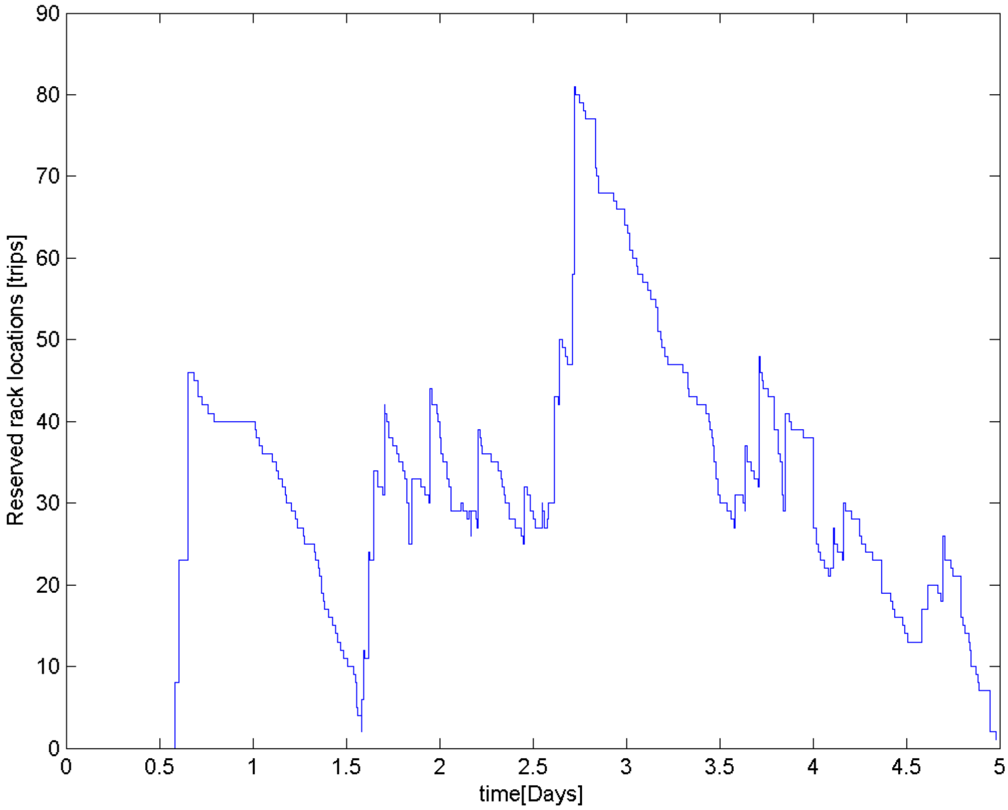



Figure 67 Reserved rack locations week 26 - 110 layers per hour - Heuristic 3

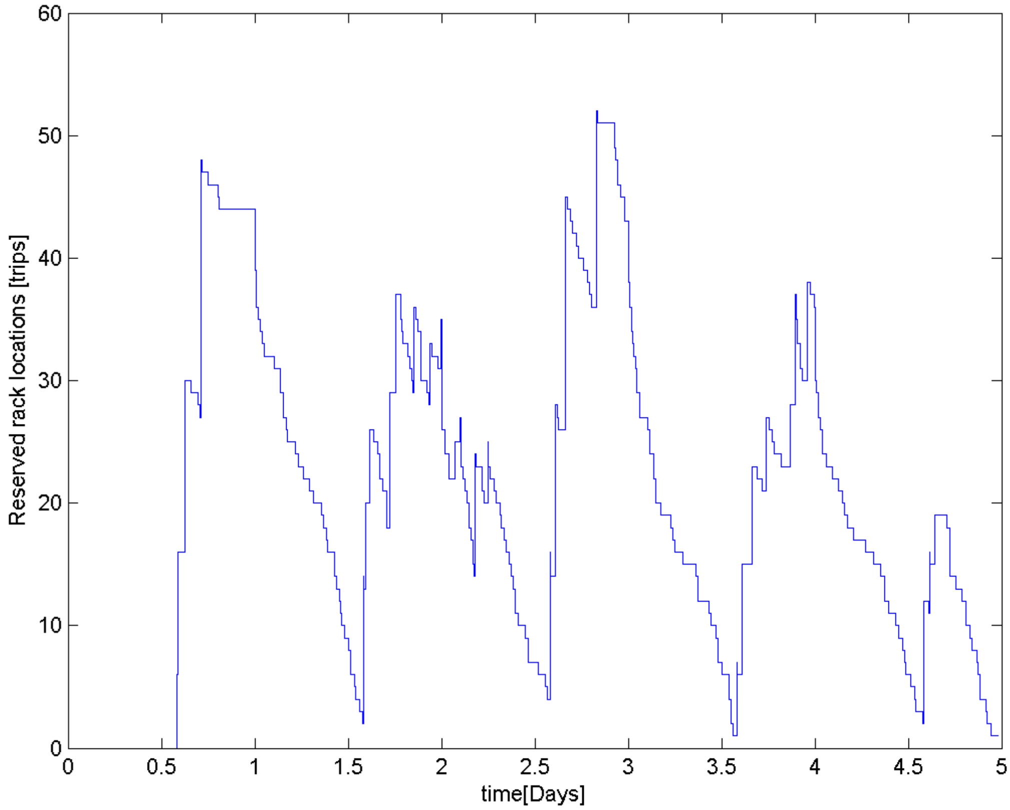



Figure 68 Reserved rack locations week 16 – 115 layers per hour - Heuristic 3

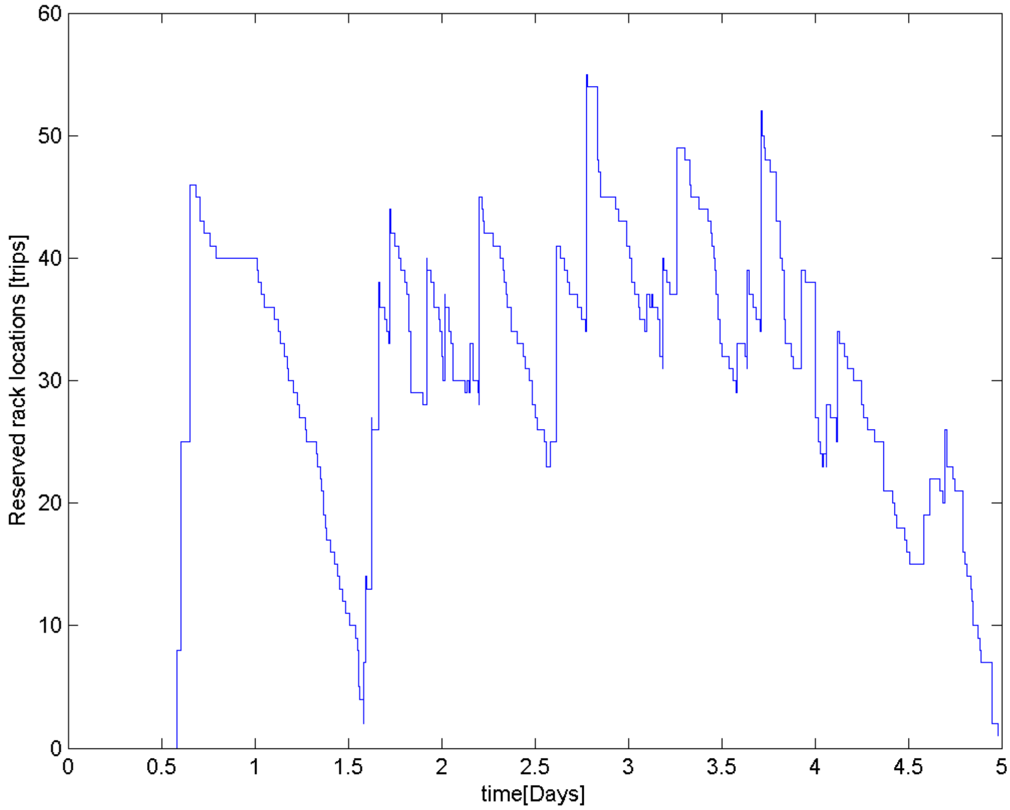



Figure 69 Reserved rack locations week 26 - 115 layers per hour - Heuristic 3

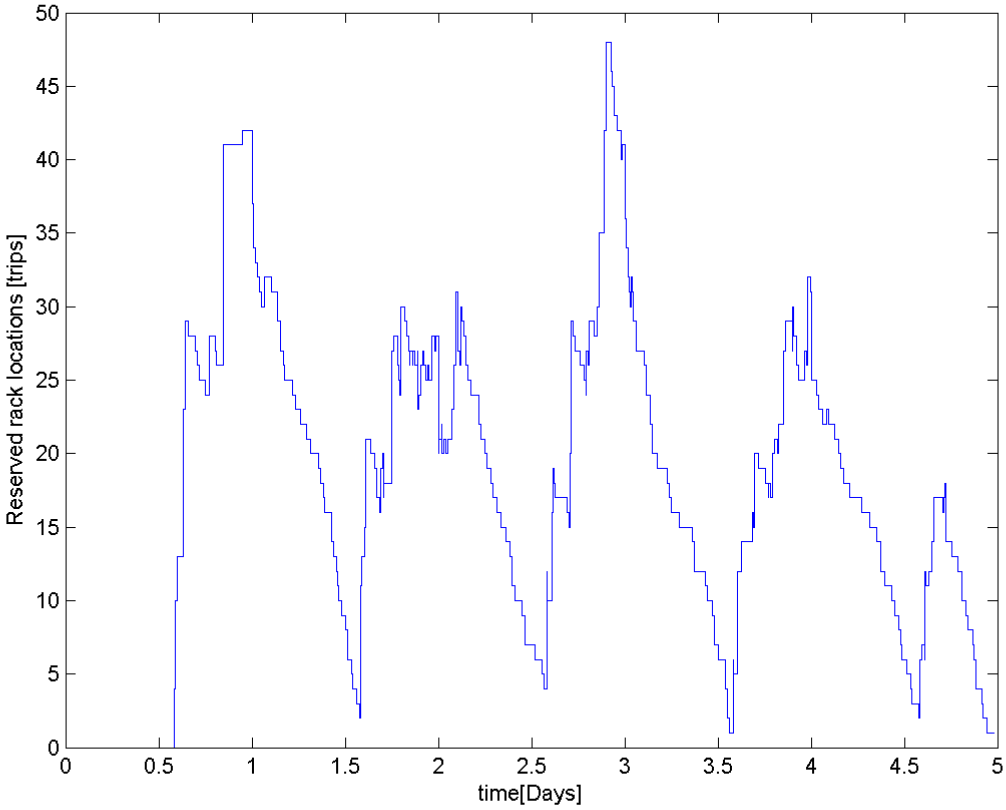



Figure 70 Reserved rack locations week 16 - 75 layers per hour - Heuristic 6

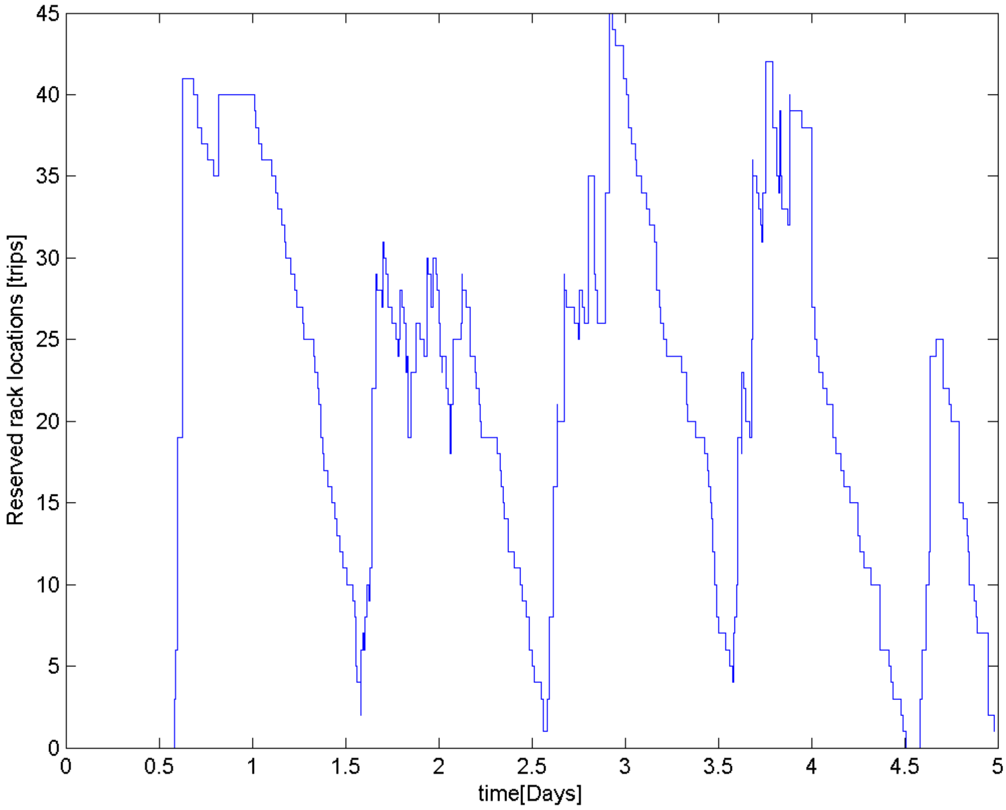



Figure 71 Reserved rack locations week 26 - 75 layers per hour - Heuristic 6

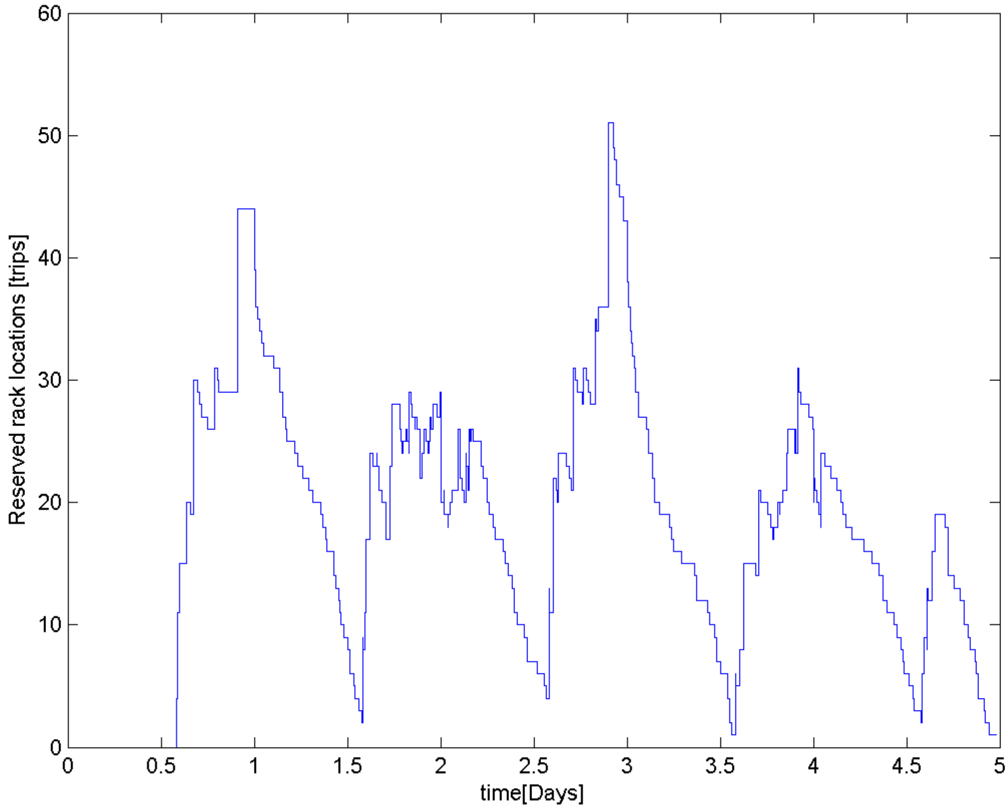



Figure 72 Reserved rack locations week 16 - 85 layers per hour - Heuristic 6

