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Master thesis

Operational control of cooperative tractors and chaser bins in the agricultural sector

Thijs Broekhuijsen

Industrial Engineering and Management

University of Twente

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Operational control of cooperative tractors and chaser bins in the agricultural sector

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Author

T.K. Broekhuijsen (Thijs) s1561073

Examination committee

Dr.ir. E. Lalla-Ruiz (Eduardo) University of Twente

Dr.ir. M.R.K. Mes (Martijn) University of Twente

B. Gerrits, MSc (Berry) Distribute

Organization

University of Twente,

PO Box 2017,

7500AE, Enschede

+31(5)34899111

Study

Industrial Engineering and Management (IEM)

Specialisation

Production and Logistics management (PLM)

Department

Industrial Engineering and Business Information Systems

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Management Summary

Due to the increasing demand for food, a shortage of specialised labour in the agricultural sector and lower yields in field, the agricultural sector needs to make drastic changes. One project that might provide solutions for this industry is the DurableCASE, spearheaded by the Hogeschool Arnhem Nijmegen. They started this DurableCASE project to incorporate robust robotics within the agriculture.

The goal of this research is to create the operational logic for an autonomous harvester chaser bin combination called the EOX, developed by H2Trac.

This operational logic makes all decisions that need to be made during harvesting, like when to change chaser bins, where to drive next and how to drive there. The research question corresponding to this goal is: *"How can robust, cooperative behaviour be developed for harvesting vehicles, assuming variable communication connection quality, a variable amount of chaser bins, and a varying field size?"*

To answer this question, first the current situation was examined. The EOX has some major advantages when compared to traditional farming tools. For one, it is capable of Controlled Traffic Farming. This means that with the use of GPS locations, the harvester and chaser binc can drive precisely in between the crops, so they are not run over during harvesting. Another advantage of the EOX is that it is much more lightweight than the previous traditional farming harvesters. This choice was made to combat soil compaction. This soil compaction occurs when a heavy vehicle drives over the field, and it stunts the growth of crops on that spot for years to come, so it is best to be avoided with the use of lighter machinery. Finally, the EOX has much manouverability when compared to the traditional setup. Because the chaser bins are programmable, no pulling tractor is required. This makes it possible to drive forward and backward without any issues. The goal of the operational logic should be on maintaining a high harvester utility whilst achieving the lowest possible soil compaction. This problem was identified as an arc routing problem, where the decisions need to be made on the strategic level (chosing the number of chaser bins) and the operational level (where and when to switch chaser bins).

The solution design focussed first on the pre-defined plan for the harvesting route. For this a program was developed in Python with the use of google ORTtools that finds solutions for the arc routing problem. The operational logic for the harvester- chaser bin combination took the form of a master- slave principle, where the harvester gives instructions to the chaser bin.

This solution design was then tested in the evaluation method, developed in Technomatix Plant Simulation. This evaluation design is capable of converting real life gps data to a graph where the operational logic could be tested on. This was tested on the types of switch, either on the headlands or during driving or a hybrid of the two, the recommended amount of chaser bins and their capacity in three different fields and finally how they compared to a system with the same amount of chaser bins.

From these experiments it could be concluded that the best type of switch is a hybrid switch, where in the first and last 25% of the field a switch occurs at the headlands and in the other 50% the switch happens during driving. For a general field the best solution is to have 4 chaserbins, either with a capacity of 2800 kg or 4200 kg. When comparing these best solutions to the traditionional harvester, the soil compaction can be decreased with at least 15% and as high as 30%. For the sensitivity analysis the variance of the crop distribution was altered from 20% to 40% and 60% to see what this did to the performance, and the difference between a pre-defined plan for switching chaser bins, an updated plan and no plan. Here it turned out that the use of the pre-defined plan can improve the harvester utilisation slightly.

Recommendations for H2Trac include install sensors to keep track of the capacity of the chaser bin, make estimates on the amount of crops per meter in a field and to use offline planning before a harvest to ensure that the harvester always travels in the correct paths.

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Chapter 1. Introduction

In this thesis, a robust operational logic is created for a harvester and chaser bin combination that allows these vehicles to cooperate. This research is done at the company Distribute, and was commissioned by the Hogeschool Arnhem Nijmegen.

Currently, the Dutch agriculture sector is facing a plethora of problems (HAN Automotive Research, 2018):

- There is a growing staff shortage in the agriculture sector. Because of this shortage, the cost of labour is high. With self-driving vehicles, harvesting can save up to €800/hectare in labour cost.
- Soil compaction is becoming a substantial problem. When a tractor drives over the loose ground, the soil becomes compacted, and this soil is less suitable to produce crops the year(s) afterwards.
- Cow tables need to be clean to prevent infected cow hoofs. This takes up much of the time of the farmers.
- The Dutch agricultural sector is currently scaling up its production, as the world population is ever-growing.
- Because of climate change, Dutch farmers need to work more durable and look for fossil fuel alternatives. Durability means that they need to produce more crops with the same or even fewer resources and reuse their assets.

Fortunately, there are positive developments in the sector as well that combat these problems. The agriculture sector is in one of its most fascinating times since the development of the first tractors. Technologies like robotics and sensors are becoming cheaper and more easily accessible, which opens many possibilities for farmers to upscale production, reduce cost, and use fewer resources (Ruiz-Garcia et al., 2009). While these technologies are already widely used in indoor farming to control temperature and humidity, they are still in the initial stages in (cow) stables and harvesting fields. The Hogeschool Arnhem Nijmegen (HAN) wants to advance this modern technology. To stimulate this advancement, they started a project regarding the implementation of robotics in agriculture, which are also called agrobotics. This project is called the Durable Cooperative Agrobotics System Engineering, or DurableCASE. The goal of the DurableCASE is to build two robotic systems for two different use cases and showcase these at an exhibition called the Floriade. These robotic systems need to be able to make decisions by themselves. This is also called autonomous behaviour. The first use case focusses on cleaning cow stables and the second on creating an autonomous robotic system for harvesting fields. The latter is the focus of this research.

The HAN does not have all required knowledge available for the DurableCASE. Therefore, they cooperate with 24 companies from different branches and sectors. One of the companies that contribute to the DurableCASE is Distribute. This thesis takes place at this company. Distribute is a creative innovator that designs and simulates distributed planning and robots.

The remainder of this chapter serves to introduce the needs, motivation, and research objective of the thesis. First, Section 1.1 describes the company and its stakeholders. Then, Section 1.2. introduces the Electronic Ox. Afterwards, Section 1.3. gives the problem description, alongside the problem cluster and the core problem for the thesis. Then, Section 1.4 defines the objective of the research, Section 1.5. gives the research questions, and Section 1.6 gives the approach to address these research questions. Finally, Section 1.6. concludes this chapter.

1.1. Company and stakeholder description

As stated before, 24 companies contribute to the DurableCASE. This section introduces the companies that are most relevant for this research.

1.1.1. Distribute

Distribute is an academic spin-off from the University of Twente. It is a start-up established in 2016 by Berry Gerrits. It currently has two full-time employees, one part-timer and three master graduate students. Distribute's mission is to create solutions to facilitate the transition from the latest scientific research to first-hand knowledge and practical applications (Distribute, 2019). They also actively contribute to the scientific community through industry-driven research. Their primary activity is developing highly detailed, animated, and flexible simulation models. They study the effectiveness of a distributed approach with these simulation models. Distribute is the company the research takes place. They are used as a sparring partner while doing the research.

1.1.2. Hogeschool Arnhem Nijmegen

The HAN, or Hogeschool Arnhem Nijmegen, is a vocational University of Applied Sciences. As the name suggests, they have campuses in both Arnhem and Nijmegen. These campuses have over 3200 administrative staff members and over 35000 students combined (HAN, 2020a). These students are divided into 14 different schools, ranging from sports to law. The HAN's mission is to "qualify, socialise and prepare students for their future professional practice and citizenship" (HAN, 2020b).
The automotive department of the HAN is the initiator of the DurableCASE. Therefore, they have a leading role in the project. They ensure that the goals of the master thesis align with the end goals of the project, so sparring sessions take place with this stakeholder. These sparring partners take place once a month to discuss the progress and receive input and feedback on the thesis progress.

1.1.3. H2Trac start-up

H2Trac, formerly known as MultiToolTrac, is a start-up building one of the first autonomous tractors. Their mission is to "help farmers with innovative ways to keep their soil healthy and improve their yield" (H2Trac, 2019). Currently, they are working on making their first tractor operational. They called their first line of tractors the "Electronic Ox", or EOX for short (Vlaanderen, 2020). This tractor has an adjustable track width, making it suitable to drive over all sorts of cultivation systems. It also has four-wheel steering, which makes the turning circle 9.6 meters. Figure 1 shows the side and the front of the tractors. After H2Trac makes this first electric tractor operational, they want to scale up their production and simultaneously build the first tractor capable of running on hydrogen.


Figure 1: Side and front of the EOX tractor

This thesis uses H2Trac to gain insight regarding the practical side of implementing autonomy in agricultural vehicles, as this company knows about the requirements, possibilities and restrictions of these vehicles.

1.2. EOX tractor

As stated in the previous section, H2trac is currently making an autonomous tractor, the EOX. They want to create the EOX tractor for two reasons. The first reason is the growing labour shortage in the agriculture sector. With the shrinking labour force, it is impossible to retain the same level of activity. Since the farmers need to scale up their production to keep up with the growing food demand, this is more necessary than before. The use of autonomous tractors makes it possible for the farmer to control and monitor multiple vehicles instead of one, making the process much more effective.

Another problem that farmers face is that fields yield fewer and smaller crops than in previous years. This regression is the cause of soil compaction. Soil compaction causes the ground to become compressed, which stunts the growth of the crops. It occurs when large vehicles drive over the soil. In preceding years, the machines have become heavier and more sizable, which helps the farmers in the amount of time they need to harvest, but it works counterproductive for soil compaction. H2Trac built the EOX tractor with soil compaction in mind, making the tractor as light as possible. The autonomous tractors are also capable of so-called Controlled Traffic Farming, enabling the EOX tractor to drive precisely within specified rows. These are rows only destined for driving so that the tractor does not travel over the parts containing the crops. To ensure the EOX tractor can do this with any crop type, H2Trac built the EOX tractor with an adjustable track width. The EOX tractor can have a track width from 2,25 meters up to 3,2 meters. Figure 2 shows the range of these wheels. The image also shows that the front and rear wheels have the same size. Usually, rear wheels are about twice the width of the front wheels.

One of the unique properties of the EOX tractor is that the cabin can be removed and replaced by bins. This way, chaser bins have the same "smart" capabilities as a harvester. As an added benefit, no harvesting equipment is attached to the back of the chaser bins, making it possible for them to drive in reverse without any restrictions. This perk enables the chaser bin to go from one row of the field to the row directly next to it. The thesis refers to the combination of chaser bins and tractors as vehicles or robots.

The only downside of these chaser bins is that they do not have the same capacity as the chaser bins that are currently used. The current chaser bins have a capacity of 12 crates (2 rows of 6 crates), and in each crate a total of 700 kg can be stored for a total capacity of 8400 kg. The EOX chaser bins on the other hand, only have room for 3 crates in a row. It is currently uncertain if the EOX chaser bins are also capable of having 2 crates next to each other, which would make the capacity 4200 kg, or only 1 crate, which would make the maximum capacity 2100 kg.

