Dynamic Matching in Truck Platooning



Date: 26-07-2018

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Management Summary

Truck platooning is a new technology that allows two or more trucks to drive closely behind each other on public roads in so called platoons. Driving in a platoon saves fuel and possibly wages. Although the technology is almost completely developed, implementation for commercial use is yet to happen.

The process of deciding which trucks should platoon with each other is called truck platoon matching. The company Distribute has been working on a study for TNO into truck platoon matching, for which they have developed and tested a matching process. In this matching process trucks try to find a match while taking a break at a parking lot. In Distribute's system a created match is a fixed agreement. It is not possible to improve existing matches when new trucks arrive in the system, resulting in the loss of potential earnings. The goal of this thesis is to develop a new matching process in which this is possible and compare the performance of this new process with the old process. In this new matching process it is possible for trucks to break up their existing match in order to platoon with someone who is a better match for them. The truck who loses his match then starts to search for a replacement.

The new matching process has been designed based on existing literature on truck platoon matching. An algorithm called the Best-Pair-Heuristic was used as the basis for the new matching process, because of its suitability and proven effectiveness.

To measure the performance, a case was simulated using a real world location in the port of Rotterdam. The arrival rate and destination of the trucks have been modelled according to real world data.

Both the old and the new process have been implemented in a simulation environment and their performance has been measured through experiments. From these experiments it became clear that in the old matching process 93 percent of the trucks finds a platoon partner, while this is only 84 percent in the new matching process. The platoons that were created in the new matching process are however more profitable. On average, the platoons created in the new matching process achieve 76 percent more earnings than platoons created in the old matching process. This results in the new matching process.

A restricted version of the new matching process was also tested. In this restricted version it is no longer possible to break up a match if the other truck already made waiting costs. Implementing the restriction resulted in slightly lower earnings per platoon than the unrestricted version of the new matching process, but also in creation of slightly more platoons. The earnings per hour did not significantly differ between both versions of the new matching process.

Preface

I wrote this thesis as part of my graduation assignment for the bachelor industrial engineering. While working on this thesis I learned a lot, both about the subject and research in general.

I would like to thank Berry for taking the time to discuss the contents of this research with me and for sharing his knowledge of simulation software with me. I would like to thank Robbert Jansen, from TNO, for sharing his thoughts on this research and providing me with more practical insights into the subject. I would also like to thank Martijn for providing feedback on this report and my research, which enabled me to improve it further.

Last I would like to thank everyone who gave me coffee while I was working on this thesis. This thesis might be printed with ink, but it was written with coffee.

Joey Klein Koerkamp

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List of abbreviations

Dutch abbreviations are translated into English. The Dutch version is added in italics.

CACC Cooperative Adaptive Cruise Control
 MSER Marginal Standard Error Rule
 NDW National Database Traffic Data (*Nationale Databank Wegverkeersgegevens*)
 TNO Netherlands Organisation for Applied Scientific Research (*Nederlandse organisatie voor Toegepast Natuurwetenschappelijk Onderzoek*)

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1 Introduction

In this chapter, the subjects truck platooning and truck platoon matching are introduced. The company Distribute is currently working on a study into truck platoon matching called the Truck Platoon Matching Project. This study and the assignment are introduced as well.

1.1 Introduction to truck platooning

Truck platooning involves trucks using a new technology called Cooperative Adaptive Cruise Control (CACC). CACC allows trucks to drive together in a platoon while connected to each other through wireless communication. The first truck is fully manually driven and the other trucks steer, brake and (de)accelerate automatically based on the actions of the first truck (Bhoopalam et al., 2018). The technology is largely developed and successful tests have been performed on the road but the implementation for commercial use has yet to happen.

Truck platooning has various benefits. Trucks that drive in a platoon use less fuel because of reduced air drag. Fuel savings differ between 2-5 percent for the first truck, 11-21 percent for the middle truck and 9-15 percent for the last truck depending on driving speed and distance between trucks (Boysen et al., 2018).

Besides the fuel savings, truck platooning also has the potential to save wages. The following trucks are automatically following the first truck and the drivers in the following trucks do not have to do anything while platooning. They are however required to be in this trucks because of legal regulations, but this might change in the future (Bhoopalam et al., 2018).

It is possible that waiting costs need to be made in order to form a platoon. If a truck driver has to wait a short time for his platoon partner, he still needs to get paid during this time. Therefore the earnings of a platoon are considered instead of the savings. The earnings of a platoon are defined as the savings of a platoon minus the costs.

Both the fuel and wage savings are higher for the following trucks than for the leading truck. This means that larger platoons have higher savings per truck. There is however a maximum platoon capacity, the largest number of trucks that can be in one platoon. The maximum platoon capacity is not yet known but it is restricted by the platooning technology and expected to be restricted by legal regulations in the future (Bhoopalam et al., 2018).

1.2 Introduction to truck platoon matching

In order to exploit the benefits of truck platooning technology, trucks need to be matched to platoon with each other. This is called truck platoon matching, sometimes referred to as truck platoon coordination (Hoef et al., 2018) or truck platoon planning (Bhoopalam et al., 2018). When matching trucks, one needs to consider that each truck has its own starting location, destination, release time and arrival deadline. This makes truck platoon matching a complicated task.

Matching trucks with each other is done by creating so called platoon plans. A platoon plan contains the following information:

- Which trucks are in the platoon
- The route of the platoon
- The starting time of the platoon

- The speed profile on the route (optional)
- The order of the trucks (optional)

Common objectives when creating platoon plans are to maximize the earnings, either for individuals or for the entire system or to maximize the number of trucks that drives in a platoon.

Truck platoon matching can be done in different ways. It is for example possible to create the platoon plans before the trucks depart or while they are driving. The most researched settings and their (dis)advantages are described in Chapter 3.

1.3 Current situation: Distribute's Truck Platoon Matching Project

As a project for TNO, Distribute is researching the potential of a real-time, agent-based matching system for truck platooning. Real-time matching means that the platoon plans are created while the trucks are driving or shortly before they depart. The term agent-based is explained in section 3.1.2. In the context of truck platoon matching, agent-based means that the truck drivers, or software representing them, can choose for themselves with whom they want to match, instead of a controller telling them who they need to platoon with. The (dis)advantages of these types of truck platoon matching compared to other systems are described in Chapter 3.

Distribute has designed a matching system in which each truck tries to find a platoon partner for himself. To achieve this goal they have two possibilities. They can find a platoon partner while driving or while taking a break. In both cases, they try to match with the partner with whom they can achieve the highest earnings using a best-match-algorithm. Both options are further explained here.

1.3.1 Matching while driving

While driving on the highway, trucks scan their neighbourhood for potential partners. The proposed system has access to the destination and time window of the other trucks and uses this to calculate the earnings if the candidate truck platoons with the searching truck. If a profitable candidate is found, or the most profitable candidate if there is more than one, a match is made. The two trucks than drive to a matching location from where they start platooning. This matching location is, for example, a parking lot or gas station next to the highway.

1.3.2 Matching on a break

While driving their routes truck drivers need to take obligatory breaks, because of labour regulations. They often hold their breaks at the same location as other drivers. For example at big distribution centres, ports and well-known truck stops. The other trucks at these locations are potential platooning candidates. When a new truck arrives at the matching location it searches for a profitable partner amongst the already present trucks. If he finds a profitable candidate, or the most profitable candidate if there is more than one, they agree on a departure time. The truck drivers then finish their breaks and leave together in a platoon. If the arriving truck does not find a partner he still takes his break. He still has the possibility to find a partner amongst the trucks that arrive while he takes his break. If this is not the case he continues his assignment alone after his break. In this setting all the possible candidates for a truck are already at the same location as the truck. This is referred to as the same-start-platooning-problem (Larsson et al., 2015).

1.3.3 Room for improvement

Distribute has developed a simulation model to test the performance of the matching system described in the previous two paragraphs. This model shows positive results, but the idea exists that potential earnings are lost because the algorithm used to create matches in the matching-on-a-break-setting is not optimal. Therefore, the assignment is to look for ways to improve the algorithm and thereby increase the earnings that can be obtained within this matching-on-a-break-setting.

2 Problem Identification & problem solving approach

In the previous chapter, the subject of truck platoon matching and the assignment have been introduced. To determine which problem to solve, a problem identification is done according to Heerkens & Winden (2012). This is followed by the creation of a problem solving approach, which is used to guide the further execution of the assignment. To conclude this chapter, the deliverables are listed.

2.1 Problem identification

To reduce the loss of potential earnings, the causes of this loss need to be identified. By taking a closer look at the current match making process and studying a report from Distribute about the project, three causes of loss of potential earnings are found.

The first cause is that two trucks that are already matched never wait for a third truck that wants to join, not even when this benefits them. Potential earnings are lost here because the third truck cannot join the platoon and the first two trucks could have increased their earnings by letting the third truck join.

The second cause is that in the current matching system, a truck that wants to join an already formed platoon cannot platoon further with one of the other trucks than the overlapping distance of the first two trucks. When the third truck and one of the other trucks are going in the same direction after the original two trucks go separate ways, there is a potential for more earnings that is not used.

The third cause is that once two trucks have agreed to platoon after their breaks this is a fixed agreement. This means that should a better candidate for one of the trucks arrive during their break, they cannot break up their match with their original partner to go with the better candidate. Potential earnings are also lost here since matching with the better candidate would have resulted in higher earnings.

These three causes all relate to new information becoming available to the truck drivers after making a match. The matching algorithms that are currently used are not able to improve the existing matches when new information becomes available; once a match has been made it is fixed. This is called static matching. The opposite of these static matching algorithms are matching algorithms where a made match is not fixed, but can be altered later when new information becomes available. This is called dynamic matching.