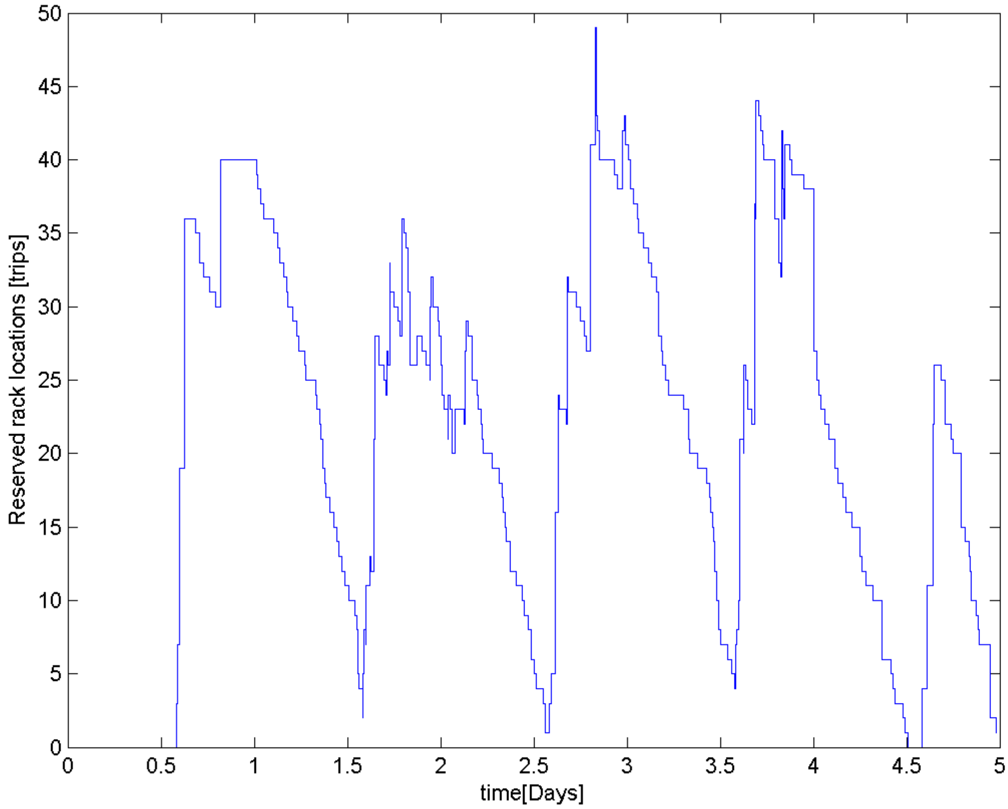



Figure 73 Reserved rack locations week 26 - 85 layers per hour - Heuristic 6

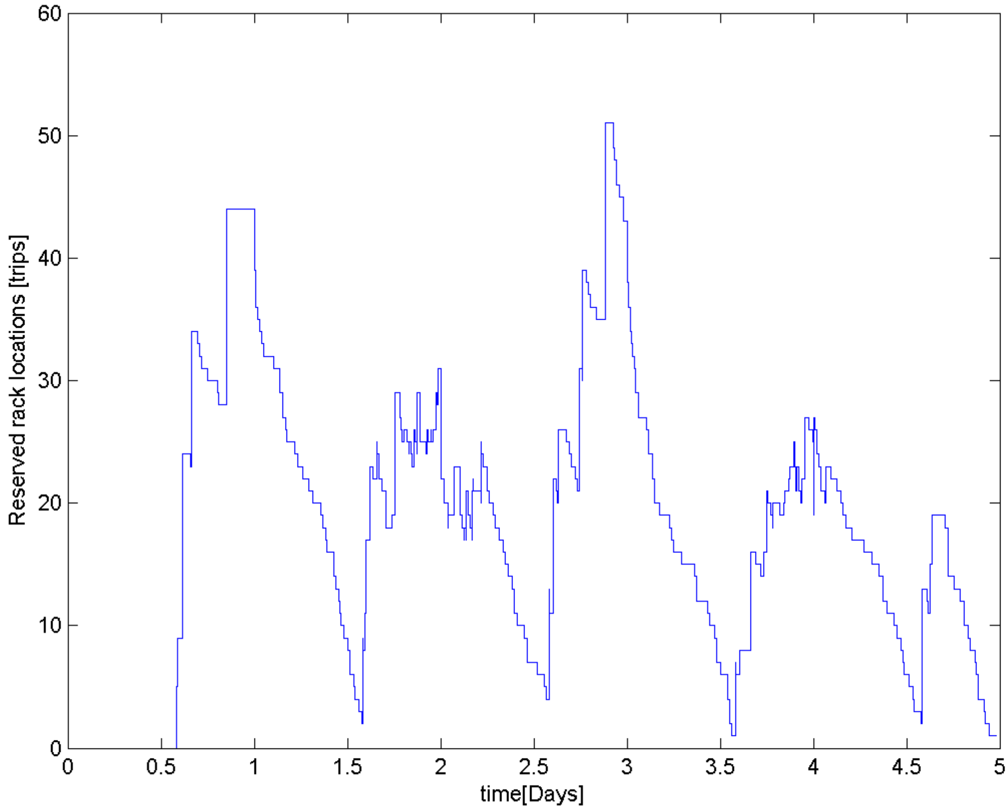



Figure 74 Reserved rack locations week 16 - 95 layers per hour - Heuristic 6

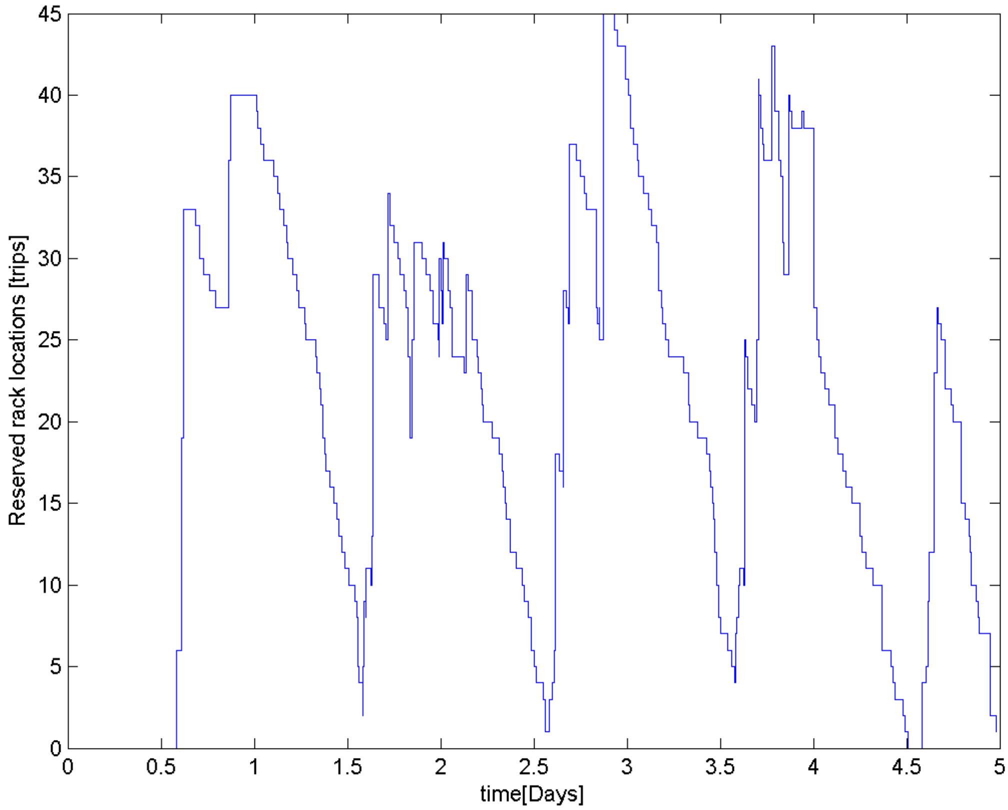



Figure 75 Reserved rack locations week 26 - 95 layers per hour - Heuristic 6

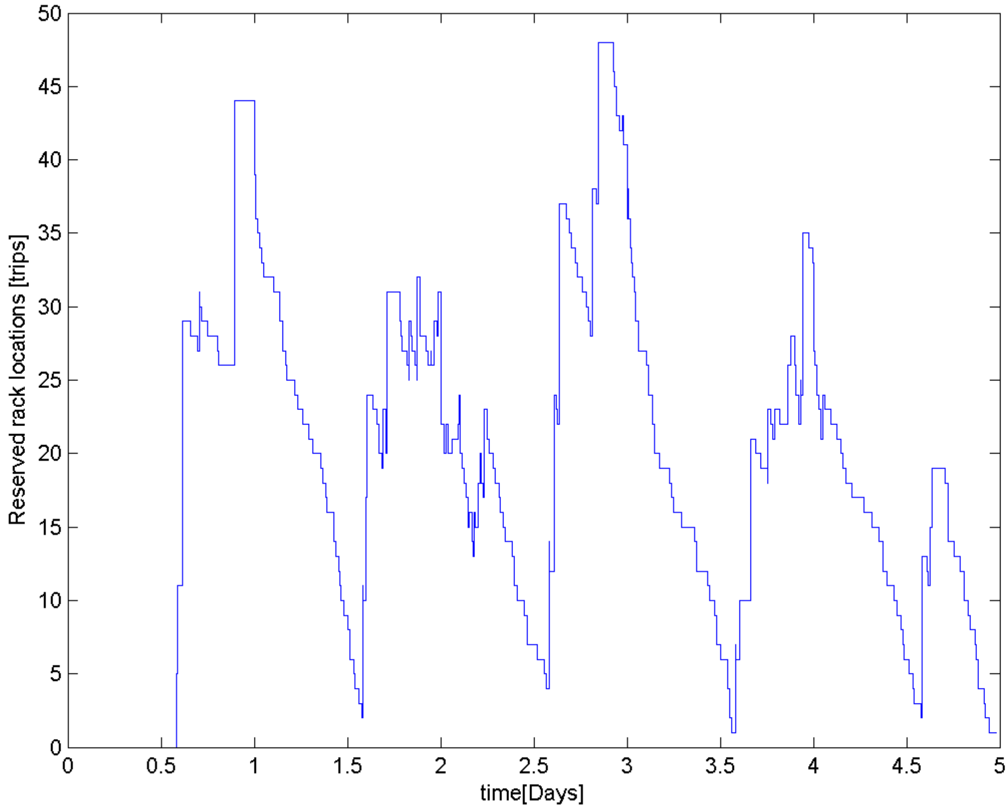



Figure 76 Reserved rack locations week 16 - 105 layers per hour - Heuristic 6

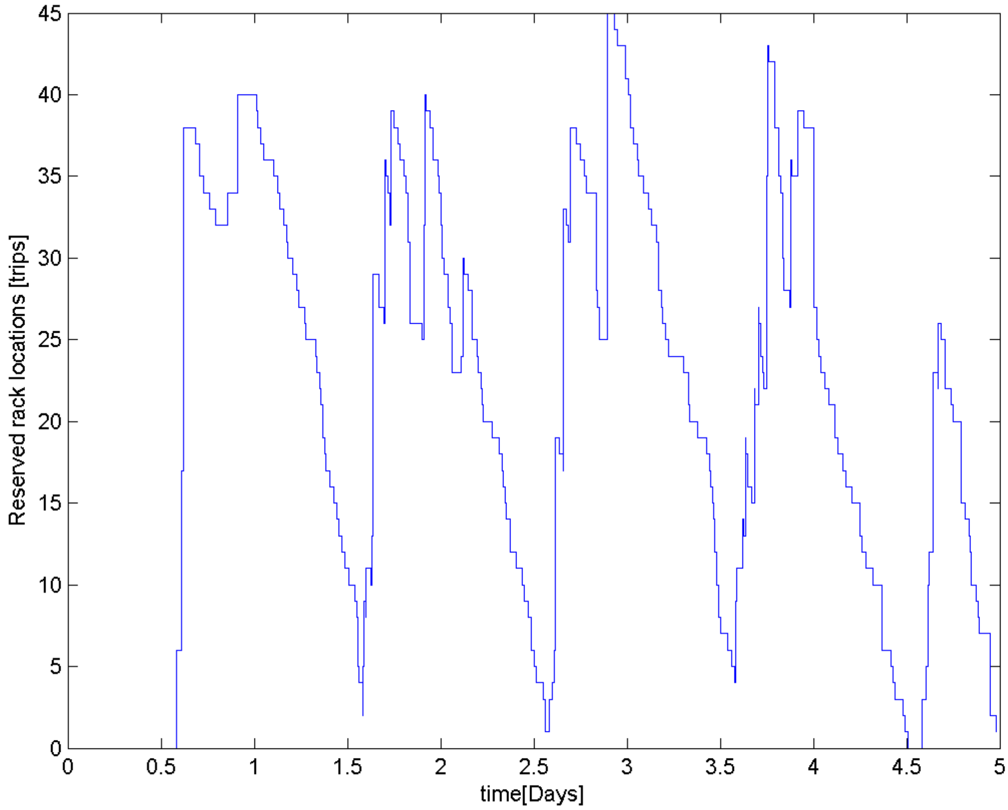



Figure 77 Reserved rack locations week 26 - 105 layers per hour - Heuristic 6

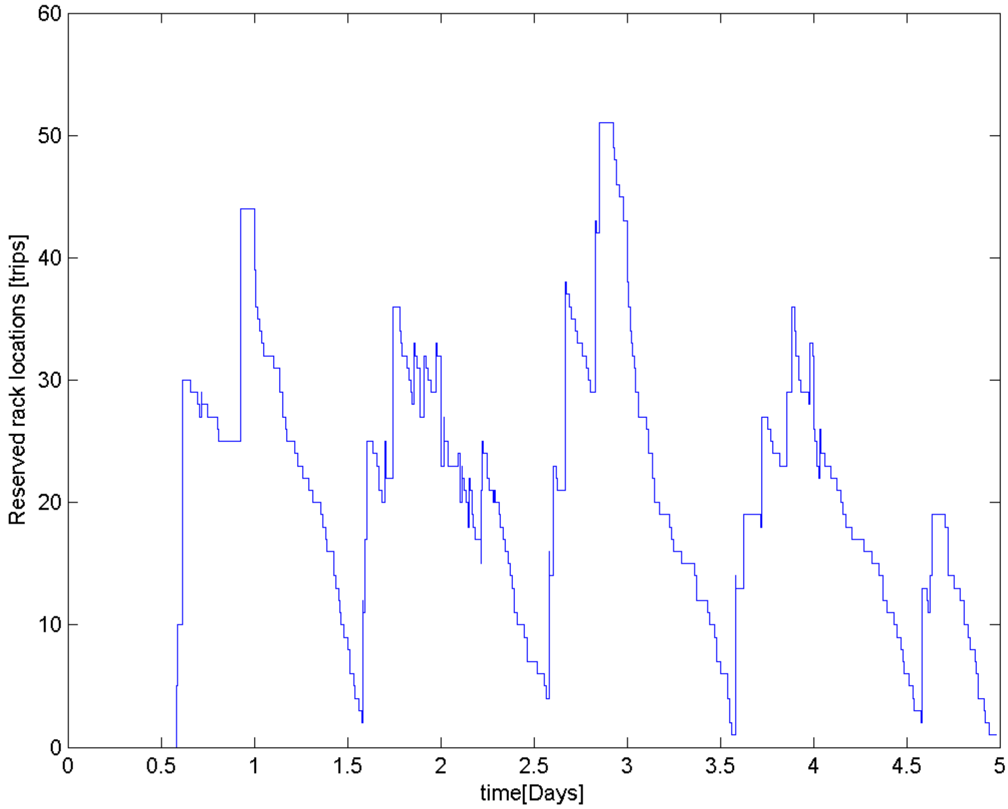