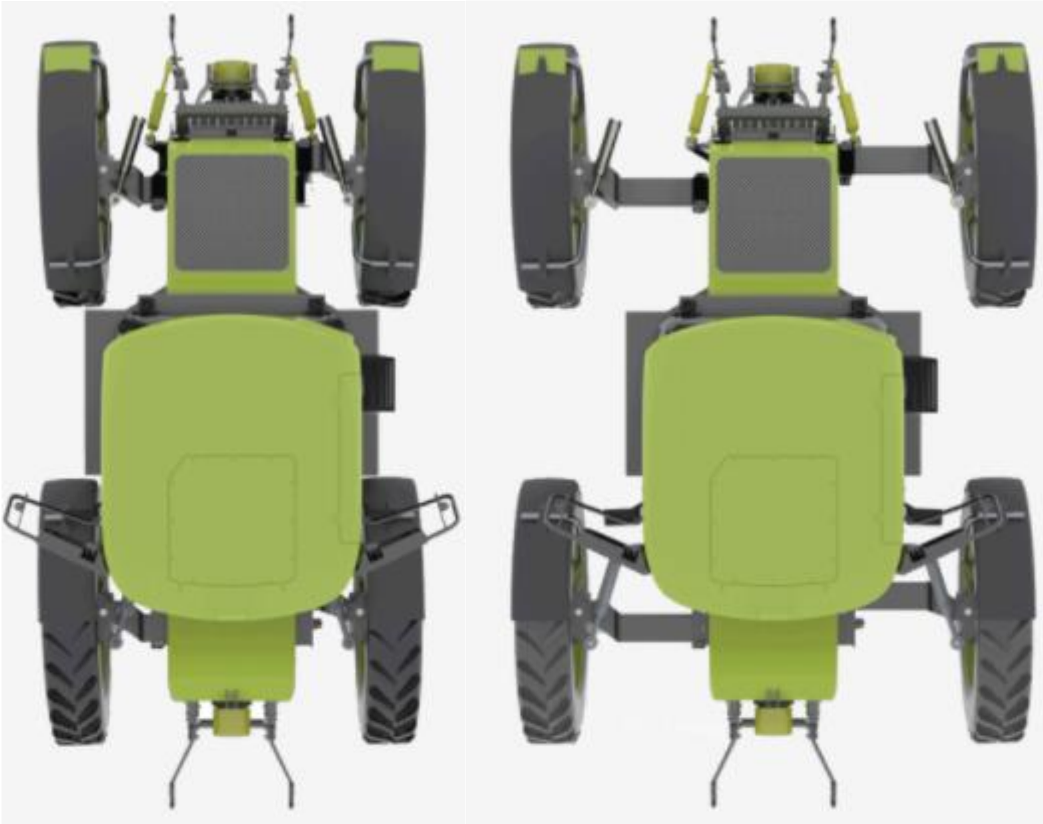


Figure 2: EOX with a track with of 2,25 meters (left) and 3,2 meters (right)

1.3. Problem context

While the hardware of the EOX tractor is already in developed, the software side is still lacking. More specifically, the operational logic has not been created yet. The operational logic instructs the harvester and the chaser bins what to do. This logic allows the vehicles to drive to the designated routes, where to go to next and when to switch chaser bins, align the chaser bins and the harvester while driving.

Another aspect of this is that since the operational logic is still missing, H2Trac cannot indicate what performance potential buyers can expect when they buy the EOX tractor and the corresponding chaser bins. The cause of this is the many uncertainties surrounding the performance of the EOX tractor. The acquisition of a new tractor is a considerable expense, so farmers do not make these decisions lightly. Farmers are more inclined to go for the EOX tractor if they know how much their performance improves compared to conventional methods.

When farmers want to buy a new tractor, they are generally interested otherwise they can be damaged. Therefore, farmers only have a limited window each year to harvest their crops. They need to use this window optimally, so the harvester is used as much as possible during this time. H2Trac cannot give a proper indication of the harvester utility because of 2 uncertainties:

- **New chaser bin not available in time.** When a chaser bin reached its capacity, a new one needs to take its place. If the new chaser bin does not arrive before the current chaser bin reached its capacity, the harvester needs to stop for some time to wait for the next chaser bin.
- **Harvester or chaser bin do not receive instructions.** Since the harvester and vehicle drive in rural areas, they can lose connection to the central controller. When this happens, the robot stops because it does not know what to do. This vehicle cannot drive until the server restores contact or the farmer takes control manually. They also can exchange in two things. The first one is the level of soil compaction they can expect with the EOX tractor. As discussed in Section 1.2, the EOX tractor combats soil compaction with lighter vehicles and designated driving rows. However, the

severity of the soil compaction is uncertain as the level largely depends on the number of passes the tractors make on the field. Too many passes nullify the effect of the lower weight of the EOX tractor. Therefore, it is not enough to solely lighten the harvester and chaser bins. The number of passes needs to be limited as well.

The other performance indicator is the utility of the harvester. Farmers only have a limited window to harvest their crops. If the ground is too wet, soil compaction can be more severe than on dry land. Furthermore, crops need to be very dry during harvesting, as information with each other, making it possible for one vehicle to steer and control another.

1.3.1. Problem cluster

The problems discussed in the Problem Context have been summarised in a problem cluster. Figure 3 shows this cluster. The action problem and core problem are defined according to Heerkens and van der Winden (Heerkens & van Winden, 2017). The action problem is the discrepancy between the norm and the reality, as perceived by the problem owner. In this case, H2Trac is the problem owner and the action problem they perceive is that they do not have information

The thesis solves the action problem for the client. This problem is that H2Trac cannot give any indication on the performance of the new tractors, because the operational logic does not exist yet. The arrows show the relations between the problems and their causes. Section 1.4.2. goes into detail on the core problem derived from this problem bundle.

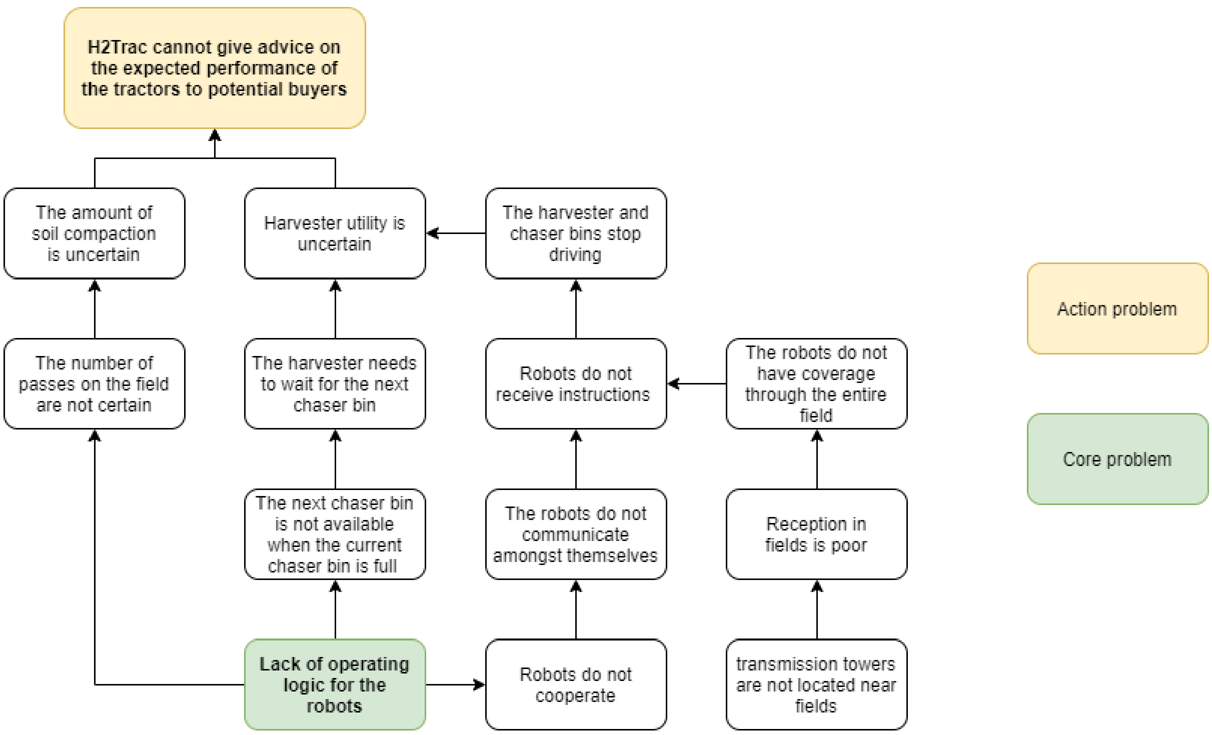


Figure 3: Problem cluster of H2Trac

1.3.1.1. Core problem

The core problem is that the robots lack operational logic. Without this operational logic, the EOX tractor cannot perform any autonomous actions and can only be controlled manually like a regular tractor. When the operational logic has been created, it is possible to predict the performance of the EOX. This information can convince potential buyers to buy an EOX tractor instead of a tractor from a competitor.

1.4. Research objective

This subchapter provides the research objective. First, this section describes the goal of the research. Then, it presents the scope and limitations of the thesis.

1.4.1. Research goal

The goal of this research is to design an algorithm that controls the harvester and chaser bins. Control here means that the algorithm determines the routing and sets the vehicles into action whenever necessary. This algorithm needs to meet these criteria:

- **Robust.** This algorithm needs to handle uncertain situations, like a chaser bin getting stuck or it loses its connection to the central server. If the algorithm cannot manage these types of input errors, the algorithm will fail. The algorithm needs to work on fields from all shapes and sizes without altering the algorithm with each unique cropland. The algorithm needs to find a solution that maximises the harvester utility and minimises the number of passes on the field with a variable number of chaser bins. This number is variable because chaser bins are expensive, and buyers can choose how many chaser bins they want.

- **Cooperative.** The vehicles need to cooperate. This cooperation can take several forms, like that a chaser bin can take over the tasks of a chaser bin that is stuck or that a chaser bin gets instructions from other vehicles when it loses its link.

The harvester and chaser bins currently do not have any data on how often a loss of connection happens. Therefore, scenarios and runs need to determine guidelines for the number of chaser bins required with different forms of communication with the central server. This algorithm needs to work on any field type, as all fields differ, and H2Trac needs to give personal advice to the farmer to make the EOX tractor more attractive to them.

1.4.2. Scope and limitations

This thesis aims at studying and implementing robust cooperative robots in agricultural fields. The research does not involve the actual implementation of the algorithm within the EOX tractor as H2Trac has more expertise in this part. This thesis only provides the logic and pseudocode that the vehicles should use. The dissertation also excludes the security, requirements, and characteristics of the connections between the robots and the server. While this is important for implementing the vehicles in fields, they fall outside the scope of this thesis.

Scope:

- The scope confines the thesis to an algorithm for the chaser bins and vehicles. This algorithm needs to work on fields of any shape and size.
- The algorithm needs to be robust. Robustness means that it is capable of handling unexpected situations and errors. For instance, when the vehicle fails to link to the server.
- This research investigates ways to limit the number of passes on a field and boost harvester utility.

Limitations:

- The algorithm is not implemented directly into the tractors themselves.
- The thesis only considers the routing on the field. How the crops go from the side of the field to the storage is not considered.
- Farming operations, besides harvesting, are not taken into consideration (Seeding, tillage, and possibly other activities).
- The algorithm needs to be able to find a solution within a reasonable time. Fields can become very large, and with precise algorithms, they might not find optimal solutions.

- The algorithm needs to work with variables and data that are easy to alter as farmers do not have all information, like the exact amount of crops per cubic meter.