Figure 1 The problem cluster

To explain the connections between the problems, a problem cluster is created, see Figure 1. From this problem cluster it becomes clear that the core problem is that the matching algorithms that are currently used do not support dynamic matching. This is the core problem because this problem has no other causes and it is something that can be influenced. Solving the core problem then reduces the loss of potential savings. This is then indicated by an increase in performance compared to the existing, static matching algorithms.

2.2 Problem solving approach

The problem solving approach is twofold. The first part is to design a matching process that does allow for dynamic matching in a real-time, agent-based system and fits into the implementation environment. The implementation environment is the matching-on-a-break-setting. The second part is to evaluate the performance of this new process and to compare it with the old process's performance. Both parts are further described separately.

2.2.1 Designing a dynamic matching process

For this matching process, a matching algorithm is needed that can be used for dynamic matching in a real-time, agent-based system. The algorithm is based on existing literature on truck platooning to support its credibility. In order to do this, five research questions were formulated that need to be answered. These research questions, including the plan to answer them is given below.

1. In which different settings is truck platoon matching researched and what are their (dis)advantages?

This question is answered through a literature review. Existing literature on truck platoon matching is consulted to create an overview of the different settings in which truck platooning is researched, including their (dis)advantages.

2. What matching algorithms are used for truck platoon matching in literature and in which setting are they used?

This question is answered through a literature review. Matching algorithms that have been researched for truck platoon matching and the settings in which they are researched are obtained from literature.

3. Which of the found algorithms is most suitable for dynamic matching in a real-time, agentbased system?

The found algorithms are evaluated on how easily they can be altered to function in a dynamic, real-time, agent-based matching system. Based on this evaluation, one algorithm is chosen to continue working with.

4. How does the chosen algorithm need to be altered so that it fits the purpose of the assignment?

The chosen algorithm needs to be altered so that it fits the purpose of the assignment. This means that the algorithm needs to function in the matching-on-a-break-setting described earlier and needs to support dynamic matching. Which alterations are needed depends on the chosen algorithm.

2.2.2 Testing the performance of the new system

After going through these steps and answering the research questions, a new matching process is built based on an algorithm obtained from literature. The next step is to evaluate its performance and compare it with the existing static matching system to see whether the dynamic matching system is an improvement. This will be done through simulation. To do this the following knowledge problem needs to be answered:

Under which circumstances does the dynamic matching algorithm outperform the static matching algorithm that was previously used and how big is this difference?

This knowledge problem can be split in the following research questions:

5. How to implement the matching processes in a simulation environment?

The matching processes need to be implemented in a simulation environment to measure their performance. The simulation software Plant Simulation will be the most likely candidate for this because of previous experience with this software. A case is needed to test the algorithm. If possible, one of the cases Distribute already has modelled will be used to save time.

6. Which performance indicators need to be used to measure the performance of the matching processes?

Performance indicators need to be chosen to evaluate the performance of the algorithms. These performance indicators should be chosen to represent the performance TNO is interested in.

7. How do the experiments need to be designed?

The experimental design includes the design of the different scenarios that are simulated. It also includes determining the warm-up period, the run-length, the number of replications and the values of the input variables.

8. How does the performance of the dynamic matching process compare to that of the static matching process?

To compare the performance of the dynamic and the static matching process, the results of the experiments are analysed. Statistic procedures are used to determine whether differences are significant.

2.3 Deliverables

The goal of this approach is to deliver a real-time, agent-based matching process for truck platooning with a dynamic matching algorithm that is able to improve existing matches when new information becomes available. The results of the experiments that compare the performance of the new algorithm with the performance of the old algorithms will be delivered as well.

3 Literature review

In this chapter, research question one, two and three are answered. The answers to research question one and two gives an overview of algorithms and matching settings researched in truck platooning literature. Based on this overview, research question three is answered, which choses one algorithm to continue working with. The literature consulted in this chapter is selected through a systematic literature review. A list of the selected literature can be found in Appendix A.

3.1 Different settings for truck platoon matching and their (dis)advantages

In this paragraph the answer to research question one is given: *In which different settings is truck platoon matching researched and what are their (dis)advantages?* A setting in which truck platoon matching takes place can be defined by certain characteristics, for example the moment of matching. Four characteristics were found in literature. For each of these characteristics, different options exist. Each characteristic, its different options and their (dis)advantages are described in this section.

3.1.1 Moment of matching

The moment of matching is described as the moment a platoon plan is created relative to the departure of the matched trucks. Bhoopalam et al. (2018) distinghuis between three different catagories on the moment of matching:

- Scheduled platoon matching: In scheduled platoon matching all trips are known beforehand and so platoon plans can be created before the first trucks start their trips.
- Real-time platoon matching: In real-time platoon matching the platoon plans are created shortly before the trucks start their trips or during the execution of their trips.
- Opportunistic platoon matching: In opportunistic platooning, trucks that drive in the proximity of each other form platoons spontanuously. No platoon plans are created with this form of matching.

Scheduled platoon matching has the advantage that there is more time to create platoon plans, allowing for more complex solution methods that may create better platoon plans. A disadvantage is that even small deviations from the planning, which can be expected in the real world, can disrupt a platoon plan completely. Constantly updating platoon plans is needed to keep a scheduled platoon matching system working (Hoef et al., 2018).

Real-time platoon matching has the advantage that it does not require all information about the trucks' assignments to be available long before departure. A disadvantage of real-time platooning is that platoon plans need to be created within seconds, because trucks will depart soon or are already driving. This means less complex solution methods can be used than with scheduled platoon matching (Larsson et al., 2015).

Opportunistic planning has the advantage that no planning systems are required to form platoons. The absence of these planning systems means however that opportunities to platoon are often missed because trucks are not close enough to each other to form a platoon without planning (Besselink, et al., 2016). Another disadvantage is that in order for opportunistic platoon matching to work, a large number of trucks need to have platooning capabilities, which will not be the case when truck platooning is first introduced to public roads (Bhoopalam et al., 2018).

3.1.2 Decision making

In a matching system there are different options for who makes the decisions on whom platoons with whom. The following three options are considered:

- Central controller: A central controller makes the decisions for all trucks in the system.
- Multiple controllers: There are multiple controllers. Each one makes the decisions for a subset of all trucks in the system. These subsets can be, for example trucks, within a certain geographical area or trucks from a certain company or brand. In the case of subsets based on a geographical area, trucks can switch between subsets during the execution of their trips, because they moved to a different geographical area.
- Agent-based: The truck drivers, or software representing them, decide for themselves who they match with. To make a match the consent of all drivers included in this match is needed.

The advantage of a central controller is that it has an overview of all trucks in the system (Nourmohammadzadeh & Hartmann, 2016). This allows the central controller to work towards a system optimum. A disadvantage is that a large amount of information needs to be processed, this makes it less suitable for real-time platoon matching (Larson et al., 2013).

Multiple controllers have the advantage over a central controller that they can come up with solutions faster because they need to process the information of only a subset of the total trucks. This makes the creation of platoon plans less complex (Larson et al., 2013). A disadvantage is that they might miss profitable opportunities to platoon between trucks in their subset and trucks that are in another subset. This disadvantage is reduced when the subsets are based on the geographical location of the trucks because trucks that are far away from each other are less likely to be profitable platoon partners (Bhoopalam et al., 2018).

An agent-based system consists of agents that pursue their own goals and can act and think autonomous up to a certain degree. They can use basic logic to make decisions and none of the agents has an overview of all information in the system.

In truck platoon matching the agents are the truck drivers. Their goal is to find the most profitable match and they can use basic logic to find this match. Each truck only knows how profitable it is for him to match with each other truck. They do not know which other options another truck has.

The advantage of an agent-based system where the truck drivers make the decision to match is that creating platoon plans becomes even less complex. Each truck driver only looks to make a match for himself. All truck drivers can search for a match simultaneously, allowing for even faster solutions than with multiple controllers. A disadvantage is that truck drivers might make matches that are beneficial for themselves but not for the system as a whole. For the whole system, this may lead to reduced savings compared to a central or multiple controllers.

3.1.3 Starting location of the trucks

In literature, two different options are researched regarding the starting location of the trucks. These two options are:

- All trucks start at the same starting location and the matches are made between these trucks. These trucks have varying departure times and destinations. This situation is referred to as the same-start-platooning-problem. The starting location is not necessarily the starting point of the trucks assignment but can also be the current location of the truck in a real-time matching system.
- All trucks have their own starting locations and matches can be made between trucks at different locations. Some trucks may still start at the same location but this is because of coincidence and not necessary the case.

An advantage of the same-start-platooning setting is that the number of candidates for each truck is greatly reduced, reducing the complexity. Another advantage is that no careful planning is needed to let the trucks meet while driving, since they are already at the same place (Larsson et al., 2015). A disadvantage is that trucks that could be profitable platoon partners may not match this way because they never were at the same matching location.

3.1.4 Static and dynamic matching

The difference between static and dynamic matching has already been discussed in Chapter 2, but will be repeated here for convenience:

- In static matching, once a match has been made and the platoon plan is created it cannot be altered anymore. It is therefore not possible to switch platoons when a better candidate arrives or to wait for a third truck that wants to join a platoon.
- In dynamic matching it is possible to alter an already made platoon plan. For example when a new candidate arrives or new information becomes available.

The advantage of dynamic matching over static matching is the ability to improve matches once they are made. This may lead to a higher performance of the system. The disadvantage is that these improvements are not necessary an improvement for everyone involved. With dynamic matching, a truck driver risks losing his match if his platoon partner finds a better candidate. Dynamic matching therefore leads to increased uncertainty for truck drivers compared to static matching.

3.1.5 Summary

Four characteristics that define the setting in which truck platoon matching takes place are found in literature. For each of this characteristics the different options and their (dis)advantages are discussed. Table 3.1 gives an overview of the found characteristics and their different options.