Figure 78 Reserved rack locations week 16 - 115 layers per hour - Heuristic 6

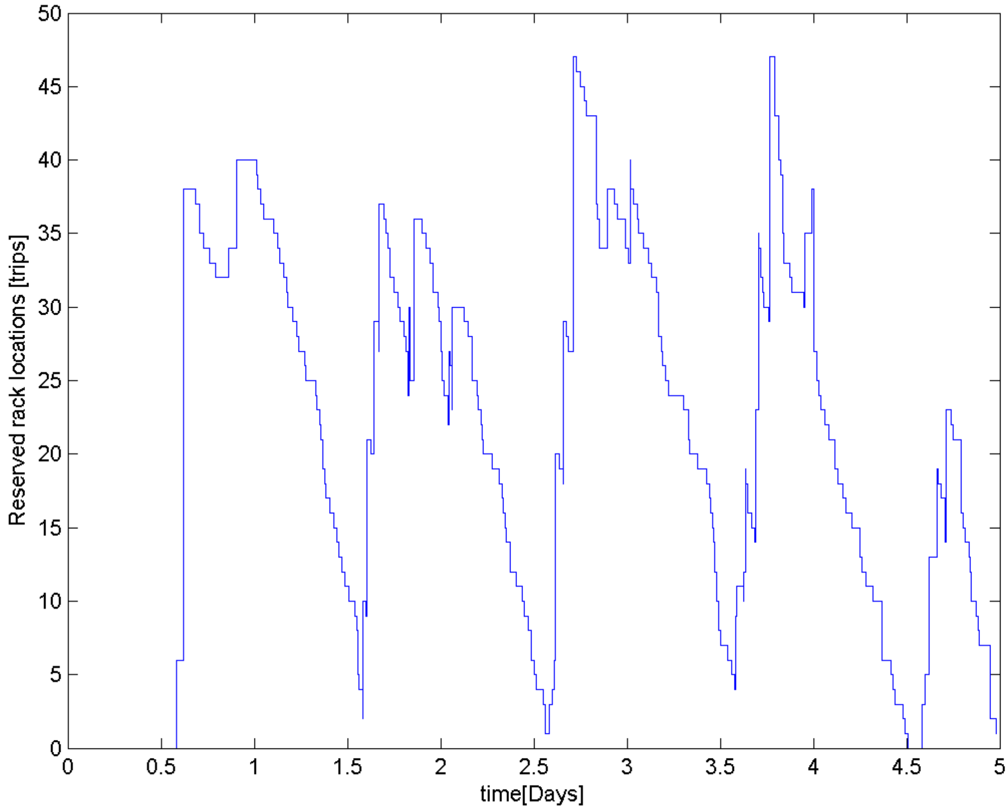


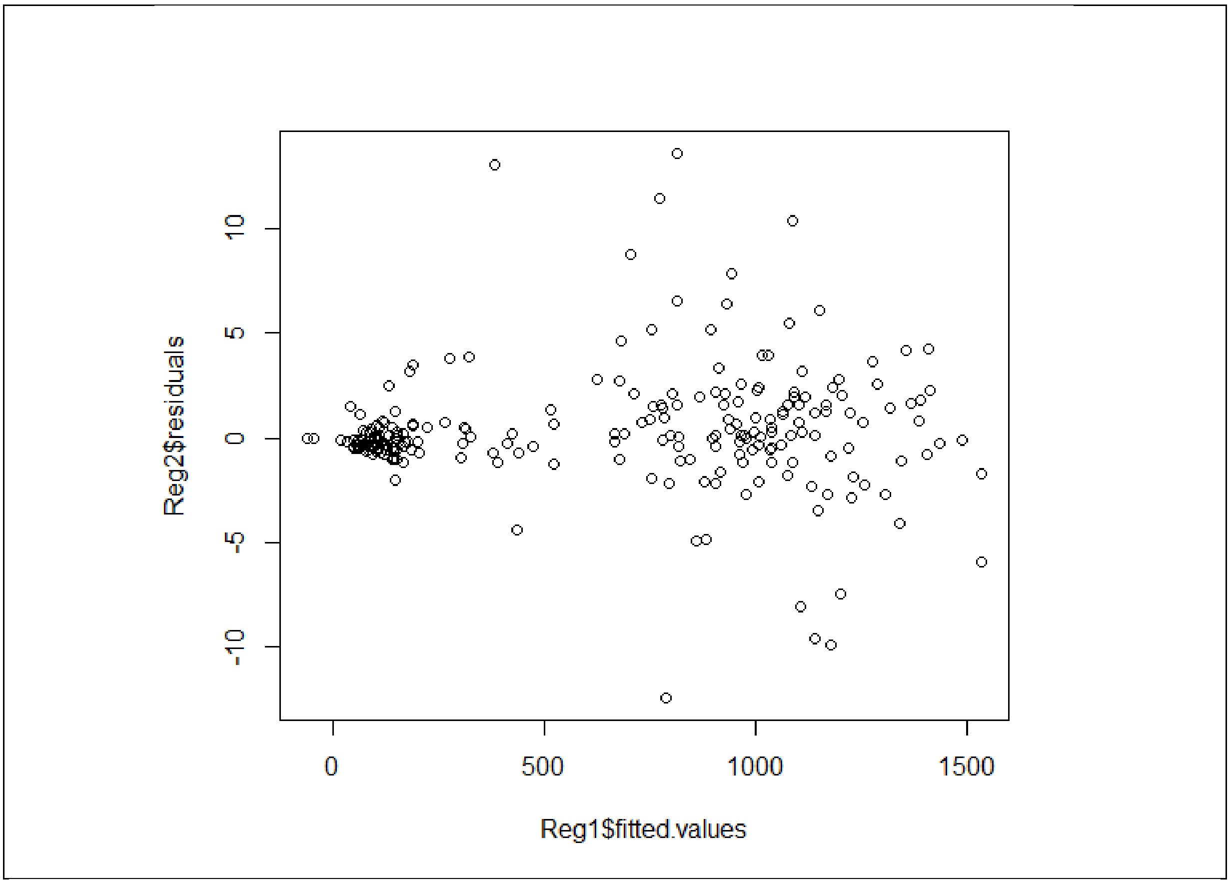

Figure 79 Reserved rack locations week 26 - 115 layers per hour - Heuristic 6

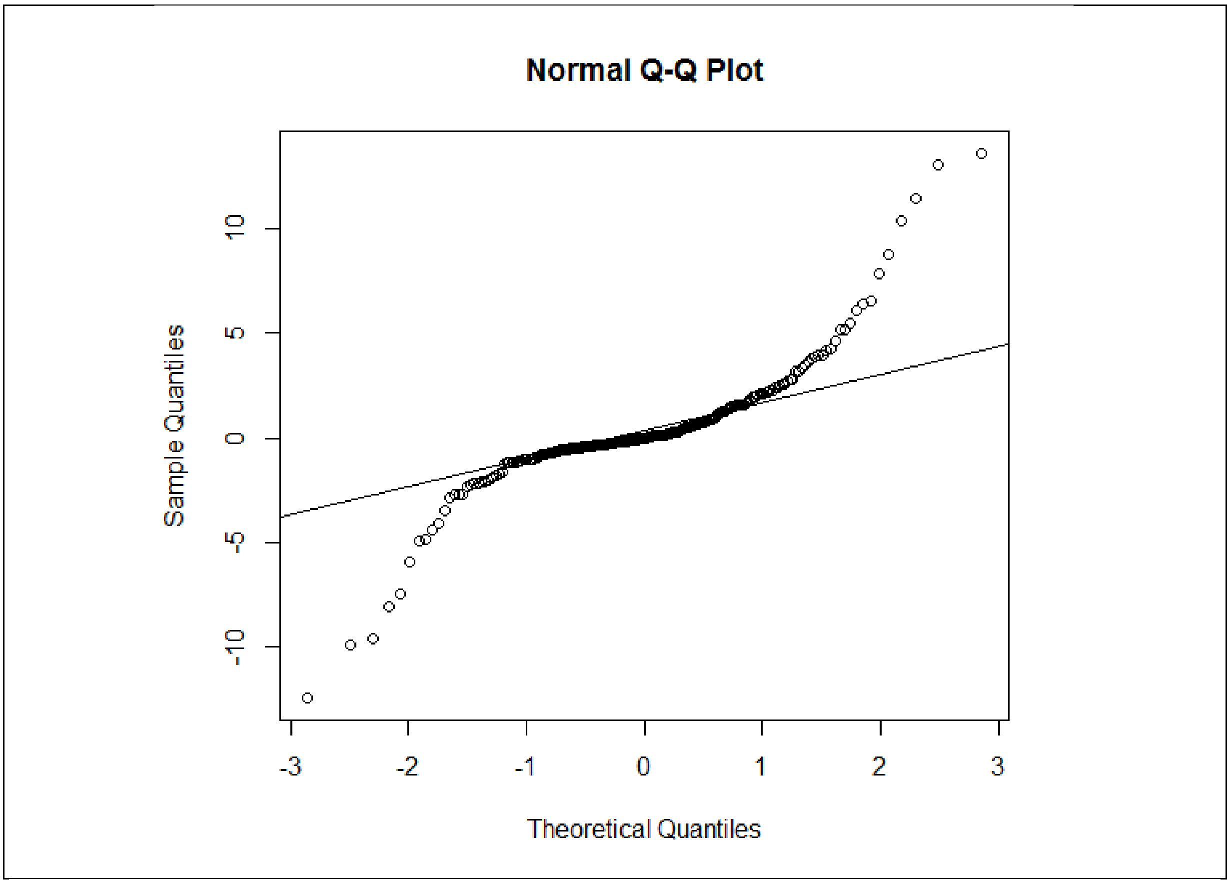
# APPENDIX L: Multivariate Statistics

```
Call:
lm(formula = tijd ~ SKU - 1, data = Book2)

Residuals:
    Min      1Q  Median      3Q     Max 
-5.1079 -0.9833 -0.1564  0.6261 14.7152 

Coefficients:
     Estimate Std. Error t value Pr(>|t|)    
SKU 0.0532785  0.0008294   64.24   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2.48 on 233 degrees of freedom
Multiple R-squared:  0.9466,	Adjusted R-squared:  0.9463 