1.5. Research questions

The thesis addresses the main research question to help H2Trac with the problems described in the problem context. This question is:

"*How can robust, cooperative behaviour be developed for harvesting vehicles, assuming variable communication connection quality, a variable amount of chaser bins, and a varying field size?*"

Since this is a complex problem to answer, the main research question is splits into smaller, more manageable research questions. Each chapter of this thesis corresponds to one of the research questions. Each chapter consists of subchapters, which also have questions associated with them. The research questions are shown below, alongside a brief explanation of the corresponding chapter.

Problem context

Research question 1: What is the context the operational logic needs to operate in?

a. What key performance indicators (KPIs) need to measure the performance of the EOX tractor according to H2Trac?
b. What requirements do the operational logic and the quantitative model need to fulfil according to H2Trac?
c. In what fields does the performance of the operational logic need to be tested?
d. As what type of operational research problem can the operational logic be identified?

The problem context focusses on the information that is required to solve the problem of the thesis. First, the key performance indicators are examined. Key performance indicators are used to measure the performance of the operational logic. The chapter then discusses the requirements for the operational logic and the quantitative model. Finally, the type of operational research problem is identified for this thesis. This information can then be used to find out how other

Literature review

Research Question 2: What tools and models are currently available in the literature?

a. How do collected works relate to the problem of harvester routing?
b. What objectives, constraints, assumptions, and challenges for implementing robot systems in agriculture mentioned in the literature are relevant for the thesis?

The literature review focuses on the (academic) knowledge that needs to be acquired to complete the thesis. At the end of each chapter that deals with a question, the conclusion summarises the information presented. This section discusses the impact of the information on the research as well.

The first question uses the definitions of the first sub-question to find out how scientific papers have identified their problem. This leads to literature a better understanding of relevant literature and valuable insight into how they solved their problems.

The second question concerns the current state-of-the-art robotic systems in the entire agriculture sector. This question looks at how the current has implemented its systems and models. This question gives insight into the possibilities and pitfalls for creating operational logic.

Solution design

Research question 3: How should the operational logic of the EOX tractors be designed?

a. How should the sequencing of harvesting rows be determined?

b. What activities of the harvester and chaser bins should be supported by the operational logic?
c. How can these activities be translated into operational logic?

The solution design focuses on the operational logic for the EOX tractors. But before the operational logic can be generated, the activities need to be determined. The first question concerns choosing the next row that will be harvested. The second question pinpoints the actions the harvester and chaser bin need to perform autonomously. The third question then translates these activities into the operational logic. Finally, different scenarios are generated to test the performance of the operational logic.

Evaluation model

Research question 4: How can the performance of the operational logic be evaluated?

a. What does the conceptual model look like?
b. What is the data that is required, and how does this data flow through the system?
c. Does the model behave in the way it is supposed to? (verification)
d. Does the model accurately represent reality? (validation)

This chapter revolves around measuring the performance of the operational logic discussed in the previous chapter. First, a quantitative model is described in which the operational logic is tested. This is done in two ways. The first one involves the conceptual level, with the ideas and concepts behind the model explained. The second way gives an overview of the functions, with a more detailed explanation of where data is required, where data is manipulated and what data is generated. This model is then verified and validated, to ensure that it simulates the real-life situation sufficiently.

Results

Research question 5: What performance can farmers expect from buying the EOX tractor with the generated operational logic?

a. What is the best type of switch for the chaser bins?
b. What are the best configurations for the examined fields?
c. How does the EOX perform when compared to a traditional harvester chaser bin combination?
d. How does the algorithm perform per scenario in the sensitivity analysis?

This chapter goes further into the results of the algorithm regarding the scenarios. First, the best type of switch is examined. Then, the best configuration for all three fields is given. After that, the performance of the best configuration is compared to that of a traditional harvester chaser bin configuration. This is done in the evaluation method with the simplification that this combination can also use the operational logic, to keep the playing field fair and only the performance of the different vehicles is examined. Then, the chapter continues with a sensitivity analysis. Sensitivity analysis determines how the indicators are affected based on changes in the input variables. In this case, the sensitivity analysis examines the influence of a higher variability and the use of adjustable chaser bin plans.

1.6. Research approach

Each chapter in the previous section has a different approach. The chapter *Problem context* addresses its research question with interviews of experts and the stakeholders. This chapter provides parameters and constraints that the thesis takes into consideration. The chapter *Literature Review* is, as the name suggests, a review of literature on the field of autonomous robots. This chapter results in knowledge of the use of vehicles in other sectors and gives insight into the types of algorithms they use in their sectors.

The chapter *Solution design* describes the operational logic that will be created for H2Trac. This operational logic is then tested with the use of a quantitative model in the chapter *Performance.* Interviews with the stakeholders and a literature review determine the scenarios that test the operational logic in this chapter. Then, the chapter *Results* use the algorithm, model, and scenarios to show the algorithm's performance per scenario. This chapter then conducts the sensitivity analysis. Finally, the chapter *Conclusion* finishes the thesis and shows H2Trac what scenario they need to implement. provides a flow chart of the inputs, methods, and outputs.

1.6.1. Research deliverables

This project has three deliverables. The first one is the operational logic itself, the second one is the quantitative model that can be used to measure the performance of the operational logic, and the last one is this report with all the findings.

1.7. Conclusion

This chapter introduced the thesis and defines the stakeholders, problem description and the research. This thesis considers an autonomous tractor-chaser bin combination called the EOX. H2Trac is the developer of these vehicles. The EOX tractor is still under development, but its features, like Controlled Traffic Farming and less weight than conventional tractors, are very appealing to potential buyers. However, H2Trac has trouble with promoting this new tractor. Potential buyers are interested in what performance they can expect from the EOX tractor in their field, but H2Trac cannot indicate this because of uncertainties. These uncertainties include the tractor utilisation rate and how much the soil will be compacted.

The goal of this research is to create the operational logic for the EOX tractors. This operational logic is then tested in a quantitative model to test the performance. This operational logic needs to work on fields of any shape and size. It also needs to handle errors in the input, like a chaser bin not responding. The ability to handle this is also called a robust algorithm. The research question corresponding with this research goal is:

"*How can robust, cooperative behaviour be developed for harvesting vehicles, assuming variable communication connection quality, a variable amount of chaser bins, and a varying field size?*"

This question is divided into sub-questions, each being answered in a separate chapter. Figure 4 shows how all these research questions connect and how the thesis approaches the questions.

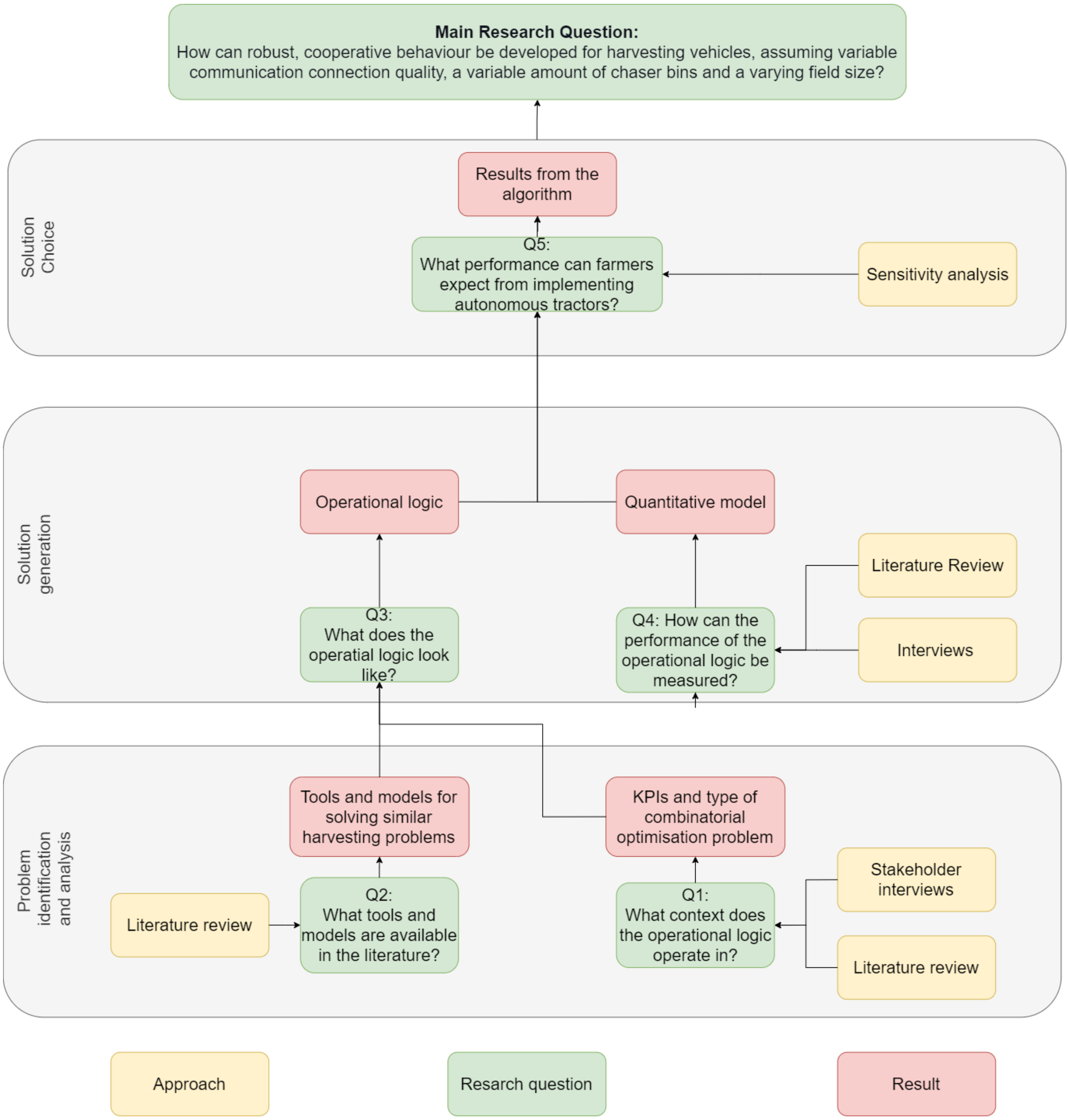


Figure 4: Research Design that shows the structure of the thesis

Chapter 2. Problem context

This chapter provides the context required for the thesis. First, Section 2.1. discusses the key performance indicators for the operational logic. Then, Section 2.2. discusses the requirements for the operational logic and the quantitative model. Then, section 2.3. discusses the fields that the quantitative model needs to embody to measure the performance of the operational logic.

2.1. Key Performance indicators

According to H2Trac, two indicators are important for measuring the performance of the operational logic of the EOX tractor. These are the utilisation rate of the harvester, and the level of soil compaction that the vehicles generate. The remainder of this section explains the reason for these performance indicators, how they are calculated and at what level of detail the indicators are calculated.

2.1.1. Harvester utility

At a certain point, crops are ready to be harvested. This point differs per crop, as some crop types are harvested if they are half grown (Albert, n.d.), and others can only be harvested if they are fully grown. The period from the start to the last day they can be harvested before the crops become overripe, is known as the harvesting window. With most crops, the harvesting window is from September through October. In theory, the farmer has this entire period to harvest the crops, but the reality is often very different. Farmers often need to wait for perfect weather conditions to harvest since when the ground and the crops are too wet, crops are damaged, and soil compaction can occur. The weather conditions shorten the harvesting window significantly for the farmers, as rainfall delays the harvest several days or even weeks before the ground is dry enough to harvest. Therefore, when conditions for harvesting are perfect, the farmer needs to harvest as much as possible as the weather the next day can be completely different. During this time, the farmers can work up to 18 hours a day.