Characteristic	Options						
Moment of matching	Scheduled	Real-time	Opportunistic				
Decision making	Central controller	Multiple controllers	Agent-based				
Starting location	Same-start-problem	Different starting					
		locations					
Matching type	Static matching	Dynamic matching					

Table 3.1: Overview of the different settings in which truck platoon matching takes place.

3.2 Existing matching algorithms

In this paragraph the answer to research question two is given: *What matching algorithms are used for truck platoon matching in literature and in which setting are they used?* To answer this question, a list of algorithms that are used for truck platoon matching in literature is obtained. This list,

together with a short description of each algorithm, can be found in Appendix B. The static matching algorithms Distribute uses, the best-match-algorithm and the first-come-first-served-algorithm, are also included in this list.

The best-match-algorithm is explained in the introduction. The first-come-first-served-algorithm is an algorithm used by Distribute in the earlier stages of the project. The first-come-first-served-algorithm matches a truck with the first profitable candidate it encounters.

For each of the algorithms it is indicated in which setting they were tested in the literature they were obtained from. These settings are defined by the characteristics found in the previous paragraph. Sometimes an algorithm is tested in multiple settings. The green marks in Table 3.2 show which algorithm has been tested in which setting(s). No algorithms for opportunistic platoon matching are found in literature because opportunistic platoon matching does not require a matching algorithm.

		Ö	Moment of		C	Decision		Starting location	ry pe	Matching
Algorithm	Scheduled	Real-time	Opportunistic	Central controller	Multiple controllers	Agent-based	Same-start	Different- starts	Static	Dynamic
Dynamic-Programming-										
Algorithm (1)										
Platoon-Leader-Algorithm (3,5,9)										
Hub-Heuristic (8)										
Best-Pair-Heuristic (8)										
Intersection-Algorithm (10)										
Genetic-Algorithm (6)										
Best-Match-Algorithm (5,D)										
First-Come-First-Served-										
Algorithm (D)										

Table 3.2: Green marks indicate that an algorithm has been tested in a setting with this characteristic. The number behind an algorithm's name corresponds with the number of the paper it was obtained from, a "D" indicates it was used by Distribute. The corresponding papers are found in Appendix A.

3.3 Choosing an algorithm

In this paragraph the answer to research question three is given: *Which of the found algorithms is most suitable for dynamic matching in a real-time, agent-based system?* As Table 3.2 shows, no algorithm is found in literature that has been tested for dynamic matching in a real-time, agent-based setting. Therefore, each algorithm is evaluated to see whether it can be altered so that it can function in real-time, function in an agent-based system and support dynamic matching.

To function in real-time an algorithm needs to fulfil two requirements. It needs to function without knowing all information in advance, because new information becomes available as time passes in a real-time system. It also needs to find solutions fast enough so that trucks do not waste time waiting

for solutions. Algorithms that do not fulfil these two requirements are deemed unsuitable for a realtime system.

To function in an agent-based system, the algorithm must allow for the truck drivers to make the decision on whom to match with. This is not possible with all algorithms, for example because some algorithms require truck drivers to do what is most beneficial for the total system and not for themselves. It is assumed here that when truck drivers make the decisions, they choose what is best for themselves.

Most of the algorithms that do not support dynamic matching can be altered to support it by rerunning the algorithm each time information changes. The exception is the First-Come-First-Served-Algorithm because the idea behind it is that it stops once a profitable match is found.

Table 3.3 is an variation on Table 3.2 and shows additional information on which algorithms can be altered to function in real-time, function in an agent-based system and support dynamic matching.

	Moment of matching		Decision making			Starting location	rype	Matching		
Algorithm	Scheduled	Real-time	Opportunistic	Central controller	Multiple controllers	Agent-based	Same-start	Different- starts	Static	Dynamic
Dynamic-Programming-										
Algorithm Blateon Loader Algorithm										
Rost Pair Houristic										
Intersection-Algorithm										
Genetic-Algorithm										
Best-Match-Algorithm										
First-Come-First-Served-										
Algorithm										

Table 3.3 Green marks indicate that an algorithm has been tested in a setting with this characteristic. Orange marks indicate that an algorithm can be altered to function in this setting.

Table 3.3 shows that there are three algorithms that can function in the right setting. Two of these are found in literature: the Best-Pair-Heuristic and the Intersection-Algorithm. The other one is currently used by Distribute: the Best-Match-Algorithm.

The Intersection-Algorithm is not chosen because it can only match trucks that approach the same intersection. It cannot be used to match trucks on a matching location, which is needed for the purpose of the assignment.

The two remaining algorithms, the Best-Pair-Heuristic and the Best-Match-Algorithm are very similar. The main difference is that with the Best-Match-Algorithm only new trucks that arrive in the system try to make a match with the trucks that are already there, while in the Best-Pair-Heuristic all trucks are constantly trying to make a match.

Because less opportunities for profitable matches are missed when all trucks constantly try to find a match, the Best-Pair-Heuristic, used by Larrson et al. (2015), is chosen to use as the basis for the design of the new matching system. The Best-Pair-Heuristic is described into detail in the next chapter, together with the alterations that need to be made so that it supports dynamic matching and can function in an agent-based system.

4 Solution design

In the previous chapter the choice for the Best-Pair-Heuristic, used by Larsson et al. (2015), as basis for the design of the new matching process has been motivaded. In this chapter, a detailed description of the Best-Pair-Heuristic is given, after which research question four is answered. The answer to this question shows how the Best-Pair-Heuristic needs to be altered so that it supports dynamic matching and can function in an agent-based system as is the matching-on-a-break setting. To conclude this chapter, a detailed description of both the old and the new matching processes are given, together with a comparison.

4.1 The Best-Pair-Heuristic

In this paragraph a step-by-step description of the Best-Pair-Heuristic is given as it was used by Larsson et al. (2015). The performance of this algorithm was also tested by them, the results of which are discussed here.

4.1.1 Algorithm description

The Best-Pair-Heuristic matches the trucks or existing platoons that can save the most from platooning together first. It then matches the trucks or platoons that can save the most, given that the first match is already made. It continues doing this until no more profitable matches can be made. Pseudocode for the algorithm is presented in Algorithm 1.

Algorithm 1:

The Best-Pair-Heuristic uses the following information as input: a Graph G, a set of trucks T. Each truck $t \in T$ has its own starting point s on G, its own destination d on G. (When a same-start-platooning- problem is solved, s is the same for all trucks.)

- 1. define platoon as: p(starting point of platoon, destination of platoon, set of trucks)
- 2. define P as set of p
- 3. $P \rightarrow \{\}$
- 4. For each t and corresponding s, d and r Do
- 5. add to P: p(s, d, t)
- 6. End
- 7. While savings can be achieved with merging Do
- 8. the platoons that can save the most by merging $\rightarrow p_1$, p_2
- 9. the merging and splitting point of p_1 and $p_2 \rightarrow v_1, v_2$
- 10. add to P: a new platoon $p(v_1, v_2, all t of p_1 and p_2)$
- 11. End

The algorithm starts by defining each truck as a single-truck-platoon, with a starting point, a destination and the truck itself (line 1 to 6). It then looks whether two single-truck-platoons can save money by merging together for the overlap of their route (line 7). When this is the case the two (single-truck-)platoons that can save the most are selected (line 8). The merging and splitting point of the overlap in their routes are determined (line 9). A new platoon is added to the set that starts at the merging point and ends at the splitting point and contains the two trucks.

4.1.2 Performance

The Best-Pair-Heuristic has been tested on a graph that represents the German Autobahn network. The performance was measured as the percentage of fuel that was saved compared to a situation in which all trucks drove alone for their entire journey. The Best-Pair-Heuristic has been tested on the same-start platooning problem for up to 200 trucks with random destinations around the network. The solutions were compared with those of an exact solution method that took a lot more time to generate a solution. In the majority of the cases the Best-Pair-Heuristc was able to find solutions close to the exact solution. However it sometimes found solutions that were a lot lower than the exact solution. No clear indication as to when this occurs was found. It is expected to happen when the Best-Pair-Heuristic makes irreverisble decisions early in the matching process that are far from the optimal solution (Larsson et al., 2015).

4.2 Alterations to the Best-Pair-Heuristic

The Best-Pair-Heuristic as described in the previous paragraph forms the basis around which the new matching process is designed. Some alterations need to be made so that the algorithm fits the purpose. This is done by answering research question four: *How does the chosen algorithm need to be altered so that it fits the purpose of the assignment?* Two of these alterations have been introduced: The algorithm needs to support dynamic matching and the algorithm needs to become agent-based.

From this point the Best-Pair-Heuristic is only considered in a setting with a same-start-platooning problem since this is the setting in which it is used. This makes it easier to do the proposed alterations.

4.2.1 Supporting dynamic matching

The Best-Pair-Heuristic as described in Algorithm 1 does not support dynamic matching, since there is no way to improve existing matches when the set of trucks T changes. This happens when a new truck arrives at the matching location.

To make the improving of matches possible, existing matches must be allowed to be broken up. The Best-Pair-Heuristic can then be rerun every time a new truck arrives at the matching location, generating a new solution. If a match that existed in the old solution does not exist in the new solution, because one of the trucks found a better match, it is deleted.

4.2.2 Agent-based matching for two-truck-platoons

In its current form, the decision making in the Best-Pair-Heuristic is done by a central controller who has the information of all trucks at the matching location. It is possible to let the truck drivers, make the decisions and come to the same solution as when a central controller uses the Best-Pair-Heuristic. In this paragraph, this is first proven for a situation where only two-truck-platoons can be formed. To achieve this the following requirements need to be fulfilled:

- 1. A truck driver knows how much he, himself, can save with each of the other trucks at the matching location. He does not know how much two other truck drivers can save if they platoon with each other.
- 2. A truck driver can switch matches as often as he wants without penalties.
- 3. A truck driver wants to maximize their own earnings.
- 4. The earnings of a platoon are divided equally amongst the participants.