F-statistic:  4127 on 1 and 233 DF,  p-value: < 2.2e-16
```

```
Call:
lm(formula = tijd ~ Lagen - 1, data = Book2)

Residuals:
     Min       1Q   Median       3Q      Max 
-12.4351  -0.5392  -0.0108   1.2732  13.6318 

Coefficients:
       Estimate Std. Error t value Pr(>|t|)    
Lagen 0.0122452  0.0002269   53.98   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2.919 on 233 degrees of freedom
Multiple R-squared:  0.9259,	Adjusted R-squared:  0.9256 
F-statistic:  2913 on 1 and 233 DF,  p-value: < 2.2e-16
```

```
studentized Breusch-Pagan test

data:  Reg2
BP = 7.0968, df = 0, p-value < 2.2e-16
```


Reg2$residuals
10
5
0
-5
-10
0
500
1000
1500
Reg1$fitted.values


Normal Q-Q Plot
Sample Quantiles
10
5
0
-5
-10
-3
-2
-1
0
1
2
3
Theoretical Quantiles

# APPENDIX M: Process improvement – Values

**Table 29 KPI absolute values – Week 26 – Heuristic 3**

| Efficiency: | 75 | 85 | 95 | 105 |
|---|---|---|---|---|
| $A_t$ | 54 | 55 | 81 | 55 |
| $A_i$ | 3283 | 3200 | 3305 | 3237 |
| $A_b$ | 2903 | 2791 | 2888 | 2815 |
| $t_p$ | 93 | 93 | 96 | 95 |
| $A_{alp}$ | 11338 | 11447 | 11774 | 11774 |
| $\eta$ | 119 | 118 | 117 | 117 |
| $n$ | 43 | 37 | 37 | 35 |
| $A_m$ | 28171 | 26156 | 16846 | 16846 |

**Table 30 KPI absolute values – Week 16 – Heuristic 3**

| Efficiency: | 75 | 85 | 95 | 105 |
|---|---|---|---|---|
| $A_t$ | 51 | 51 | 51 | 52 |
| $A_i$ | 3483 | 3649 | 3687 | 3668 |
| $A_b$ | 2973 | 3123 | 3133 | 3084 |