Therefore, the harvester needs to be utilised as much as possible during the harvesting season. Unfortunately, there are several reasons the harvester can be underutilised. One of the problems is that the chaser bins cannot keep up with the harvester. The chaser bins need to match the exact speed of the harvester, as otherwise, the crops will fall onto the ground, which makes it practically impossible to gather them up again. Another problem is that the employees can misinterpret the amount of time it takes for the chaser bins to become filled. Then when the chaser bin is at capacity, the harvester needs to wait until the next chaser bin has arrived. Waiting takes up much time and impacts the harvester utility rate.

The utilisation rate of the harvester can be quantified quite easily when compared to the level of soil compaction. This rate is the amount of time the harvester has driven over the field divided by the total time of harvesting. An example of this is a harvester that harvested 8 hours in a day, and harvesting took 10 hours that day. The utilisation rate of the harvester is 8/10= 80%.

2.1.2. Soil compaction

The agriculture sector considers soil compaction a major problem in agriculture (Wouda, 2019). The Food and Agriculture Organization defines it as "the increase in density and a decline of macro-porosity in a soil that impairs the functions of both the top-and subsoil and impedes roots penetration of water and gaseous exchanges" (FAO, 2015). Soil compaction affects about 68 million hectares of soil worldwide. These 68 million hectares are about 38% of the agricultural land and 4% of the total land area (Oldeman, 1992). Of these 68 million hectares, 33 million hectares are located in Europe, 18 million in Africa and 10 million hectares in Asia (Akker & Canarache, 2001; FAO, 2015). Europe has the most difficulty with soil compaction, as tillage with heavy vehicles is most common in this continent.

Soil compaction has implications for the growth of crops since it represses the development of the plant (Shah et al., 2017). A usual response of a root system to an increase in the bulk density of the soil is to concentrate the roots in the top layer, lessening the root penetration (Lipiec et al., 2003). Less root penetration means the crops cannot grow strong and cannot access nutrients and water, as they would have had in uncompacted soil. Ishaq (Ishaq et al., 2001) showed that soil compaction could lead to a 38% decrease in yield in wheat and grain fields and a decrease of 9% the year afterwards.

Both natural and anthropic operations factors cause soil compaction (Nawaz et al., 2013; Raper, 2005). The organic factors include rainfall, plant roots in the soil, and the foot traffic of animals. Human factors that cause soil compaction are the number of passes over the field, crop rotation and the size and weight of the vehicles (Shah et al., 2017). Soil compaction caused by the size and weight of machines is especially concerning, as farmers use more and heavier machinery to harvest crops like potatoes (Spoor et al., 2003); (Stalham et al., 2007). To keep up with the demand on the market, farmers have shortened their time between one harvest and the seeding of the new crops, decreasing the time the soil can recover.

When soil compaction takes place, its intensity is not predetermined. The degree depends on many factors and can differ. Nawaz et al. (Nawaz et al., 2013) describe the three main variables of the soil that determine its compactness: the soil structure and texture, the soil water contents and the soil organic matter. The type of soil determines the soil structure and texture. Sandy soils naturally have higher bulk densities than clay soils because of the many minuscule pores associated with clays (Raper, 2005). The final factor is the soil water content. This factor is the most influential factor for the severity of soil compaction (Batey, 2009). Following prolonged periods of rain, the subsoil will remain moist for long periods because of the physical properties of the soil (Bakker & Davis, 1995).

2.1.3. Scope of soil compaction calculations

The calculations for the soil compaction must be as simple as possible, without leaving parts out that can potentially change the results of the experiments. The reason for this approach, and not a complete calculation of the soil compaction, is to increase the simulation speed.

The severity of soil compaction depends on two factors. The first one is the pressure that the vehicle exerts on the soil. The general rule here is that the heavier the vehicle, the more severe the soil compaction. The vehicle's stress exerts on the soil consists of shear (horizontal) stresses and vertical stresses. Only the vertical stress is considered in this model because the shear stress is not required for this part.

The second factor for the severity of soil compaction is how the soil reacts to the forced stress. Soils with a higher bulk density tend to compact less under stress as there are already fewer pores than in the normal ground. According to Keller et al. (2007), for a comparative assessment of the impact of different machines, the calculation of the vertical stresses on the soil is sufficient. This is, however, not enough for the thesis, as the effect on the soil also needs to be considered. The reason for this is that with multiple passes over the same plot of land, the soil recompresses, which impacts the severity of the soil compaction in the end. Therefore, the effect on the bulk density is also considered. In the thesis, the amount of soil compaction is considered as the change in the soil's bulk density.

2.1.4. Soil compaction formulas

To calculate the soil compaction, the methods described by Keller et al. (2007) are used. They simulate the soil compaction in three steps. First, the upper model boundary condition (contact area and contact stresses) is estimated. Then, the stresses in the soil profile are computed, and third, changes in the bulk density are calculated by applying a stress-strain relationship. However, one important simplification is made in the model. This simplification is that the tire exerts the same pressure at all points of the contact area. Tires exert less pressure at the sides of the contact area with the ground in reality. This simplification reduces the number of calculations greatly while minimising the difference in the solution.

Upper boundary conditions

First, the carrying load P needs to be calculated. The carrying load is the force the vehicle exerts on the ground. This carrying load is calculated as $P = \sigma * A$ where σ is the normal stress (weight of the vehicle), and A is the contact area (the area of the tires that touch the ground). As an example, with a vehicle of 1000 kg, 4 tires and a contact area of 150 cm^2 per tier, the force on a single tire is P=1000/4*150= 37500 N (4 tires, so all tires carry roughly one-fourth of the weight).

With this information, the radial normal stress σ_r at depth, *z* can be calculated. The radial force is the pressure the vehicle exerts at a certain depth. The radial force at the contact point of the tire is equal to the carrying load. When depths at other points than the contact point are considered, the formula becomes:

$$\sigma_r = \frac{\xi P}{2\pi r^2} cos^{\xi - 2}\theta \tag{1}$$

Here, ξ is the concentration factor of the soil. This is a constant factor that differs per soil type. r is the distance from the point load to the desired point. So, if a depth of 5 cm is considered, r=5. θ is the angle between the normal load vector and the position vector from the point load to the desired point. In other words, this is the distance b

With the radial stresses at point i, the mean normal stress (also known as the octahedral stress σ_{oct}) can now be calculated:

$$p = \sigma_{oct} = \sigma_z = \sum_{i=0}^{i=n} \sigma_{r,i} \, cos^2 \theta_i \tag{2}$$

with σ_z being the stress components in the z-direction.

Then, the bulk density can be calculated:

$$\ln \rho = \ln \rho_0 - [(A + B * p)(1 - e^{-C*p}) \tag{3}$$

Where ρ_0 is the initial bulk density, and A-C are the compatibility coefficients. Finally, the change in the bulk density of the soil is calculated by the formula:

$$\frac{\rho}{\rho_0} * 100\% \tag{4}$$

2.2. Requirements for the operational logic and quantitative model

H2Trac requires the following technical and business requirements for the operational logic:

- The objective of the operational logic is to maximise the harvester utility rate while minimising the soil compaction.
- The logic needs to be able to handle a variable number of chaser bins. Chaser bins are a considerable investment for farmers, so they need to see the improvements or trade-offs when purchasing extra vehicles.
- The operational logic needs to take the turning circle of the harvester into account. The harvester has a large turning circle, which prevents it from going to the next immediate row. The chaser bins do not have this restraint, as they can reverse into a new row.
- Although the current EOX tractors in development run on hydrogen, the next generations will run on battery. Therefore, the operational logic should be able to handle battery failures.

And the following requirements for the quantitative model:

- Fields of any shape and size need to be able to be examined, preferably with their coordinates.
- The quantitative model needs to take some elements of the agricultural process into account. These are crop selection, a varying amount of weight and volume of crops and the amount of dead weight that is harvested and threshed. Appendix A has more information on the agricultural process.
- The speed of the chaser bins needs to be adjustable, as an empty vehicle is lighter and can move faster than a full chaser bin.

2.3. Field specifications

The performance of the operational logic is initially evaluated on three fields. A stakeholder of the DurableCASE selected these fields because the stakeholder is nearby one of these fields, and they do not require driving on public roads. Figure 5 shows these fields. The field near Zeewolde will be used to design and develop the model for this thesis, as more information is known about this field, and the use cases with the EOX will take place on this field when the EOX is ready for practical tests. The field near Almere can be used to verify the quantitative model. The field near Lelystad is quite a lot larger than the two other fields with a length of almost one kilometer. This can be used to find out if the operational logic also works for fields with these or greater size.

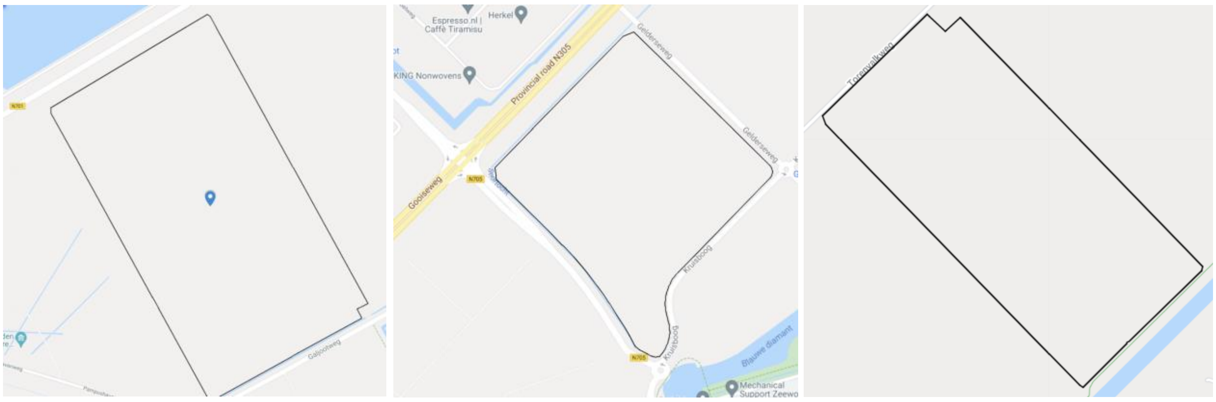


Figure 5: Selected fields for the model near Almere (left) , Zeewolde (middle) and LelyStad (right)

The stakeholder specified some more information on the field of Zeewolde. Figure 6 shows a sketch of this field with some more information on the driving direction, the turning circle, the boxes 1-5 that the field is separated in, and the dimensions of the field. Furthermore, the stakeholder elaborated that the crop rows are parallel to the Gooiseweg (the yellow road in Figure 5) and that crop rows have a width of 75 cm. Two rows are harvested simultaneously, so a width of 1.5 meters is harvested in one direction (and therefore, four rows with a width of 3 meters in a round-trip). The field is divided into five rows, each with a width of 90 meters, so 30 round trips are required to harvest a box completely. Headlands (the area where farmers turn to the next row) are also considered at the end of the fields, with a width of 9 meters.