To show that under this requirements an agent-based system would lead to the same solution as a central controller using the Best-Pair-Heuristic, a so called toy-problem is solved using both methods in the next paragraph.

4.2.3 Toy Problem 1

In this paragraph an example problem called Toy Problem 1 is described. Toy Problem 1 is then solved with both the Best-Pair-Heuristic and the agent-based approach described in the previous paragraph to show that both methods lead to the same solution.

Toy Problem 1:

Four trucks, truck A, B, C and D, stand on a matching location. No matches have been created yet and the maximum platoon size is two trucks. After a solution is found for truck A, B, C and D, truck E arrives. Now a new solution needs to be found that includes truck E. Table 4.1 shows how much a truck (row) can save if it platoons with each other truck (column), since the earnings of a platoon are equally divided amongst the two trucks the table is symmetrical. A green mark indicates a trucks' most profitable match. In the first part of the problem truck E has not arrived yet and so the last row and column are ignored.

Ϊ	Α	В	С	D	Ε
Α	Х	4	0	0	0
В	4	Х	7	0	0
С	0	7	Х	10	0
D	0	0	10	Х	15
Ε	0	0	0	15	Х

Table 4.1 An overview of the savings each truck can achieve when it platoons with another truck

Best-Pair-Heuristic solution to Toy Problem 1:

The Best-Pair-Heuristic creates the match with the highest earnings first. This is the match between truck C and D since they can earn €20 in total. The most profitable match, given that C and D are already matched is then truck A and B. The solution is:

- A and B platoon together.
- C and D platoon together.
- The total earnings are €8 + €20 = €28.

When truck E arrives the Best-Pair-Heuristic starts again from the beginning, ignoring all made matches. Truck D and E are matched first since they can save €30 in total. Truck B and C are matched next because they can earn €14 together, which is more than the €8 that truck A and B can earn together. There is no profitable match left for truck A so he drives alone. The solution is:

- A drives alone.
- B and C platoon together.
- D and E platoon together.
- The total earnings are €14 + €30 = €44.

Agent-based approach solution to Toy Problem 1:

In the agent-based approach truck B wants to save money and therefore asks truck C to platoon together. Truck C says no because he knows he can save more with truck D. Truck D says yes to truck

C because he has no options that are more profitable. Truck B then asks truck A because this is the most profitable candidate left for him. Truck A says yes because he has no better options. The solution is the same as with the Best-Pair-Heuristic:

- A and B platoon together.
- C and D platoon together.
- The total earnings are €8 + €20 = €28.

When truck E arrives he asks truck D to platoon with him since this is his most profitable option. Truck D says yes because he can save more with truck E than with truck C and he can get out of his match with C without costs. Truck C than asks truck B because this is for him the most profitable option left. Truck B says yes because he can save more with truck C than with truck A. Truck A than ends up alone. The solution is still the same as with the Best-Pair-Heuristic

- A drives alone.
- B and C platoon together.
- D and E platoon together.
- The total earnings are €14 + €30 = €44.

4.2.4 Toy Problem 2

The requirements given in section 4.2.2 guarantee that the Best-Pair-Heuristic and the agent-based approach generate the same solution when the maximum platoon size is two. That this is not the case when the maximum platoon size is three or higher is shown by the following example, called Toy Problem 2. This problem is also solved with the Best-Pair-Heuristic and the agent-based approach to show that this leads to different solutions.

Toy Problem 2:

Three trucks, called truck A, B and C stand on a matching location. No matches have been made yet. The maximum platoon size is three. The savings of each possible platoon are given in Table 4.2.

Platoon	Platoon earnings	Earnings per truck
A-B	€20	€10
A-C	€15	€7.50
B-C	€10	€5
A-B-C	€24	€8

Table 4.2 An overview of the earnings each possible platoon can achieve

Best-Pair-Heuristic solution to Toy Problem 2:

The Best-Pair-Heuristic first matches trucks A and B, because this increases the total earnings the most. Truck C is then matched with A and B because this increases the total savings with €4. The solution is:

- A, B and C platoon together.
- The total earnings are €24.

Agent-based approach to Toy Problem 2:

With the agent-based approach truck A choses truck B first and vice versa. Truck C wants to join this platoon but A and B do not want this because their personal earnings decrease from €10 to €8. A different solution is found than when the Best-Pair-Heuristic is used:

- A and B platoon together.
- C drives alone.
- The total earnings are €20.

4.2.5 Agent-based matching for three-truck-platoons

Toy Problem 2 shows that for three-truck-platoons the Best-Pair-Heuristic and the agent-based approach do not always generate the same solution. The difference occurs because the Best-Pair-Heuristic chooses the match with the highest increase in total earnings, while with the agent-based approach, trucks choose the match with the highest personal earnings. This is no problem with two-truck-platoons because the personal earnings are there always half of the total earnings. This means that the match with highest increase in personal earnings is also the match with the highest increase in total earnings. With three-truck platoons however, this leads to different solutions as shown in Toy Problem 2.

To solve this problem, the way the earnings are divided amongst the participants needs to be changed. This division needs to be done in such a way that the searching truck's earnings are half of the total increase in earnings in each situation, since that leads to the same solution as the Best-Pair-Heuristic. To achieve this the fourth requirement in paragraph 4.2.2 is removed and replaced with a new requirement. The new list of requirements looks like this:

- 1. All truck drivers know how much they can save with each of the other trucks on the matching location.
- 2. All truck drivers can switch matches as often as they want without penalties.
- 3. All truck drivers want to maximize their own earnings.
- 4. A truck that wants to join a single truck or existing platoon gets half of the increase in total earnings. The other half is for the single truck or divided amongst the trucks that were already in the platoon.

To demonstrate the effect of this new way of dividing the earnings, Toy Problem 2 is solved again using the agent-based approach, with the new way of dividing the earnings.

Agent-based approach solution to Toy Problem 2, with new earnings division:

With the agent-based approach truck A choses truck B first and vice versa. Truck C wants to join this platoon, which would earn him €4. Truck A and B both earn €1 extra if truck C joins them, so they agree. The found solution is now the same as the solution found with the Best-Pair-Heuristic:

- A, B and C platoon together.
- The total earnings are €24.

4.3 Overviews of the old and the new matching process

In the previous part of this chapter, design choices for the new matching process have been motivated with the use of example problems. In the remaining of this chapter, an overview of both the old and the new matching system is given using flowcharts, after which they are compared.

4.3.1 The old matching process

In the old matching process, trucks search for a platoon match through the process described in the flowchart in Figure 2. In the old matching process, existing matches cannot be broken up. Therefore, a truck starts the searching process only when it arrives at the matching location. The process is further explained in Figure 2.



Figure 2 Flowchart of the old searching process of a truck at the matching location.

In Figure 2, the word truck refers to the searching truck that initiated the searching process. The word candidate refers to another truck at the same matching location. The searching truck starts by creating a candidate list, containing all trucks at the matching location. It then calculates whether it is

profitable to platoon which each of the trucks on the candidate list. If a profitable candidate is found that is not in a platoon he is added to the matches list. If a profitable candidate is already in a platoon, but the platoon has not reached its maximum size, the searching truck calculates whether it is profitable for all the platoon members if he joins the platoon. If this is the case the candidate is added to the matches list.

Once all candidates have been either added to the matches list or have been discarded, the matches list is sorted from most profitable to least profitable. The truck than matches with the truck on top of the list or joins this trucks platoon. When no profitable match is found, the matches list is empty.

4.3.2 The new matching process

In the new matching process, trucks search for a platoon match through the process described in the flowchart in Figure 3. In the new matching process a truck starts the searching process when it is triggered by one of the following two events:

- The truck arrives at the matching location.
- The truck's existing match is broken up, leaving the truck with no platoon partner.



Figure 3 Flowchart of the new searching process of a truck at the matching location.

In this flowchart the word truck refers to the searching truck that initiated the searching process. The word candidate refers to another truck at the same matching location. The truck first goes through the list of all candidates. If the truck can achieve positive earnings with a candidate, the candidate is added to the matches list. Once all candidates have been added or excluded from the matches list, the process continues.

Because the truck wants to maximize his earnings, he first tries to platoon with the candidate on the matches list with the highest earnings. If this candidate is not in a platoon a match is created. If the candidate is already in a platoon, the truck asks the candidate to switch platoons, which the candidate agrees to if this is beneficial for him, regardless of whether his current platoon is full.

Otherwise the truck checks whether there is room left to join the candidate's platoon and whether this is more beneficial for him than platooning with the next candidate on the list. When there is both room left and the earnings of joining the candidate's platoon are higher than those of the next candidate on the list, the truck joins the platoon. Note, that it is no longer required to check whether all members of the candidate's platoon benefit from the truck joining the platoon. Because of the new way the earnings are divided, their earnings can only increase.

Joining a platoon is only possible when the maximum platoon size is three or higher. When the maximum platoon size is two, the answer to the question "Platoon full?" is always yes.

4.3.3 Calculating the earnings if a truck joins a platoon

If a truck joins an existing platoon, the new earnings need to be calculated. This is more complicated than calculating the earnings of a new (two-truck-)platoon. This subsection explains the difficulties of adding a truck to an existing platoon.

Four different scenarios can arise if a truck joins a platoon, depending on the departure time of the truck, relative to that of the platoon, and whether the overlap in route between the truck and one of the platoon members is larger than the platoon distance. The platoon distance being the overlap in route between the platoon members themselves. The different scenarios and the extra costs and savings that they generate are displayed in Table 4.3.