| $t_p$ | 106 | 107 | 108 | 109 |
| $A_{alp}$ | 13108 | 13626 | 13926 | 14089 |
| $\eta$ | 120 | 126 | 129 | 130 |
| $n$ | 58 | 48 | 41 | 36 |
| $A_m$ | 38081 | 26309 | 17704 | 13250 |

**Table 31 KPI Relative – Week 26 – Heuristic 3**

| Efficiency: | 90 | 100 | 110 | 115 |
|---|---|---|---|---|
| $A_t$ | 67% | 68% | 100% | 68% |
| $A_i$ | 136% | 132% | 137% | 134% |
| $A_b$ | 88% | 87% | 87% | 87% |
| $t_p$ | 78% | 78% | 80% | 79% |
| $A_{alp}$ | 90% | 91% | 94% | 94% |
| $\eta$ | 99% | 98% | 98% | 98% |
| $n$ | 478% | 411% | 411% | 389% |

**Table 32 KPI Relative values – Week 16 – Heuristic 3**

| Efficiency: | 90 | 100 | 110 | 115 |
|---|---|---|---|---|
| $A_t$ | 63% | 63% | 63% | 64% |
| $A_i$ | 143% | 150% | 152% | 151% |
| $A_b$ | 85% | 86% | 85% | 84% |
| $t_p$ | 88% | 89% | 90% | 91% |
| $A_{alp}$ | 105% | 109% | 111% | 112% |
| $\eta$ | 98% | 102% | 105% | 106% |
| $n$ | 387% | 320% | 273% | 240% |

**Table 33 KPI absolute values – Week 16 – Heuristic 6**

| Efficiency: | 75 | 85 | 95 | 105 | 115 |
|---|---|---|---|---|---|
| $A_t$ | 48 | 51 | 51 | 48 | 51 |
| $A_i$ | 3359 | 3502 | 3615 | 3667 | 3712 |
| $A_b$ | 2895 | 3022 | 3103 | 3124 | 3159 |
| $t_p$ | 104 | 105 | 108 | 109 | 109 |
| $A_{alp}$ | 12363 | 12861 | 13456 | 13828 | 14019 |
| $\eta$ | 116 | 117 | 122 | 125 | 131 |
| $n$ | 83 | 68 | 60 | 50 | 40 |
| $A_m$ | 54385 | 42412 | 30317 | 19885 | 16032 |