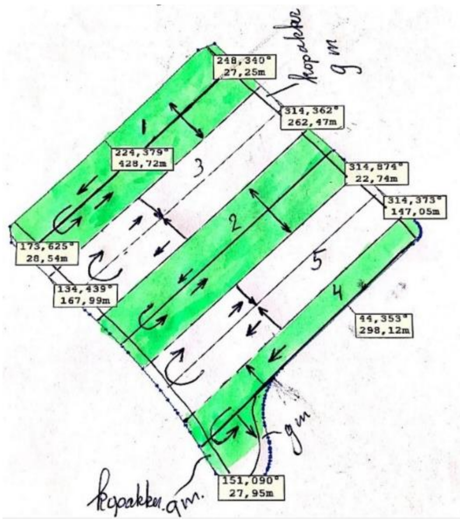


Figure 6: Sketch of the field near Zeewolde

Furthermore, this stakeholder provided some more information on the current harvesting process. In the current harvesting process, the chaser bins contain six crates that are filled with crops. On average, harvesting a hectare of crops yields approximately 140 crates, and a crate is full after approximately 48 meters. The speed of harvesting is between 3 and 5 kilometres per hour. The chaser bins can achieve a speed of 10 kilometres per hour.

2.4. Identification of the type of problem

Now, the operational logic can be identified in three parts. The next chapter uses this information to quickly classify relevant and less relevant papers. First, the consideration is made what type routing problem this is. Then, the level of planning is decided. This is the scope on which the decisions are made.

2.4.1. Routing problem

This problem can be seen as an instance of the arc routing problem. The arc routing problem consists of required arcs and non- required arcs (Corberán et al., 2021). The goal of this problem is to visit all required arcs once while minimising the distance travelled on non-required arcs. In this case, the crop rows are the required arcs, and the headlands are the non-required arcs, which were discussed in the previous section. When looking at similar problems in the literature, the distinction can be made between papers that focus on routing a single vehicle (only the harvester), on multiple vehicles (chaser bins included), or a hybrid approach between the two, which will be used here. In this hybrid approach, a predetermined, efficient route is used for the harvester, and the routing for the chaser bins is done during the actual harvest. Palmer (2003) stated that this hybrid approach reduces the travelled distance to cover a field up to 16%.

2.4.2. Level of planning

The level of planning (Chopra & Meindl, 2007) determines the scope of the operational logic. Long-term decisions are made on the higher levels, while more short-term decisions are made on the lower level(s). The three levels and what decision the operational logic needs to consider on each level are as follows.

The first one is the strategic level. This level is the longest term. Farmers decide what kind of resources they allocate, the types of resources they require and which fields they use. On this level, the amount of chaser bins is considered.

The tactical level focuses on a shorter time frame, mostly a quarter of a year. In this period, companies start planning their operations for the coming months. For farmers, this is the agricultural cycle specified in Chapter 2, and what type of crops they will grow in the coming months.

On the operational level, decisions are made on the day-to-day operations. It does this based on the planning at the tactical level. On this level, there exists low flexibility, as many decisions on higher levels have demarcated the scope for the operational level decision making. The operational level can be further split into an offline- and an online part (Hall, 2012). The offline part entails that this planning level concerns the planning of operations. It comprises the detailed coordination of the activities regarding current demand. Online operational planning involves control mechanisms that deal with monitoring the process and reacting to unforeseen events. On the offline routing level, the predetermined routing is made, as discussed in Section 2.4.1. This predetermined route is the route the harvester follows while harvesting. On the online operational planning level, the operational logic is used to deal with unforeseen events.

2.4.3. Planning type

Bochtis et al. (2014) did a literature review on available harvesting problems. They classified all papers into three categories that deal with the problem of the area covering. These classifications are used to quickly identify relevant information in the literature review.

- The first approach Bochtis specified is spatial configuration planning. Here, a geometrical representation of a field area is generated to provide a concise representation of the operational environment. This is required for the quantitative model.
- The second approach is that a continuous path covers the entire area. Here, a single continues path is generated for the harvester. This is used in the predetermined routing of the harvester.
- The final approach is route planning. Route planning concerns the optimal connection of the entities defined previously by a spatial configuration plan.

2.5. Conclusion

This section answered the question*: What is the current situation of the agricultural sector?* This question is answered with several sub-questions:

What key performance indicators (KPIs) need to measure the performance of the EOX tractor according to H2Trac?

The performance of the EOX tractor with regards to the challenges of soil compaction and utilisation rate need to be measured. The number of passes and the weight-driven over the field indicates the soil compaction and harvester utilisation rate is calculated by dividing the time the harvester was active by the total harvesting time.

What requirements do the operational logic and the quantitative model need to fulfill according to H2Trac?

The operational logic needs to maximise the harvester utilisation rate while minimising the soil compaction. The operational logic needs to be able to handle input for a varying amount of chaser bins, chaser bin speeds, different turning circles and different shapes and sizes of fields.

In what fields does the performance of the operational logic need to be tested?

Three fields near Zeewolde are used to test the operational logic. One of these fields has the constraint that the field is separated into 5 different boxes that need to be harvested in sequential order (box 1 -5), but these boxes are not adjacent to the next box. The other fields do not have this restriction, so for these another routing method should be found.

As what type of operational research problem can the operational logic be identified?

This problem can be seen as an arc routing problem. First, a single, continuous path is generated for the harvester. This is the route the harvester follows during the harvest. The chaser bins drive next to the harvester during the harvest, but unlike the harvester they need to switch from time to time whenever they are full. Since the number of crops is only certain after the crops have been harvested, the exact point a switch needs to take place is uncertain. Therefore, the decision of where to switch the harvested needs to be made during the online operational planning.

Chapter 3. Literature review

This chapter answers the question: What tools and models are available in the literature? First, Section 3.1. discusses how authors have tackled this problem. Then Section 3.3. goes into how other agriculture sectors use robotics and the challenges encountered. Finally, Section 3.4. gives a summary of this chapter.

3.1. Related works

In the previous chapter, the operational logic was identified. This section identifies related works by the same metrics. Table 1 shows how the literature on the harvesting process can be classified, as well as the type of data that the paper used. First, the planning types are discussed. Then, the optimisation methods to find suitable methods and models.

3.1.1. Path planning

As stated in the previous chapter, path planning is defined as a continuous path that covers an entire field area (Bochtis et al., 2014). Early works in harvester routing focussed on path planning with deterministic input data on solely primary units (Ali et al., 2009; Ali & VanOudHeusden, 2010; Bochtis & Sørensen, 2010; Palma & Nelson, 2009). These early works focussed on creating exact solutions for small instances.

Palma (2009) solved the mixed-integer problem using the simplex method. He was the first to incorporate stochastic data in the harvesting process by using a protection level. This protection level resulted in a model that was feasible more often, but as a trade-off the objective function decreased a bit (up to 2%). Both methods did not consider the capacity problem. Ali et al. (2009; 2010) did do this. They used branch-and-bound to solve the problem as a vehicle routing problem and a minimum cost network flow, and generated places where the harvester needs to unload. They did, however, not consider the on- the go unloading. They concluded that this algorithm found a solution with small instances, but when fields became larger than 5 ha, the time to find the solution increased significantly.

The focus on the path planning problem then came more on aiding the farmers in making decisions with a decision support system (DSS) (Edwards et al., 2015; Orfanou et al., 2013; Stray et al., 2012). To achieve this, the computational time for the solutions needed to decrease. These authors used Tabu search to find a solution within a reasonable time. Tabu search is an algorithm where a list of (partial) solutions is stored that is forbidden to be visited if the criteria do not allow it, hence the name. Stray et al. (2012) stated that the DSS they proposed can easily be used to evaluate different scenarios, but some alterations need to be made to the DSS for it to be able to handle larger instances.

He et al. (2018) expanded these methods by incorporating fragmented farmlands and multiple harvesters. They did this with Tabu search and with genetic algorithms, where good solutions are found based on a selection process that mimics natural selection.

		Planning type							
Indice	Paper	Spatial configuration	Route planning	Path planning	SU considered?	Datatype	Routing problem/ solution method	Objective function	Notes
1	Palmer et al.(2003)	X			No	Deterministic	Enumeration	Minimise overlap and misses	
2	Crowe et al. (2005)	X	X		No	Deterministic	Simulated annealing	Maximise NPV harvest activities	
3	Palma et al. (2009)			X	No	Deterministic and stochastic	Mixed Integer Program (MIP)	Maximise NPV of the harvest plus value final inventory	
4	Ali et al. (2009)			X	No	Deterministic	Two methods: Vehicle routing problem with turn penalty (ILP) and minimum cost network flow (MIP)	First approach: Minimise the total distance travelled and the weighted number of turns in the field. Second approach: minimise flow cost.	Both Ali's papers cannot find solutions for large problem instances (over 5 ha) in a reasonable time.
5	Ali et al. (2010)			X	No	Deterministic	Minimum cost network flow (IP)	Minimise the flow costs of all combined harvesters	
6	Bochtis & Sørensen (2010)			X	Yes	Deterministic and Stochastic	Vehicle routing problem with time windows (VRPTW)	Minimise the number of vehicles used	Only a theoretical approach is presented
7	Stray et al. (2012)			X	No	Deterministic	Travelling salesman problem (Tabu search)	Maximise total harvesting operational profit	
8	Jensen et al. (2012)	X	X		Yes	Deterministic	Dijkstra's algorithm	Two objectives: minimise travel distance and minimise operating time	The discrepancy between the two objectives in the range of 2-10%
9	Orfanou et al. (2013)			X	No	Deterministic	Tabu search	Minimise maximum makespan	Multiple sequential machine operations

Indice	Paper	Spatial configuration	Route planning	Path planning	SU considered?	Datatype	Routing problem/ solution method	Objective function	Notes
10	Oksanen & Visala (2014)			X	Yes	Deterministic	Two greedy heuristics (simulation)	Minimize cost criteria	
11	Edwards et al. (2015)			X	No	Stochastic	Tabu Search	Minimise maximum makespan	Find optimal schedule multiple fields and vehicles
12	Zhou et al. (2015)	X	X		Yes	Stochastic	Simulation	Minimise total distance and time	
13	Busato et al. (2015)	X	X		Yes	Stochastic	Simulation	Minimise required manpower	
14	Edwards et al. (2017)	X	X		No	Deterministic	Optimised route planner (simulation)	Minimise travel distance	
15	He et al. (2018)			X	No	Deterministic	Tabu Search and genetic algorithm	Minimize wheat harvesting period	Fragmented farmland and multiple harvesters
16	Rodias et al. (2019)			X	No	Deterministic	Simulation and mixed-integer program	Minimise the cost of operation	
17	Evans et al. (2020)	X	X		Yes	Deterministic	Genetic algorithm	Minimise travel length	
18	Khajepour et al. (2020)	X	X		No	Deterministic	Adaptive large neighbourhood search	Minimize travel length	

Table 1: Related works on area coverage planning

3.1.2. Spatial configuration

Recall that the spatial configuration is a geometrical representation of the field area, which is required for the quantitative model. Several authors focus on the spatial configuration of the field. Palmer et al. (2003) were the first ones to do this. They first mapped a field, then proposed a (continuous) path and compared this with the travel paths of the farmers. They found that the use of predetermined paths can reduce the total travelled path by approximately 16%.

Jensen et al. (2012) go further into detail on the geometric description of different fields. They called the method they used for this a "metric map". The metric map represents a field with coordinates placed in an x,y graph. This metric map is then further simplified as a graph. On this graph, a route planning algorithm is used. Figure 7 shows a metric map and the graph that has been derived from this map.