		Largest overlap in route between joining truck and a platoon member					
		< platoon distance	> platoon distance				
		Extra costs:	Extra costs:				
_		waiting costs truck	waiting costs truck				
ru		Extra savings:	Extra savings:				
ck's	> platoon's	increased savings for part of the	increased savings for the whole of				
de	departure time	platoon's route	the platoon's route.				
par		Extra costs:	Extra costs:				
tu		increased waiting costs for all	increased waiting costs for all				
e t		platoon members	platoon members				
im		Extra savings:	Extra savings:				
Ū	< platoon's	increased savings for part of the	increased savings for the whole of				
	departure time	platoon's route	the platoon's route				

Table 4.3 Overview of the different scenarios that can occur if a truck joins an existing platoon

Although slightly more complicated than calculating the earnings of a new platoon, this does not provide any real problems. The real difficulty is that if a truck has a larger overlap with one of the platoon members than the platoon distance, he can form a new platoon with this platoon member immediately after the original platoon splits up. The earnings of this second platoon influence the decision of the truck to join the first platoon. Although not impossible, taking these into account makes the matching process a lot more complex. Because of time constraints this subject is not discussed in this research.

4.3.4 Differences between the old and the new matching processes

In this section the most important differences between the old and new matching process are listed:

- In the new matching process it is possible to break up an existing match to form a better match.
- Because trucks can lose their existing match, trucks do not only start searching for match when they arrive at the matching location but also when they lose their existing match.
- The earnings of a three-truck-platoon are divided in a different way in the new matching process compared to the old matching process
- Because the savings are divided in a different way, members of a two-truck-platoon cannot see a decrease in their earnings if a third truck wants to join their platoon. Therefore a situation where members of a two-truck-platoon do not want a third truck to join their platoon no longer occur.

5 The simulation model

In the previous chapter the new matching process was described and compared with the old process. In this chapter, the performance of these two processes is made measurable. This is done by answering research question five, that shows how the matching process is implemented into simulation software, and research question six, that makes the performance of the processes measurable. The chapter is concluded with the validation of the simulation model.

5.1 Implementation in a simulation environment

In this subchapter, the answer is given to research question five, *How to implement the matching processes in a simulation environment?* To save time, one of the models Distribute already used for this project is altered for the purpose of this assignment. The simulation software that is used is Plant Simulation 14. The altered simulation model is described in the rest of this chapter. A list of the alterations that have been made to the original simulation model can be found in Appendix C.

As described in the previous chapter, the complexity of a platoon matching process increases by a large degree when the maximum platoon size is increased beyond two. Because of the time constraints of this research, the matching processes are only simulated with a maximum platoon size of two.

5.1.1 The matching location

To simulate the matching processes, a matching location is needed. The real-world location "Maasvlakte Plaza", or Plaza for short, is used for this purpose. The Plaza is a truck stop located on the Maasvlakte 2 area in the port of Rotterdam in the western part of the Netherlands. Truck drivers, who need to visit the port of Rotterdam, can take their obligatory rest periods here.



Figure 4 The Maasvlakte Plaza as it is modelled in the simulation model

Figure 4 shows the layout of the Plaza in the simulation model. The trucks enter the figure at (A), after which they continue this road until they arrive at the entrance of the Plaza (B). At (B) the arriving trucks searches for a match to platoon with. When he has completed his search, whether he

is successful or not, he goes to one of the parking spots in **(C)** and takes his break. When it is time for a platoon to leave, the first truck goes to **(D)** and waits there until the platoon is complete. Once the platoon is complete they start their journey and leave the figure at **(F)**. A truck that leaves the Plaza alone exits the parking lot through **(E)** as to not receive hinder from uncomplete platoons that are waiting. The trucks that leave alone also exit the figure at **(F)**.

5.1.2 The trucks

In this simulation, the trucks and the truck drivers are one entity, which is referred to as a truck. Each truck that arrives at the Plaza has two goals. His first goal is to take his obligatory break, which is modelled in the simulation as the truck standing still for the duration of the break. His second goal is to find a platoon partner with whom he can achieve the highest positive earnings. A truck always achieves his first goal, but a truck might fail to find a platoon partner with whom he can achieve positive earnings and leave alone.

The earnings of a platoon are calculated by subtracting the platoon costs from the platoon savings. The platoon savings consists of the fuel savings and potentially the wage savings, both depend on the length of the overlap in route between two trucks. The platoon costs consist of the waiting costs one truck has to make to wait for the other truck, which depends on the deviation in departure time between the two trucks.

The overlap in route between two trucks depends on the destinations of the trucks. Each truck has a destination that is chosen from a list of fifteen different options. Each option is a region or city in Western-Europe.

5.1.3 Input data and input variables

TNO provided data obtained from the NDW, which is used for this simulation model. The intensity with which trucks arrive at the Plaza is modelled so that it represents the NDW data during rush-hour. The different destinations of the trucks are chosen with an intensity, so that it represents the NDW data as close as possible.

To calculate the overlap in routes for trucks with different destinations an origin/destination matrix is used, that shows the overlap in route between two destinations. This matrix is also provided by TNO.

There are a number of input variables that influence the benefits and costs of a platoon. These include the percentage of fuel a platooning truck saves, the hourly wage of a truck driver and the fuel price. A complete list and description of these variables and their values can be found in Appendix D.

5.2 Performance measurement

In this subsection, the answer is given to research question six, *which performance indicators need to be used to measure the performance of the matching processes?* The performance of a platoon matching process can be defined in many different ways. Since the goal of the Truck Platoon Matching project is to obtain insights for TNO in truck platoon matching, the performance indicators need to be chosen so that they represent the interests of TNO.

TNO's main areas of interest are the quantity with which platooning technology can be used and the financial benefits that can be achieved. The performance indicators therefore need to be chosen so that they represent these interests. In addition to this, another point of interest is the influence of

the switching of platoons on the individual trucks. To get insights in this influence, statistics on the switching of platoons are also gathered.

5.2.1 The quantity of platoons

To measure the quantity with which platooning technology is used, the following two performance indicators are used:

- The percentage of trucks that leave the Plaza in a platoon. This provides insights in the number of trucks that use platooning technology.
- The average kilometres per platoon. This measures how much the trucks use platooning technology. (Note that if two trucks platoon together for 50 kilometre, the total of platooned kilometres for that platoon is 100, since both trucks platooned for 50 kilometres.)

5.2.2 The financial benefits

The financial benefits of truck platooning can be measured at multiple levels. Three performance indicators are used to measure the financial benefits:

- The average earnings per platooned kilometre. The savings that are achieved per platooned kilometre consist of the fuel and wage savings, which are fixed per kilometre. The earnings per kilometre therefore only change because of varying platoon costs. (Note that if two trucks platoon together for 50 kilometre the total of platooned kilometres is 100, since both trucks platooned for 50 kilometres.)
- The average earnings per platoon. The earnings of a platoon are the sum of the earnings of all platoon members.
- The earnings per hour. These are equal to the sum of the earnings of all platoons that are created at the matching location in an hour.

5.2.3 The influence of switches

To provide insights in the influence of switches on the individual trucks, the following information is collected:

- The distribution of the number of times a truck loses his match during his stay at the Plaza: This tells which percentage of the trucks gets dumped zero times, one time, two times etc.
- The percentage of the trucks that at some point had a match but in the end leave the Plaza alone: The reasoning behind this measurement is that it is assumed that a truck driver experiences losing his match as a bigger loss if he is unable to find a replacement match.

5.3 Validation of the simulation model

To increase confidence in the simulation model, validation is needed. Robinson (2014) distinguishes two types of validation, black-box validation and white-box validation. Black-box validation compares the output of the model with the real world data. The problem with black-box validation, in this case, is that there is no real-world data to compare the simulation output against, neither are their accurate predictions which can be used for comparing. White-box validation checks the insights of the simulation model.

Multiple methods exist for white-box validation. Besides checking the code, visual checks have been used. Used visual checks include: the tracing of single trucks through the model; pausing the model and predicting the short term future; creating extreme conditions to and see whether the model behaves as expected. The model behaved as expected through the visual checks, increasing the confidence in the simulation model.

6 Experimental design

In this chapter the different scenarios in which the experiments are conducted are described as well as the different experimental settings. The warm-up-period of the simulation model and the run length of the experiments are determined as well.

6.1 Experiment scenarios

Experiments are conducted with three different scenarios. In the first scenario the old, static matching process is used. The other two scenarios use the new, dynamic matching process, but the last scenario uses extra restrictions on the switching of platoons.

Scenario A: The static matching process. This scenario uses the old, static matching process as shown in Figure 2. Switching platoons is not possible at all in this scenario.

Scenario B: The unrestricted dynamic matching process. This scenario uses the new, dynamic matching process as show in Figure 3. There are no restrictions on or penalties for switching platoons in this scenario.

Scenario C: The restricted dynamic matching process. This scenario is similar to scenario B, but in this scenario it is no longer possible for a truck to switch platoons if the truck with whom he has a match has already started waiting past his own departure time, and therefore making extra costs. This restriction takes away the risk for trucks of waiting for nothing.

6.2 Input variables for the experiments

Although truck platooning has the possibility to achieve savings on the wages of the truck drivers, this is not expected to be possible when truck platooning is first used in commercial road transport. To see whether the new matching system is an improvement overall it should therefore be tested in a situation with and without the possibility to save wages. Each of the scenarios will therefore be simulated for a situation in which 90 percent wage savings are achieved for each of the following truck drivers in a platoon and a situation in which no wage savings are achieved. This means that six experiments will be conducted, for an overview see Table 6.1.

Experiment	Scenario	Wage savings
1	А	90%
2	В	90%
3	С	90%
4	А	0%
5	В	0%
6	С	0%

Table 6.1 Experiments overview

The other input variables are chosen as to represent the real-world as close as possible. The values of these variables can be found in Appendix D. Each experiment is run with the same random numbers and the values of the performance indicators are calculated after each hour.