**Table 34 KPI absolute values – Week 26 – Heuristic 6**

| Efficiency: | 75 | 85 | 95 | 105 | 115 |
|---|---|---|---|---|---|
| $A_t$ | 45 | 49 | 54 | 45 | 47 |
| $A_i$ | 3223 | 3252 | 3308 | 3338 | 3353 |
| $A_b$ | 2861 | 2912 | 2909 | 2948 | 2960 |
| $t_p$ | 91 | 93 | 94 | 95 | 97 |
| $A_{alp}$ | 10901 | 11202 | 11385 | 11569 | 11774 |
| $\eta$ | 117 | 119 | 116 | 117 | 119 |
| $n$ | 57 | 49 | 47 | 45 | 43 |
| $A_m$ | 40306 | 32348 | 27175 | 22505 | 16846 |

**Table 35 KPI Relative – Week 16 – Heuristic 6**

| Efficiency: | 75 | 85 | 95 | 105 | 115 |
|---|---|---|---|---|---|
| $A_t$ | 59% | 63% | 63% | 59% | 63% |
| $A_i$ | 138% | 144% | 149% | 151% | 153% |
| $A_b$ | 86% | 86% | 86% | 85% | 85% |
| $t_p$ | 87% | 88% | 90% | 91% | 91% |
| $A_{alp}$ | 84% | 88% | 92% | 94% | 95% |
| $\eta$ | 94% | 95% | 99% | 102% | 107% |
| $n$ | 553% | 453% | 400% | 333% | 267% |

**Table 36 KPI Relative values – Week 26 – Heuristic 6**

| Efficiency: | 75 | 85 | 95 | 105 | 115 |
|---|---|---|---|---|---|
| $A_t$ | 56% | 60% | 67% | 56% | 58% |
| $A_i$ | 133% | 134% | 137% | 138% | 139% |
| $A_b$ | 89% | 90% | 88% | 88% | 88% |
| $t_p$ | 76% | 78% | 78% | 79% | 81% |
| $A_{alp}$ | 87% | 89% | 91% | 92% | 94% |
| $\eta$ | 98% | 99% | 97% | 98% | 99% |
| $n$ | 633% | 544% | 522% | 500% | 478% |

Table 37 Costs – Week 16 – Heuristic 3

| Efficiency: | 90 | 100 | 110 | 115 |
|---|---|---|---|---|
| $c_{alp}$ | 4.876,00 | 4.922,00 | 4.968,00 | 5.014,00 |
| $c_i$ | 1.640,18 | 1.718,35 | 1.736,25 | 1.727,30 |
| $c_b$ | 1.600,42 | 1.681,16 | 1.686,55 | 1.660,17 |
| $c_m$ | 2.654,13 | 1.833,66 | 1.233,92 | 923,48 |
| $c_r$ | - | - | - | - |
| $c_{total}$ | 10.770,73 | 10.155,17 | 9.624,71 | 9.324,95 |
| $c_{total}/A_l$ | 0,73 | 0,69 | 0,66 | 0,64 |

Table 38 Costs – Week 26 – Heuristic 3

| Efficiency: | 90 | 100 | 110 | 115 |
|---|---|---|---|---|
| $c_{alp}$ | 4.278,00 | 4.278,00 | 4.416,00 | 4.370,00 |
| $c_i$ | 1.546,00 | 1.506,91 | 1.556,36 | 1.524,34 |
| $c_b$ | 1.562,73 | 1.502,44 | 1.554,66 | 1.515,36 |
| $c_m$ | 1.963,43 | 1.822,99 | 1.174,12 | 1.174,12 |
| $c_r$ | - | - | - | - |
| $c_{total}$ | 9.350,17 | 9.110,35 | 8.701,13 | 8.583,81 |
| $c_{total}/A_l$ | 0,75 | 0,73 | 0,69 | 0,68 |

Table 39 Costs – Week 16 – Heuristic 6

| Efficiency: | 75 | 85 | 95 | 105 | 115 |
|---|---|---|---|---|---|
| $c_{alp}$ | 4.784,00 | 4.830,00 | 4.968,00 | 5.014,00 | 5.014,00 |
| $c_i$ | 1.581,79 | 1.649,13 | 1.702,34 | 1.726,83 | 1.748,02 |
| $c_b$ | 1.558,43 | 1.626,79 | 1.670,40 | 1.681,70 | 1.700,54 |
| $c_m$ | 3.790,47 | 2.955,99 | 2.113,00 | 1.385,92 | 1.117,38 |
| $c_r$ | - | - | - | - | - |
| $c_{total}$ | 11.714,69 | 11.061,91 | 10.453,74 | 9.808,45 | 9.579,94 |
| $c_{total}/A_l$ | 0,80 | 0,75 | 0,71 | 0,67 | 0,65 |

Table 40 Costs – Week 26 – Heuristic 6

| Efficiency: | 75 | 85 | 95 | 105 | 115 |
|---|---|---|---|---|---|
| $c_{alp}$ | 4.186,00 | 4.278,00 | 4.324,00 | 4.370,00 | 4.462,00 |
| $c_i$ | 1.517,74 | 1.531,40 | 1.557,77 | 1.571,90 | 1.578,96 |
| $c_b$ | 1.540,13 | 1.567,58 | 1.565,96 | 1.586,96 | 1.593,42 |
| $c_m$ | 2.809,21 | 2.254,56 | 1.894,02 | 1.568,53 | 1.174,12 |
| $c_r$ | - | - | - | - | - |
| $c_{total}$ | 10.053,07 | 9.631,54 | 9.341,75 | 9.097,39 | 8.808,50 |
| $c_{total}/A_l$ | 0,80 | 0,77 | 0,75 | 0,73 | 0,70 |

# APPENDIX N: Pick profiles

Table 41 Pick profiles per heuristic

| Heuristic: | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Week 26 | 3,59 | 3,85 | [-] | 3,42 | 3,31 | 3,36 | 3,41 |
| Week 16 | 3,54 | 3,96 | [-] | 3,71 | 3,61 | 3,71 | 3,68 |

Table 42 Pick profiles heuristic 6 - process improvements

| Efficiency | 75 | 85 | 95 | 105 | 115 |
|---|---|---|---|---|---|
| Week 26 | 3,38 | 3,44 | 3,44 | 3,47 | 3,51 |
| Week 16 | 3,68 | 3,67 | 3,72 | 3,77 | 3,78 |

Table 43 Pick profiles heuristic 3 - process improvements

| Efficiency | 90 | 100 | 110 | 115 |
|---|---|---|---|---|
| Week 26 | 3,45 | 3,58 | 3,56 | 3,64 |
| Week 16 | 3,76 | 3,73 | 3,78 | 3,84 |