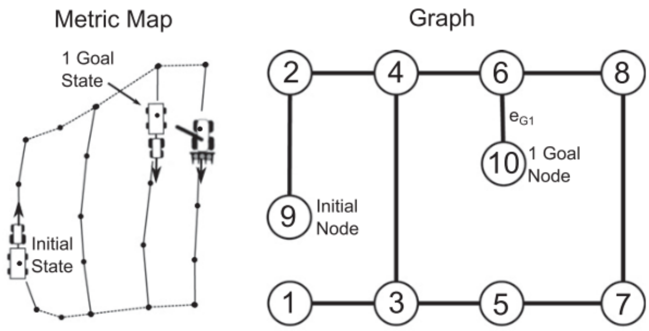


Figure 7: Metric map and corresponding graph from Jensen et al. (2012)

Several other authors have also incorporated the spatial configuration in their models but described them in far less detail (Busato & Berruto, 2016; Edwards et al., 2017; Zhou et al., 2015). They used information retrieved from a tractor on which they put a GPS tracker. They then imported this data into their respective software and did their experiments with it. Evans et al. (2020) used a mapping tool to convert the GPS coordinates to the Universal Transverse Mercator (UTM) for simplified distance calculations. The UTM divides the earth into 60 zones of equal length and height, making mapping onto an x,y plane easier. This method focuses on the turns on the headlands, with the time and exact positioning considered.

Khajepour et al. (2020) considered several fields to show the validity of the algorithm. Some of the used fields were realistic field representations and some fictional fields. They looked at how the position of the depot affected the total distance driven, which showed that the depot location has a significant impact on the distance driven.

3.1.3. Route planning

Recall that route planning concerns optimal spatial configuration routes, with both non-working and working elements. The distinction was made between route planning of a sole primary unit and the service units (alongside a primary unit). If the papers consider service units with the route planning, the primary unit is unloaded on the go by the service units, as is the case within the thesis.

3.1.3.1. Solely primary units

Crowe et al. developed a simulated annealing algorithm to maximise the net present value of the harvesting activities. This algorithm approximates the global optimisation in large solution spaces and can escape local optima. Edwards et al. (2017) created a planning tool based on a combinatorial optimisation algorithm but does not further specify which algorithm. They state that the tool they created struggles with optimising routes for fields with narrow areas. They showed that a reduced travel distance of up to 18% on the field could be achieved with their tool.

Khajepour et al. (2020) defined the problem differently than other authors. Most authors stated the problem as an instance of the vehicle routing problem, where the crops are defined as the customers with demand. Khajepour et al. defined their problem as a capacitated arc routing problem. The capacitated arc routing problem means that they were only interested in the arcs the vehicles drove over instead of the crops they needed to visit. They generated solutions with the use of a large neighbourhood search. This algorithm selects different solution heuristics and the neighbourhood that is considered. Their conclusion is that due to the number of variables in scheduling agriculture, conventional harvesting patterns are not always necessarily the most efficient.

3.1.3.2. Service units

Jensen et al. (2012) focused on a chaser bin that needs to go from its current position to the harvester that is operating in the field. To accomplish this, they used the Dijkstra algorithm with two objectives. The first one is to minimise the travel distance, and the second one is to minimise the operating time. They found a discrepancy between the two objectives ranging from 2 to 10%. This difference indicates that the identification of the appropriate objective is significant for the outcome of the model. The method they developed was quick enough to be used on the operational level.

Zhou (2015) did a simulation study on the effects of different scenarios on the performance of primary and service units. They discovered that the operation time of the process is influenced by driving direction, fieldwork pattern, machine capacity, and the position of the service units. Zhou specified that their simulation model can be used as a DSS and can be used to evaluate alternative scenarios.

Busato et al. (2015), like Zhou, created a simulation model, but their model was designed for rice harvesting. Their method provides a low error in the prediction of the operational parameters (2.59%-3.12%). Furthermore, they showed that the area capacity, the field area in which the crop can be harvested and transported in a unit of time, can increase up to 7% when the Service Units are the bottleneck.

Edwards (2017) made a tool called the Optimised Infield Route Planner (ORP). They showed that their ORP tool could reduce the total distance travelled by as much as 18% when compared to how the farmers would normally operate. They, however, did not specify the exact characteristics of the used algorithm, other than that it was based on a combinatorial optimisation algorithm. The algorithm attempted to find the shortest possible non-working distance for the machine, so the amount of travel on the headlands. This paper also discusses that when speed and acceleration were considered, reversing was faster than forward turning for distances below 10 m.

Evans (2020) went further into turning on the headlands, showing five different techniques that can be used for travelling between two adjacent rows. Besides this, a U-turn is also described when multiple rows are skipped between rows. They used a mathematical model, and this was formulated as a TSP and solved using a genetic algorithm. Their method showed a decrease in non-working in-field travel by 5.9% to 17.2%.

3.1.4. Quantitative model

There are generally two quantitative models described in the literature as presented in this section. The first one states the model as an analytical model, like an (mixed) integer program, and the second one uses a simulation model. One significant advantage of the analytical model over simulations is that an optimal solution can be found. However, because of complexity and stochastic relations, not all real-world problems can be represented in this form adequately (Winston, 1971). Here, simulation models come into play. These simulation models use a set of assumptions on the real-life system, which are expressed as mathematical and logical relations.

This thesis uses a combination of both an analytical model and a simulation model. An analytical model is used to find an optimal, continuous path for the harvester. This path is created before harvesting and is not affected by other stochastic relations like the capacity, the number of crops and the failures. This is where the simulation model comes into play, as these relations can be modelled here. The simulation model is then used to evaluate the operational logic.

3.2. Robotic systems in agriculture

The previous section discussed how other authors had tackled the problem of harvester planning in agriculture. While this gave useful insight into the logistical side of this problem, implementing this within the robots themselves has been omitted so far. This section first identifies the type of robotic system and then goes into robotic systems that have been incorporated in (other areas of) agriculture, what objectives, constraints, parameters, and assumptions they had to consider and how these findings are used in the thesis.

3.2.1. Background

The agricultural sector lags behind sectors like the automotive industry when comparing the level of automation achieved (Bechar & Vigneault, 2016). In other sectors, either the robots or the environment is structured. This is exemplified by an automated car factory where both the environment is always the same, and the robots always move in the same pattern. This is different in agriculture, as this domain has both structured objects and unstructured objects. Therefore, sophisticated, and intelligent algorithms for sensing, planning, and controlling are required in this domain to keep up with the unstructured and dynamic environment.

The current academic trends and research in agricultural robotics focus on building a swarm of small-scale robots and drones that collaborate to optimize farming inputs and reveal denied or concealed information (Shamshiri et al., 2018). In addition to this, small vehicles also enable reduced environmental impact by avoiding the over-application of chemicals and overlapping coverage, and their lighter weight and lower ground pressure cause less soil compaction. In addition, smaller systems generally cost less than larger ones (Bechar & Vigneault, 2017).

3.2.2. Objectives

Literature on robotic systems in agriculture generally falls into one of two different categories (Shamshiri et al., 2018). The first category focuses on developing or advancing vision-based control, advanced image processing techniques, and gripper design for automated harvesting of valuable fruits. The second category concerns navigation algorithms and robust machine vision systems for developing field robots that can be used in yield estimation, thinning, weeding and targeted spraying, seeding, and transplanting, delicate handling of sensitive flowers multipurpose autonomous field navigation robots.

The usage of robotics must comply with the following rules:

1. The capricious requirements for manipulating specific products must be considered first.
2. The agricultural task and its components must be feasible using the existing technology and the required complexity.
3. The cost of the agricultural robotics alternative must be lower than the expected revenue. However, it does not have to be the most profitable alternative.

Therefore, at least one of the following requirements must be met:

1. The cost of utilising robots is lower than the cost of any concurrent method.
2. Robots enable increasing farm production capability, produces, profit, and survivability under competitive market conditions.
3. The use of robots improves the quality and uniformity of the produce.
4. The use of robots minimises the uncertainty and variance in growing and production processes.
5. The use of robots enables the farmer to make decisions and act at higher resolution and increase the product quality compared to the concurrent system to achieve optimisation in the growing and production stages.
6. The robot can perform specific tasks that are defined as hazardous or that cannot be performed manually.

In agriculture, it is expected that for completing the objective, different automated vehicles need to perform various sub-tasks at the same time. This scenario is common since many field operations require two or more vehicles to execute the task. For example, a harvester and a chaser bin. These systems with multiple vehicles consist of different sensors, actuators and computers that work synchronously in a specific architecture (Gonzalez-de-Soto et al., 2016) and require precise collaboration abilities (Bechar et al., 2015). Therefore, a master-slave system (MSS) has to control the (relative) positioning of all vehicles in the operation (Bechar & Vigneault, 2017). The "master" vehicle performs decision-making processes and commands the "slave" vehicle. This vehicle in turn follows the instructions received and reports its status by transmitting information about its location, orientation, and operating conditions.

3.2.3. Challenges

The implementation of robotics in agriculture is still facing some challenges. One often-mentioned challenge is that of "Smart Farming" (Shamshiri et al., 2018; Villa-Henriksen et al., 2020; Wolfert et al., 2017). Smart farming not only includes robotics, but sensing and monitoring the robotics, and analysing the results, and adjusting the robotics after that as well. While regular farming just takes in-field variability into account, Smart Farming goes beyond that by basing management tasks not only on location but also on data, enhanced by context- and situation awareness, triggered by real-time events (Wolfert et al., 2014). Figure 8 shows how these elements interact with each other.

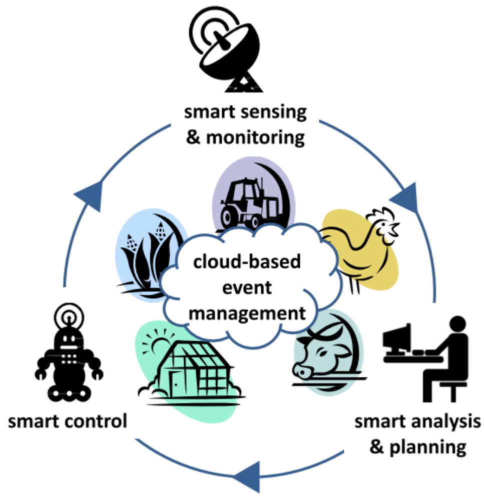


Figure 8: Smart farming cycle

Shamshiri et al. (2018) stated that, although data is available, robotics are still not widely incorporated. Farmers do not have the time or resources to analyse all data carefully, and therefore they still make many decisions on gut feelings. To overcome this, robots need to be made "smarter". Smarter here means that the robots need to be able to gather data, analyse it and make decisions based on it all in real-time. This is exemplified by crop plant sensors that analyse, recommend, and apply a treatment to a plant in one go.

Villa-Henriksen et al. (2020) performed literature research on the challenges of Smart farming. This paper showed how they categorised these challenges and how the challenges evolved (see Figure 9). They showed that the literature is now starting to focus on data analysis, communication protocols and latency issues.

Other challenges relevant to the thesis are listed below.

System heterogeneity

Different data systems are used within farms. Sensor data can be encoded in many different forms, such as json, XML, CSV, or even proprietary files.

Data heterogeneity

The type and the accuracy of the data that is used in agriculture can differ by a large amount. There are generally three types of data generating (Devlin, 2012): human-sourced, process-mediated and machine-generated. Human sourced data is the record of human experiences, this part is rarely discussed in the context of smart farming. Process mediated data, or the traditional business data, result from agricultural processes that record and monitor business events of interest. Machine-generated data are derived from sensors and smart machines used to measure and record farming processes. This development is currently boosted by what is called the Internet of Things. This type of data is well structured for computer processing, but the size and speed required is beyond traditional approaches.