6.3 Warm-up period

Before experiments can be conducted the initialisation bias needs to be dealt with. Robinson (2014) proposes two ways to do this. The first option is to use a warm-up period at the beginning of the simulation during which no output data is collected. The second option is to set initial conditions for the simulation model so that the model starts in a realistic state.

Because of the difficulty of determining realistic initial conditions, a warm-up period is used. To determine the length of the warm-up period a MSER procedure was run. For this procedure scenario B was simulated for a 48 hour time period. Scenario B has been used to determine the warm-up period because it is expected that, because of the lack of restrictions on switching platoons, this scenario takes the longest to reach a steady state.

After running the MSER procedure, a warm-up period of eight hours was found. Details on the execution of the MSER procedure can be found in Appendix E.

6.4 Run length

Because of the significant warm-up period, a single long run is performed for each scenario. This has the advantage over multiple replications that the warm-up period needs to be run only once for each scenario.

To determine the length of this single long run, the convergence method proposed by Robinson (2014) is used. With this method, the required run length for each performance indicator can be determined through three replications. The performance indicator that requires the longest run length determines the run length.

Using the convergence method, a run length of 24 hours was found. This is extended with a 50 percent safety margin. Including the earlier found warm-up period of eight hours, each experiment is simulated for 44 hours. Details of the execution of the convergence method can be found in Appendix F.

7 Experiment results

In the previous chapter the experimental design has been described. In this chapter the results of the experiments are analysed. This provides the answer to research question eight, *how does the performance of the dynamic matching process compare to that of the static matching process?* The analysis of the results is split in two parts. First all three scenarios are compared on the scores of the performance indicators, for both the situation with 90 percent wage savings and the situation without wage savings. After this, scenario B and C are compared on the switching statistics to see the influence of the restriction on switching. This chapter ends with a summary of the findings.

7.1 Comparing the different scenarios on performance

Table 7.1 provides a summary of the numerical results of the experiments. This summary includes the mean and variance of each performance indicator for each experiment.

For the situation without wage savings there is no difference in data between scenario B and C. This is because of the lower savings that can be achieved without wage savings, it is not profitable to wait for a long time. Resulting in trucks only matching with trucks with similar departure times. The waiting times are so low that the restriction on switching is never used to prevent a switch, resulting in the same output data as scenario B.

		90 Percent Wage Savings			e Savings No Wage Savings		
					Scenario	Scenario	Scenario
Performance indicator	Statistic	Scenario A	Scenario B	Scenario C	А	В	С
Dercontago in Platoon	Mean	92.7%	83.7%	90.5%	54.1%	56.2%	56.2%
	St. Dev.	3.99%	7.16%	5.57%	7.57%	6.78%	6.78%
Average Distant KMc	Mean	151.9	233.8	223.8	208.7	235.1	235.1
Average Platoon Kivis	St. Dev.	17.60	34.50	30.21	38.21	45.51	45.51
Farnings nor hour	Mean	€ 772.85	€ 1,224.73	€ 1,231.82	€ 24.64	€ 35.93	€ 35.93
Earnings per nour	St. Dev.	123.67	194.58	191.15	7.34	10.30	10.30
Fernings nor Distant	Mean	€ 33.24	€ 58.62	€ 54.29	€ 1.82	€ 2.52	€ 2.52
Earnings per Platoon	St. Dev.	5.05	9.46	7.82	0.51	0.58	0.58
Earnings per Platooned	Mean	€ 0.2180	€ 0.2503	€ 0.2424	€ 0.0087	€ 0.0107	€ 0.0107
KM	St. Dev.	0.01090	0.00766	0.00558	0.00166	0.00125	0.00125

Table 7.1 Numerical results. Red indicates a decrease in performance compared to scenario A. Green indicates an increase in performance compared to scenario A.

To see whether the differences between the scenarios are significant, confidence intervals are used. For each performance indicator, 95 percent confidence intervals are made for the difference between each of the scenarios. This means that, for both the situation with 90 percent wage savings and the situation without wage savings, three confidence intervals are made for each performance indicator. One for the difference between scenario A and B, one for the difference between A and C and one for the difference between B and C. To account for correlation in the data from consecutive hours, the batch mean method is used (Robinson, 2014). A batch size of three hours is used, resulting in thirteen batches. Details on the calculation of the confidence intervals can be found in Appendix G.

The results for the situation with 90 percent wage savings can be found in Table 7.2. For the situation without wage savings the results can be found in Table 7.3. Each scenario is given a rank for each performance indicator. The ranks are as follows:

- Initially each scenario is given the rank one.
- If a scenario scores significantly lower on a performance indicator than another scenario, it is given the rank two for that performance indicator.
- If a scenario scores significantly lower on a performance indicator than both other scenarios, it is given the rank three for that performance indicator.



Table 7.2 Ranks for situation with 90 percent wage savings

Scenario B outperforms scenario A on the performance indicators that measure the average quality of a match (average kilometres per platoon, earnings per platoon an earnings per platooned kilometre). Of these performance indicators, the earnings per platoon show the largest improvement. On average, the earnings per platoon increase with 76 percent when dynamic matching is used. It is therefore concluded that the unrestricted dynamic matching process, on average, creates higher quality matches than the static matching process.

Scenario A outperforms scenario B on the percentage of trucks that leave in a platoon, with on average nine percent. Showing that more matches are created with the static, than with the dynamic matching process. However, the increased quality of the matches created with the dynamic matching process is high enough to compensate for the reduction in the number of matches with respect to the total earnings created at the matching location. This becomes clear from scenario B outperforming scenario A on the earnings per hour. On average scenario B generates 58 percent more earnings per hour.

The restriction on switching platoons that has been added in scenario C has a negative influence on the average quality of the matches compared to scenario B, where there are no restrictions. The restricted dynamic matching process however, creates better matches than the static matching process.

The restriction on switching platoons reduces the negative influence of the dynamic matching process on the percentage of trucks that leave in a platoon, showing no significant difference with the static matching process. The increase in the percentage of trucks that leave in a platoon compared to the unrestricted dynamic matching process compensates for the reduced quality of the matches with respect to the earnings per hour. The earnings per hour do not differ significantly between scenario B and C.

Rankings with No Wage Savings								
Scenario	Percentage in Platoon	Average Platoon KMs	Earnings per hour	Earnings per Platoon	Earnings per Platooned KM			
Α	1	3	3	3	3			
В	1	1	1	1	1			
С	1	1	1	1	1			

Table 7.3 Ranks for situation without wage savings

Comparing scenario A and B, results in the conclusion that also without wage savings the dynamic matching process produces on average more profitable matches. There is however no reduction in the percentage of trucks that leave the Plaza in a platoon between these two matching processes in the situation without wage savings. A significant increase in the earnings per hour is therefore found when comparing scenario A and B.

As is mentioned earlier, there is no difference in output data between scenario B and C for the situation with no wage savings. All comparisons drawn between scenario A and B therefore also apply to the comparison of scenario A and C.

7.2 The influence of restrictions on switching

In this paragraph the effect of the restricted switching on the individual trucks is analysed. Because the restriction has not made a difference in the situation without wage savings, the analysis is limited to the situation with 90 percent wage savings.



Figure 5 Graph of switching statistics

Figure 5 shows which portion of the trucks loses his match how many times for both the unrestricted and restricted switching. With unrestricted switching a truck loses his match on average 0.60 times. With restricted matching this is 0.53 times, a marginal improvement.

A much larger improvement is found in the percentage of trucks that are not successful in finding a new match once they lose theirs. With unrestricted matching 12.2 percent of the trucks that loose their match end up leaving the plaza alone. With restricted matching this is only 6.7 percent. Restricted matching therefore reduces the number of trucks to whom this happens by 45 percent.

7.3 Sensitivity analysis

Each experiment has been conducted with the arrival intensity of the trucks representing the NDW data during rush-hour. In reality the arrival intensity of the trucks varies. To determine how a change in arrival intensity influences the performance of the system a sensitivity analysis has been performed. Scenario A and B have been simulated with a ten percent decrease and with a ten percent increase in arriving trucks, with 90 percent wage savings. The results of these experiments are compared with the results of the experiments with the standard number of trucks arriving in Table 7.4.

	Static matching			Dynamic matching		
Arriving trucks	-10%	100%	+10%	-10%	100%	+10%
Performance indicator						
Percentage in Platoon	-1.0%	0.927	-0.2%	-1.3%	0.837	+1.8%
Average Platoon KMS	+2.1%	151.9	-0.7%	+0.8%	233.8	-0.8%
Earnings per hour	-9.5%	772.85	+8.7%	-11.2%	1224.73	+11.1%
Earnings per Platoon	+1.6%	33.24	-1.1%	+0.3%	58.62	-1.0%
Earnings per Platooned KM	-0.8%	0.2180	-0.2%	-0.5%	0.2503	-0.1%

Table 7.4 The relative performance of the experiments compared to the normal arriving intensity.

Decreasing or increasing the arrival intensity by a small number has little influence on the quality of the matches. The earnings per platoon do not change more than 1.6 percent. The chance to find a platoon partner does not change a lot either, 1.8 percent at most. The only performance indicator to show large changes are the earnings per hour. This is because the earnings per hour are a function of the earnings per platoon, the percentage of trucks that forms a platoon and the number of trucks that arrive at the Plaza. Since the first two factors are barely influenced by the decrease in the number of trucks, this decrease must affect earnings per hour.

Although the earnings per hour are largely influenced by the arriving intensity of the trucks. The influence on an individual truck is really low. The truck's expected earnings do not change by a lot.