Robustness

Robust wireless connectivity is an important limitation in many setups (Oksanen et al., 2016). Faults, errors, and unforeseen events need to be considered to ensure the reliability of the system. In this scenario, the human capabilities of perception, thinking and action are still unrivalled by any computerised system (Tervo & Koivo, 2014).

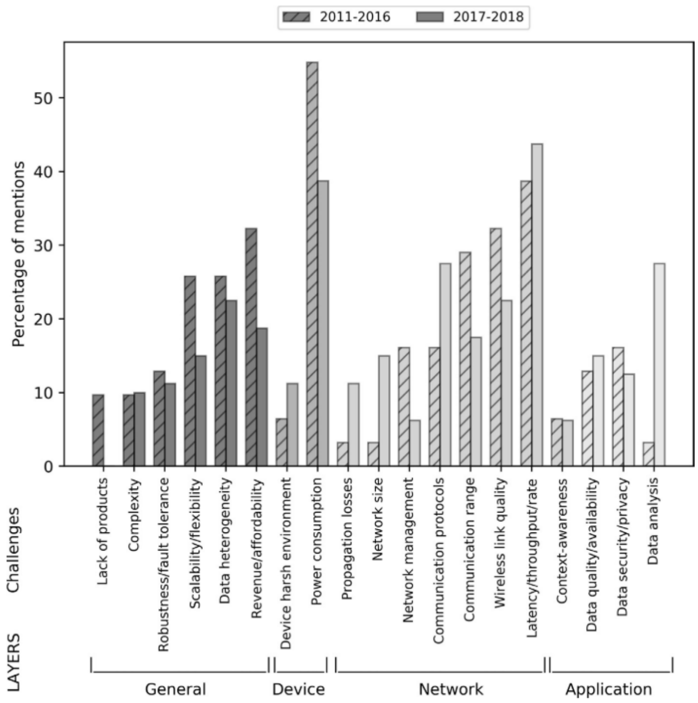


Figure 9: Percentage of challenges mentioned by literature, split into the categories general, device, network and application (from Villa-Henriksen (2020)

3.3. Conclusion

This chapter identifies the problem this thesis is tackling concerning related literature. This chapter answers the questions:

a. *How do collected works relate to the problem of harvester routing?*

The collected works on harvester routing were categorized into spatial configuration, path planning, and route planning. Most sources remain vague on the exact methods of how they converted the GPS coordinates into their models, with the notable exception of Jensen (2012) and Khajepour (2020). They explained how they turned their data into graphs. These papers are used as inspiration for this thesis. First, the spatial configuration is made in the model and then used as input for the route planning.

Several findings can be found in the literature regarding quantitative models. The first one is that both a simulation model and a mathematical model work to evaluate the performance of the harvester routing problem. In this thesis, a continuous path for the harvester is created in an analytical model. But because of the complexity of the model and the stochastic relations, the analytical model alone is not sufficient to evaluate the operational logic. Therefore, the operational logic is incorporated in a simulation model where the performance is evaluated. Here, stochasticity is incorporated in the failure rate of the vehicles and the total amount of crops harvested per square meter. For the deterministic part, a path is generated that minimises the non-working time over the field, as is specified in the paper of Edwards et al. (2017). Then, Dijkstra's algorithm is used to find the shortest route from the current position of the chaser bin to the harvester whenever this is necessary, as discussed in Jensen et al.(2012).

b. What objectives, challenges, and limitations for implementing robot systems in agriculture mentioned in the literature are relevant for the thesis?

Summary of the findings of robotic systems in agriculture:

- Because both the environment and the robots are unstructured in agriculture, most robotics is still developing. Therefore, not many commercial products are available yet.
- A list of criteria for implementing robotic systems in agriculture was stated. In the conclusions of the thesis, this list is used to identify what criteria the EOX meets.
- For this thesis, a master-slave system needs to be made. The harvester (master) makes decisions, and the chaser bins (slaves) need to follow these orders and give the harvester their position and orientation.
- Smart farming needs to be considered with the EOX tractor. The harvester and chaser bins can provide valuable data, so sensors need to be installed to ensure this data is revealed.

Chapter 4. Solution design

This chapter focusses on operational planning. First, offline planning is discussed in Section 4.1. Then, Section 4.2. focusses on online planning. The online planning focusses on the decisions that need to be made during the harvest. Since the EOX tractors are currently in development, the harvest is simulated in the evaluation model, which is the subject of Chapter 5.

4.1. Offline planning

The offline planning is the part of the planning that takes place before the start of the harvest. The offline planning consists of two parts. The first part focusses on the continuous path that the harvester will take, and the second part aims to estimate where the chaser bins will need to switch. Both offline planning components require information on the length of the crop rows, the distance between the crop rows. For the second part, the capacity of the chaser bin and the average amount of crops per square meter are required as well. This information can either be measured in the real field, or this information can be extracted from the metric map which is created in the evaluation model (see Section 5.2.2).

4.1.1. Harvester path planning

As stated in the previous chapters, this is an arc routing problem where the problem is to minimize the amount of travel the harvester needs to do on the headlands. Therefore, only a single vehicle (the harvester) is considered, without any capacity constraints. The only constraint that is considered is that the turning point of the harvester is too large to go to the adjacent row. The input for the path planning is the distance matrix between the depot (which in this case is the location where the chaser bins can unload the harvested crops and refuel) and the crops rows. The distance matrix is calculated from the data in the quantitative model, which is described in further detail in Section 5.2.2. This distance matrix is created by calculating the Euclidean distance between the start of two rows and the endings of two rows, and the average is then taken and placed in the distance matrix. Note that the distance matrix is undirected, so, for example the distance from row 1 to row 3 is the same length as the distance between row 3 to row 1. The exception in this matrix is going from a row to the adjacent one, as the harvester cannot make this turning circle. This distance is given a value of 10000, as this number is sufficiently big to prevent the solver from ever picking this as a possible solution.

First, an initial solution is generated from the distance matrix. Two different strategies are used and compared to find out what initial solution strategy is the most accurate. The strategies that will be evaluated are:

1. Cheapest arc insertion. Here the closest crop row is selected that has not been visited yet until all crop rows have been visited.
2. Savings algorithm (Clarke & Wright, 1964). This strategy consists of 4 steps (MIT, n.d.). First, the savings s(i,j)=d(D, i)+d(D,j) -d(i,j) for every pair of rows (i,j) is calculated, with D being the depot. The savings s(i,j) is the amount that reduces the total tour length by combining row i and j in a single tour. In step 2, these are all ranked from the most to the least savings (as long as they do not violate any constraints). Then, in step 3, starting from the most savings, work down the list and include link i,j in the route if neither i or j are already in the route, either one of the two points is in the route and the other point is not used adjacent to the depot, or both points are already in a route and no other rows are left. Finally, return to step 3 if there are still points left.

After the initialinitial solution strategies, a local search is done to see if this initial solution can be improved further. Three local search algorithms are used to get out of local optima:

1. Tabu search.
2. Greedy Descent
3. Simulated Annealing.

These local search algorithms were allowed to run for 120 seconds before they were terminated to ensure that path generation did not take too long. Then, the best solution that was found is used as input for the online route planning.

This harvester path planning was made in Python with the use of the OR-Tools library developed by Google. This library allows quick selection for developing an initial solution and iterating on this solution using a local search. The initial solutions that are used are either the savings algorithm or the cheapest arc insertion. These were used either with or without a local search algorithm, namely Tabu search or the simulated annealing algorithm. Additional settings for the local search, like the length of the tabu list and the initial temperature of the simulated annealing algorithm, were left on automatic.

4.1.2. Chaser bin switch estimation

An estimation of where the chaser bins will switch is made before the harvest. This is done to ensure that the chaser bin is at least close to where it needs to be for a switch, so the harvester does not need to wait for the new chaser bin for longer than necessary. The estimation is made with the use of information of the length of the crop rows, the harvester path that was discussed in the previous section, the capacity of the chaser bins and the average number of crops per square meter. First, the average crops are multiplied by the length of the crop row. This is the expected number of crops in that row. If this amount can be included in the current chaser bin, the remaining capacity of the current chaser bin is updated, and the next row is evaluated. If the remaining capacity is too low to get all crops, a new switch is stored in the table, including which row it takes place, and if it occurs closer to the left or the right side of the row. Then, the remaining capacity is restored to the maximum capacity of the chaser bin, and this process is repeated until all rows have been evaluated.

4.2. Online planning

The online planning is the planning and the decisions that are made during harvesting. This online planning takes the form of a master-slave system, as discussed in Section 3.3. The harvester (master) needs to command the chaser bins (slaves) to their supposed positions, and in turn, the chaser bin needs to give information on the orientation, location, and capacity level to aid the harvester. The harvester controls the chaser bins based on their activity, so these activities need to be discussed before discussing the master-slave system and the decisions that are made in which situation. Four activities have been identified that both the harvester and the chaser bin can participate in:

1. **Driving over the field.** During this activity, the harvester and chaser bin drive in a row over the field. In this activity, the differentiation is made whether the vehicles are **linked** or **not linked**. If the harvester and a chaser bin are linked, the chaser bin drives beside the harvester. The harvester, in turn, can give over the harvested crops to the chaser bin.
2. **The vehicle has reached the end of the row.** The vehicle reaches the end of the row once the entire row has been travelled. Once either the harvester or the chaser bin reaches the end of the row, the vehicles are decoupled to sever the link between them. Once the harvester reaches the end of the row, it decides where to go next.
3. **Driving to the next row.** Once the next row that will be travelled has been determined, the vehicles drive over the headlands to the next destination. Both the harvester and the chaser bin drive over the headlands to the next row to avoid driving over crops.
4. **Drive back to the unloading point and the charging station.** In this state, the harvester or the chaser bin drives back to the charging station and unloading area. For the harvester, this only happens once the entire field has been harvested. For the chaser bin, this can happen when it is at capacity.

Of these four activities, the vehicles will spend the most time driving over the field. The vehicles also have activities that the other vehicle type cannot do. For harvesters, this activity is:

- **Harvesting.** The harvester is capable of harvesting crops, unlike the chaser bins. During this activity, the harvester drives over the field, and the harvesting tool gathers the crops from the field. The tool harvests the tools and places it in the chaser bin with the use of a spout. This spout is situated at the right side of the tool, so the active chaser bin always needs to drive on the right side of the vehicle.

And for the chaser bins:

- **Drive forward or backwards interchangeably.** Unlike the harvester, the chaser bins do not have a specific front or a back end. Therefore, it can travel in both directions at the same speed without difficulties. To specify which end of the harvester is meant, the driving direction is always referred to as the front side of the vehicle. Because the vehicle can drive in both directions, the chaser bin has virtually no turning circle. Which makes it capable of going from one row to the row adjacent to it (Recall that the harvester needs at least 2 rows in between)

The remainder of this section focusses on the decisions the harvester makes when it is participating in a certain activity, as well as what happens when the chaser bins need to be switched. For each of the harvester activities, a flowchart is made for the chaser bin activities, and the corresponding decisions that are taken when those activities occur. In the explanation for the activities, a number indicates the step in the flowchart.