7.4 Summary of findings

To summarize the findings it can be said that the dynamic matching process improves the average quality of the matches at the costs of a small reduction of the number of formed platoons. The increased quality of the matches by the dynamic matching process is however large enough to greatly increase the earnings per hour compared to the static matching process.

A restriction on the switching of platoons reduces the quality of the matches a little, but has a positive effect on the number of matches created. This results in earnings per hour comparable to the unrestricted dynamic matching process. The restriction has a marginal effect on the total number of switches, but reduces the percentage of trucks that cannot find a new match after losing theirs by almost half.

8 Conclusions, discussion and recommendations

The answers to the research questions are summarized in the conclusion. In the discussion the limits of this research are discussed. This chapter ends with recommendations for further research.

8.1 Conclusions

The goal of this research was to design a dynamic matching process for real-time truck platoon matching in an agent-based environment. The performance of this dynamic matching process needed to be compared with that of an already existing static matching process.

Through a literature review, the different settings in which truck platoon matching is researched have been defined based on four characteristics: the moment of matching, the decision making, the starting location and the type of matching. The (dis)advantages of each setting have been identified.

This information has been combined with a list of matching algorithms found in platooning literature to decide which algorithm is most suitable for dynamic matching in a real-time, agent-based system. The Best-Pair-Heuristic used by Larrson et al. (2015) has been chosen as the most suitable. The Best-Pair-Heuristic has been altered so that it supports dynamic matching and functions in an agent-based environment, to fit the purpose of this research.

The performance of the new dynamic matching process was compared with that of the static matching process through simulation. To save time, an existing simulation model was altered and reused. The performance of the process was measured through various indicators focussing on both the quality and quantity of the matches that were created.

In a situation with wage savings, platoons created with the dynamic matching process have, on average, 76 percent more earnings than platoons created with the static matching process. With the dynamic matching process 84 percent of the trucks find a platoon partner, compared to 93 percent with the static matching process. This high increase in the earnings per platoon, together with the relative small decrease in the number of platoons, result in the dynamic matching process generating 58 percent more earnings per hour compared to the static matching process.

When there are no wage savings, the dynamic matching process creates matches with, on average, 38 percent more earnings, but without a reduction in the quantity of the matches. In this case the earnings per hour increase with 46 percent.

The dynamic matching process has also been simulated with restrictions on the switching of platoons. This lead to a slightly lower quality of matches compared to unrestricted switching. The quantity of the matches was however slightly increased resulting in similar earnings per hour. This restriction reduced the number of trucks that loose their match and are unable to find a new match with 45 percent.

8.2 Discussion

The new matching process has been designed based on existing literature on truck platoon matching. Truck platoon matching is however a relative new subject in literature. It should therefore be considered that better matching algorithms and setting for matching might exists but have not been researched yet in the setting of truck platoon matching. In the experiments conducted in this research a maximum platoon size of two trucks has been used to reduce the complexity of the problem. The expected maximum platoon size in real-world situations is larger than two. The effects of a larger maximum platoon size on the performance of the dynamic matching process are unknown.

The performance of the matching processes has only been measured at one matching location. It is therefore not known how the specific characteristics of the matching location influence the performance of the matching process.

Only one restriction on the switching of platoons has been tested. Other restrictions might exist that provide more certainty to truck drivers or have a less negative impact on the quality of the matches. Possible restrictions could be:

- A monetary penalty for switching platoons. The height of this penalty can be time dependent, with higher penalties for switching platoons last-minute. The height of the penalty can also depend on the earnings of the lost match.
- A restriction on the number of times a truck can switch platoons.

The simulation model can be used to understand how different restrictions affect the performance of the matching process. However, the way different restrictions influence the experience of the truck drivers is not known and should be researched in another way.

8.3 Recommendations for further research

The following recommendations have been derived from this research:

- The research should be extended to the performance of the matching processes with a maximum platoon size larger than two, since this can be expected in the real world.
- Research into the influence of matching location specific variables. The distribution of destinations, the length of their brakes etc. on the performance of the system. This information is needed when assessing the suitability of a real-world location as a matching location.
- Modelling the arriving intensity of the trucks so that it varies during the day, representing the real-world would provide a more realistic view of the long term profits that a matching location can generate.
- The simulation model can be used to determine how different restrictions on the switching of platoons affect the performance of the matching process.
- It is currently not known how truck drivers react to the uncertainty that comes along with a dynamic matching process. This knowledge can be used to develop specific restrictions on the switching of platoons that minimize the impact on the truck drivers, while maximizing the earnings that can be achieved.

References

- Besselink, B., Turri, V., Van De Hoef, S., Liang, K.-Y., Alam, A., MÃrtensson, J., & Johansson, K. (2016). Cyber-Physical Control of Road Freight Transport. *Proceedings of the IEEE*, 1128-1141.
- Bhoopalam, A. K., Agatz, N., & Zuidwijk, R. (2018). Planning of truck platoons: A literature review and directions for future research. *Transportation Research Part B: Methodological*, 107, 212-228.
- Boysen, N., Briskorn, D., & Schwerdfeger, S. (2018). The identical-path truck platooning problem. *Transportation Research Part B: Methodological, 109*, 26-39.
- Heerkens, H., & Winden, A. (2012). Geen Probleem. Niewegein: Van Winden Communicatie.
- Hoef, S., Johansson, K., & Dimarogonas, D. (2018). Fuel-Efficient en Route Formation of Truck Platoons. *IEEE Transactions on Intelligent Transportation Systems*, *19*, 102-112.
- Larson, J., Kammer, C., Liang, K., & Johansson, K. (2013). Coordinated Route Optimization for Heavyduty Vehicle Platoons. *IEEE Transactions on Intelligent Transportation Systems*, 1196-1202.
- Larsson, E., Sennton, G., & Larson, J. (2015). The vehicle platooning problem: Computational complexity and heuristics. *Transportation Research Part C: Emerging Technologies, 60*, 258-277.
- Nourmohammadzadeh, A., & Hartmann, S. (2016). The fuel-efficient platooning of heavy duty vehicles by mathematical programming and genetic algorithm. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 46-57.
- Robinson, S. (2014). *Simulation the Practice of Model Development and Use.* London: Palgrave MacMillan.

Appendix A

The following table gives an overview of the literature that was obtained from the literature review. The number in the first column is used refer to the article in other tables.

Number	Title	Year	Summary
1	The identical-path truck platooning	2018	A platooning problem in which all trucks
	problem		have the same start and destination is
			researched, including the influence of
			various constrains on possible the fuel
			savings.
2	Planning of truck platoons: A	2018	An overview of previous research into
	literature review and directions for		truck platooning and identification of
	future research		gaps of knowledge.
3	Fuel-Efficient en Route Formation of	2018	Researches a setting in which a central
	Truck Platoons		planner appoints leader trucks that
			other trucks can follow to platoon. The
			setting is simulated on a large scale.
4	A consensus-based algorithm for	2017	Researches the problem of closing the
	truck platooning		gap between trucks that want to
			platoon together by changing driving
			speeds.
5	Cyber-Physical Control of Road	2016	Researches a setting in which a central
	Freight Transport		planner appoints leader trucks that
			other trucks can follow to platoon.
6	The fuel-efficient platooning of heavy	2016	A central planner that creates all
	duty vehicles by mathematical		platoon plans before the trucks depart is
	programming and genetic algorithm		researched. This is done by improving a
			random solution many times.
7	Computing Feasible Vehicle	2016	A central planner that doesn't create
	Platooning Opportunities for		platoon plans but identifies possible
	Transport Assignments		platooning partners is researched.
8	The vehicle platooning problem:	2015	A central planner that creates all
	Computational complexity and		platoon plans before the trucks depart is
	heuristics		researched. This done by using a
			construction heuristic and improved
			with a local search algorithm.
9	Coordinating Truck Platooning by	2015	Researches a setting in which a central
	Clustering Pairwise Fuel-Optimal Plans		planner appoints leader trucks that
			other trucks can follow to platoon.
10	Coordinated Route Optimization for	2013	A setting in which multiple controllers
	Heavy-duty Vehicle Platoons		are researched instead of a central one.
			A controller tries to form platoons with
			the trucks that enter their intersection
			by letting them alter their speeds before
			arriving at the intersection.

Table A.1 Literature list

Appendix B

This Appendix contains a table with the matching algorithms obtained from literature, the article in which they were found and a short description of the algorithm. A "D" in the article column shows that an algorithm was found because it was used by Distribute for truck platoon matching.

Algorithm	Article	Description
Dynamic-Programming-	1	A dynamic-programming algorithm that can find optimal
Algorithm		solutions for a small number of trucks with the same start
		and destination.
Platoon-Leader-Algorithm	3, 5, 9	Through pair-wise comparison platoon leaders are chosen
		before the trucks depart. Platoon leader follow the shortest
		route to their destination. Other trucks can follow platoon
		leaders for part of their route if this is beneficial for them.
Hub-Heuristic	8	Subsets of all trucks in the system are forced to go through a
		certain hub. For trucks leaving the hub a same-start-
		platooning problem is solved. For trucks approaching the
		hub a reversed version of the same-start-problem is solved.
Best-Pair-Heuristic	8	The two trucks that can save the most by platooning
		together are matched first. Then the match that increases
		the savings the most, given the first match is made. This is
		repeated until no more profitable matches can be made.
Intersection-Algorithm	10	When two trucks approach the same intersection a
		controller checks whether they can achieve savings by
		platooning together. If this is the case he tells them to form a
		platoon. When more than two trucks approach the same
		intersection the pair with the highest savings is selected first,
		after which the next best match is chosen, if any.
Genetic-Algorithm	6	A random solution of profitable matches is created, after
		which a genetic algorithm tries to improve this solution
		through iterations.
Best-Match-Algorithm	5, D*	All trucks within a certain range of the searching truck are
		considered as candidates. The candidate with whom the
		searching truck can save the most is chosen to platoon with.
First-Come-First-Served-	D*	All trucks within a certain range of the searching truck are
Algorithm		considered as candidates in a certain order. A match is made
		with the first candidate with whom savings can be achieved.

Table B.1 Algorithm list

Appendix C

A list of the changes made to the original simulation model is provided here.

- Made it possible to break up a match, or in other words to delete a platoon that has not yet departed yet.
- Made it possible for trucks that are not just arriving at the Plaza to search for a platoon partner (when they lose their match).
- Added logic so that a truck can decide whether it is beneficial for him to switch platoons.
- Added the possibility to put a time-based restriction on the switching of platoons.
- Trucks that are already in a full platoon are not excluded as candidates (because they can still switch platoons).
- Trucks that are in a platoon that cannot be joined are not excluded as candidates (because they can still switch platoons).
- The waiting time and route overlap is always reset for a new candidate to prevent wrong calculation of the platoon earnings.
- Changed the departure procedure to prevent trucks from getting stuck at the Plaza exit.
- Added switching statistics.
- Added the collection of performance indicators each hour.

Appendix D

The following table shows a list of the input variables together with their units and a short description.

Variable	Value	Unit	Description
ArrivalIntensity	50	Trucks	The intensity with which trucks arrive at the
			Plaza. The trucks arrive according to a
			Poisson distribution. The value represents
			the average number of trucks per hour.
HourlyWage	45	Euro	The hourly wage of a truck driver
HourlyWageSavingsinPlatoon	0 or 0.9	Percentage	The percentage of the hourly wage that a
			following truck saves while platooning
TruckFuelEfficiency	0.222	Litre	The amount of fuel a truck uses to drive one
			kilometre
FuelPrice	1.08	Euro	The price of one litre of fuel
AvgRestTime	15	Minutes	The average length of the rest period of a
			truck driver
MaxPlatoonSize	2	Integer	The maximum of trucks that can be in one
			platoon
MaxDrivingDist	360	Kilometre	The maximum distance one platoon can
			drive together
PlatoonSavingsFirst	0.04	Percentage	The percentage of fuel the first truck in a
			platoon saves
PlatoonSavingsSecond	0.16	Percentage	The percentage of fuel the trucks in the
			middle a platoon save
PlatoonSavingsThird	0.10	Percentage	The percentage of fuel the last truck in a
			platoon saves
NumUrgent	0.20	Percentage	The percentage of trucks that is marked as
			urgent
MaxTimeDev	5	Minutes	The maximum time an urgent truck can wait
			for a platoon partner

Table D.1 The input variables

Appendix E

In this appendix, the warm-up period is determined using the MSER procedure. Although this procedure has been performed for each performance indicator it is only shown here for the performance indicator "percentage in platoon", since this performance indicator requires the longest to reach a steady state.

$$MSER(d) = \frac{1}{(m-d)^2} \sum_{i=d+1}^{m} (Y_i - \bar{Y}(m,d))^2$$

Figure 6 MSER formula (d = the proposed warm-up period, m = the number of observations, Y(m,d) = the mean of the observations from Y_{d+1} to Y_m)

The MSER procedure calculates the MSER value according to the formula in figure 6 for each possible warm-up period. The warm-up period that generates a minimum MSER value is the suggested warm-up period. When this suggested warm-up period is in the second half of the data, the suggestion is rejected.

Figure 7 shows that a minimum MSER value is obtained with a warm-up period of eight hours for the performance indicator percentage in platoon. This performance indicator has the longest warm-up period, therefore this warm-up period is used.



Figure 7 MSER graph

Appendix F

In this appendix, the run length is determined using the convergence method. Although this method has been performed for each performance indicator it is only shown here for the performance indicator "average earnings per platoon", since this performance indicator required the longest run length.

The last column of Table F.1 shows the convergence of the cumulative means of the three replications. The convergence should not only be below a certain threshold, but should also stay below this threshold afterwards (Robinson, 2014). The convergence is calculated using the formula in Figure 8.

$$Convergence = \frac{Max(r_1, r_2, r_3) - Min(r_1, r_2, r_3)}{Min(r_1, r_2, r_3)}$$

Figure 8 The formula for convergence. The symbol r_i represents the cumulative mean of replication i.

A threshold value of five percent is used in this case. Although the convergence drops below five percent as early as hour fourteen, it does not stay under the five percent until hour 32. Taken into account the warm-up period of eight hours, this results in a run length of 24 hours.

	Replica	ation 1	Replication 2		Replica		
	Earnings	Cumulative	Earnings	Cumulative	Earnings	Cumulative	
hour*	per platoon	mean	per platoon	mean	per platoon	mean	Convergence
9	57.89	57.89	73.14	73.14	52.05	52.05	40.52%
10	63.81	60.85	56.56	64.85	71.95	62.00	6.57%
11	58.92	60.21	58.47	62.72	49.71	57.90	8.33%
12	71.93	63.14	59.59	61.94	49.36	55.77	13.21%
13	54.04	61.32	60.34	61.62	63.97	57.41	7.33%
14	57.02	60.60	44.81	58.82	65.59	58.77	3.11%
15	66.80	61.49	72.59	60.79	62.23	59.27	3.74%
16	88.65	64.88	48.32	59.23	61.41	59.53	9.55%
17	54.78	63.76	75.39	61.02	55.10	59.04	7.99%
18	55.41	62.92	66.65	61.59	60.22	59.16	6.36%
19	46.95	61.47	45.88	60.16	67.02	59.87	2.67%
20	57.34	61.13	64.56	60.52	75.27	61.16	1.04%
21	57.53	60.85	63.16	60.73	44.75	59.89	1.60%
22	46.72	59.84	68.59	61.29	65.37	60.29	2.42%
23	48.22	59.07	48.35	60.43	51.44	59.70	2.30%
24	47.55	58.35	79.40	61.61	58.50	59.62	5.59%
25	61.00	58.50	57.43	61.37	86.93	61.23	4.89%
26	61.39	58.66	63.05	61.46	58.54	61.08	4.76%
27	51.99	58.31	62.86	61.53	75.47	61.84	6.04%
28	43.71	57.58	78.80	62.40	45.23	61.00	8.36%
29	62.80	57.83	70.16	62.77	71.90	61.52	8.53%
30	60.68	57.96	46.30	62.02	45.94	60.82	7.00%
31	55.55	57.86	46.38	61.34	58.96	60.73	6.02%
32	69.07	58.32	56.42	61.13	47.00	60.16	4.82%
33	43.88	57.75	47.36	60.58	53.90	59.91	4.91%
34	58.18	57.76	60.87	60.59	56.32	59.77	4.90%

35	94.43	59.12	70.70	60.97	49.64	59.40	3.12%
36	58.32	59.09	49.69	60.56	53.57	59.19	2.49%
37	54.00	58.92	67.43	60.80	54.33	59.02	3.20%
38	53.83	58.75	61.04	60.81	48.12	58.66	3.66%
39	61.60	58.84	53.45	60.57	59.48	58.69	3.21%
40	73.73	59.30	80.95	61.21	70.92	59.07	3.62%
41	66.42	59.52	49.63	60.86	59.60	59.08	3.00%
42	57.20	59.45	52.40	60.61	54.43	58.95	2.82%
43	71.17	59.79	58.86	60.56	58.78	58.94	2.74%
44	65.46	59.94	82.82	61.18	57.63	58.91	3.85%
45	48.53	59.64	67.47	61.35	64.69	59.06	3.87%
46	51.80	59.43	71.92	61.63	54.22	58.94	4.56%
47	61.08	59.47	55.97	61.48	47.23	58.64	4.85%
48	52.06	59.29	62.99	61.52	58.06	58.62	4.94%

Table F.1 The convergence test

Appendix G

This appendix shows how the confidence intervals of the differences are calculated. This has been done for each performance indicator for both the experiments with and without wage savings. For the purpose of demonstration this is only shown for the earnings per platoon for the situation with 90 percent wage savings.

Table G.1 shows the average earnings per platoon for each batch for each scenario, as well as the differences between the scenarios. The 95 percent confidence intervals for the difference between the scenarios are calculated using the data in the last three columns.

Table G.2 shows the confidence intervals of the differences between the scenarios. Based on the conclusion column in Table G.2 a ranking is made for the different scenarios on the performance indicator earnings per platoon.

r						
Scenario	А	В	С	A – B	A - C	B - C
Batch						
1	36.27	57.90	53.04	-21.63	-16.76	4.86
2	35.82	59.64	54.81	-23.825	-18.994	4.831
3	31.77	59.58	52.04	-27.810	-20.267	7.543
4	2.99	5.18	2.34	-2.192	0.642	2.835
5	35.31	53.85	50.29	-18.537	-14.978	3.560
6	31.81	67.99	61.99	-36.177	-30.173	6.004
7	31.54	64.20	55.34	-32.654	-23.800	8.854
8	30.93	50.63	52.69	-19.705	-21.766	-2.061
9	34.16	53.29	50.06	-19.126	-15.894	3.233
10	32.10	52.01	54.35	-19.907	-22.245	-2.338
11	34.64	63.33	57.18	-28.696	-22.546	6.151
12	37.77	56.03	59.22	-18.257	-21.450	-3.193
13	29.81	56.05	50.57	-26.242	-20.761	5.480

Table G.1 Batches mean per scenario

Difference	Mean	St. Dev.	95% CI lower bound	95% CI upper bound	Conclusion
A - B	-22.67	8.39	-27.74	-17.60	B > A
A - C	-19.15	7.10	-23.45	-14.86	C > A
B - C	3.52	3.83	1.20	5.84	B > C

Table G.2 Confidence intervals for the differences