4.2.1. Harvester drives over the field

When the harvester drives over the field (1), the chaser bin can be in three activities (see Figure 10). The chaser bin activities and the corresponding decisions are:

- The chaser bin is driving to the next row (2), while the harvester is already in the new row. When this happens, the harvester needs to stop until the chaser bin has reached the required row (3).
- The chaser bin is also driving over the field (4, 5, 7, 9). When this happens there can be a total of three scenarios. The first scenario is that the harvester and the chaser bin are not linked (4), and that the chaser bin is in front of the harvester (5). When this happens, the chaser bin is commanded to stop until the harvester has reached the position next to the chaser bin (6). During this time, the harvester still collects crops but does not give these over. The second scenario is when the chaser bin and the harvester are not linked (4), and that the chaser bin is driving behind the harvester (7). In this case, the harvester stops until the chaser bin has reached the position next to it, after which both resume the harvest (8). The third and final scenario is when the chaser bin is linked to the harvester (9). When this scenario occurs, the harvester and chaser bin can continue driving at the same speed (10).
- The chaser bin reaches the end of the row (11). When the chaser bin has reached the end of the row while the harvester is still driving over the field, the link between them is broken if it this had not been done already (12), and the chaser bin needs to stop until the harvester has reached the end of its row since the next row the chaser bin needs to go to is still unknown (13). If it was already severed (14) the harvester continues, and the chaser bin stops (15).

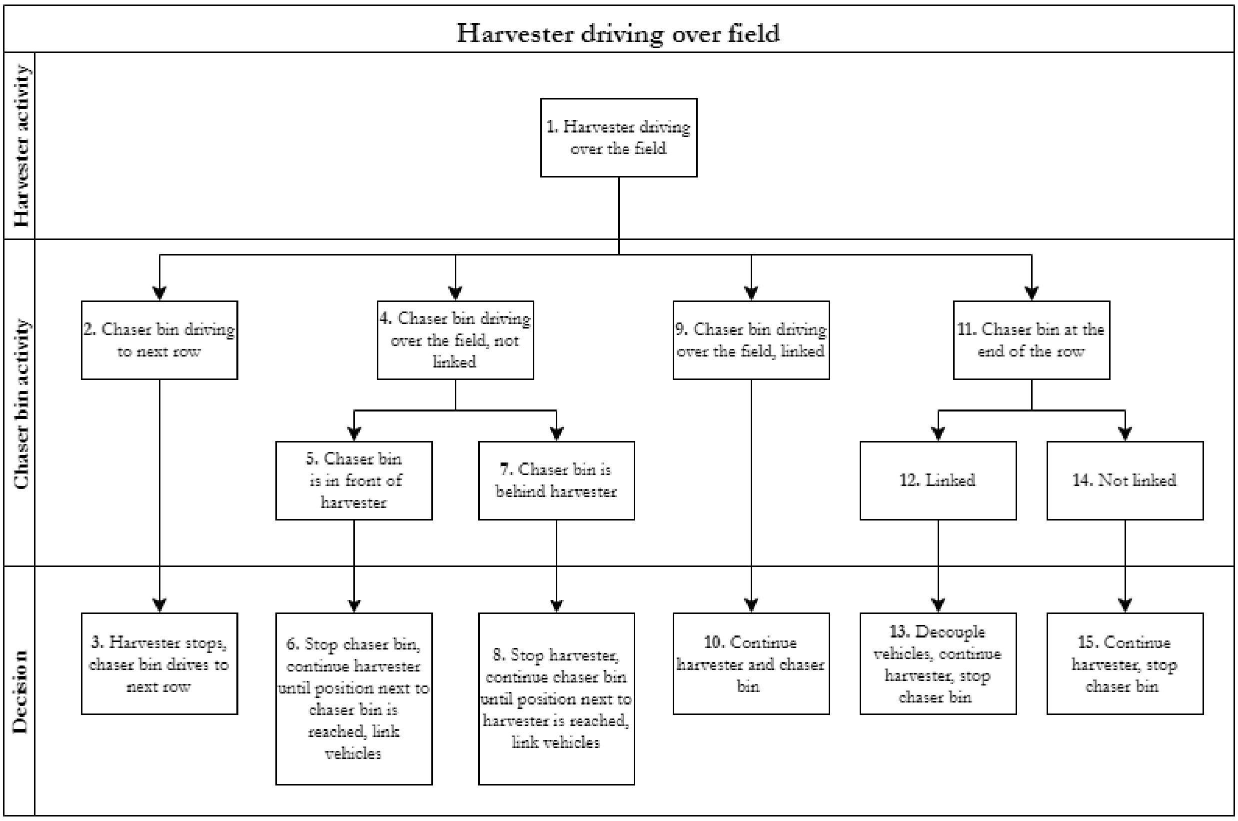


Figure 10: Harvester driving over the field, chaser bin activities and decisions

4.2.2. Harvester is at the end of the row

When the harvester reaches the end of the row (1), only two activities of the chaser bin are viable (see Figure 11activities 4 and 6 are available).

Not viable:

- The chaser bin is driving to the next row (2). This scenario is not possible, since the chaser bin does not know the next row it needs to go to yet.
- The chaser bin also reaches the end of the row, but the vehicles are not linked (3). This scenario is not possible since the harvester and the chaser bin are linked up before the end of a row is reached.

Viable:

- The chaser bin is still driving over the field and is linked with the harvester (4). If this is the case, the link between the two vehicles is severed and the harvester finds a new row to harvest (5). The chaser bin can continue driving until it reaches the end of its row.
- The chaser bin reaches the end of the row simultaneously with the harvester (6). If the harvester and the chaser bin reach the end of their row simultaneously, the harvester finds a new route (8,10). First for itself, and then for the chaser bin. The vehicles are decoupled if they are still linked (7,8).

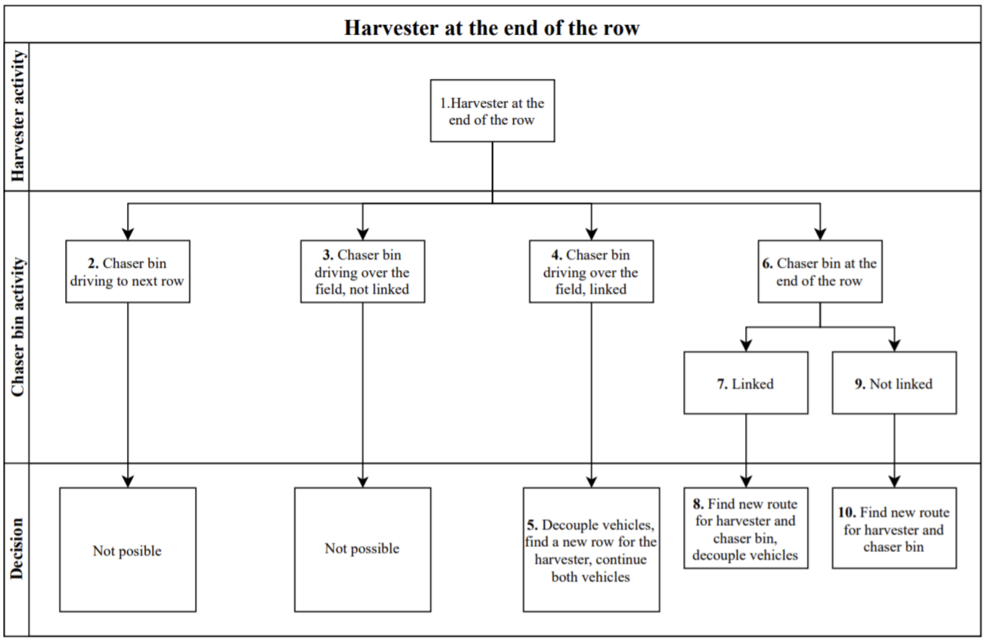


Figure 11: Harvester reaches the end of the row, chaser bin activities and decisions

4.2.3. Harvester drives to the next row

When the harvester is driving to the next row (1), three activities are available to the chaser bin (see Figure 12 activities 2, 4 and 6). No differentiation is made between whether the vehicles are linked or not. This is because the chaser bin and the harvester have been decoupled already.

- The chaser bin is also driving to the next row (2). When this happens both vehicles drive to the next row (3). The harvester states its location, so the chaser bin can move out of the way to avoid collisions.
- The chaser bin is at the end of row (4). When this happens, the harvester finds a new row for the chaser bin (5). The harvester drives to the next row. Again, the chaser bin is instructed to avoid collisions.
- Chaser bin (still) drives over the field (6). It is unlikely, but one row may be significantly longer than the one next. When this happens, the harvester drives to the next row and the chaser bin continues to drive in the row until the end is reached (7).

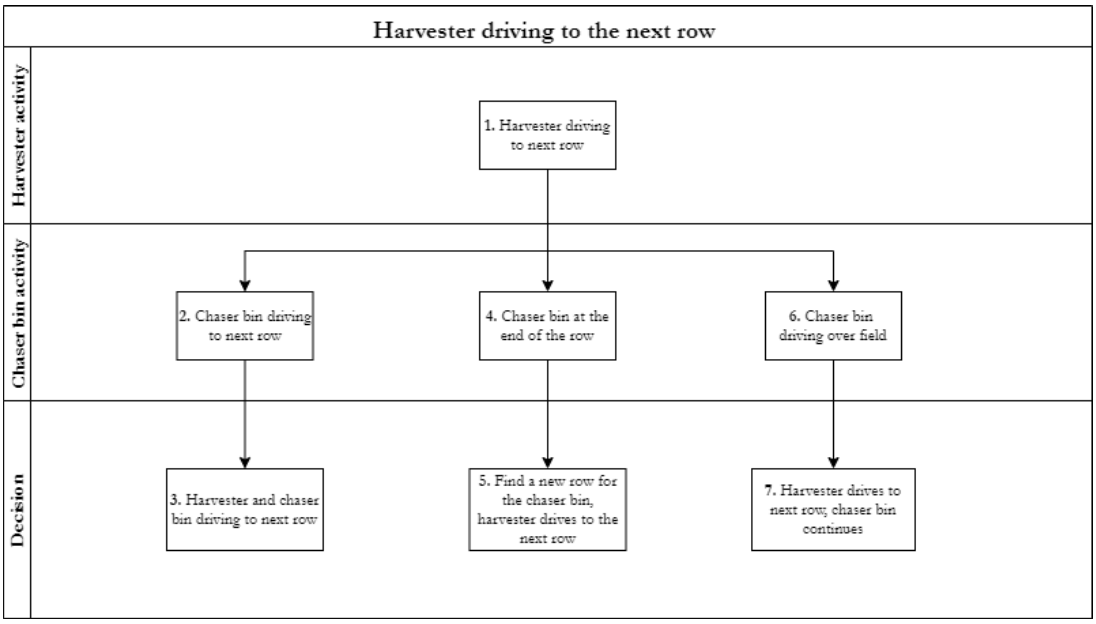


Figure 12: Harvester driving to the next row, chaser bin activities and decisions.

4.2.4. Harvester is driving back to the unloading point and charging station

Once the harvester has reached the end of the field, the harvester can drive back to the charging station and unloading point (1). For readability, the charging and unloading point is called home in Figure 13. The chaser bin can be busy in two activities (2 and 4), and the vehicles are always decoupled so no differentiation is made on that front. One thing to note is that no new decisions are made after the harvester and the chaser bin are driving home. Therefore, the activity of a chaser bin driving home is neglected.

- Chaser bin at the end of the row (2). Since the harvester has already completed the main tasks, the chaser bin is instructed to drive back home as well (3).
- Chaser bin driving over the field (4). The harvester is already on the way back home, but the chaser bin still has not finished the row. The harvester keeps driving back home, and the chaser bin continues until it reaches the end of the row (5).

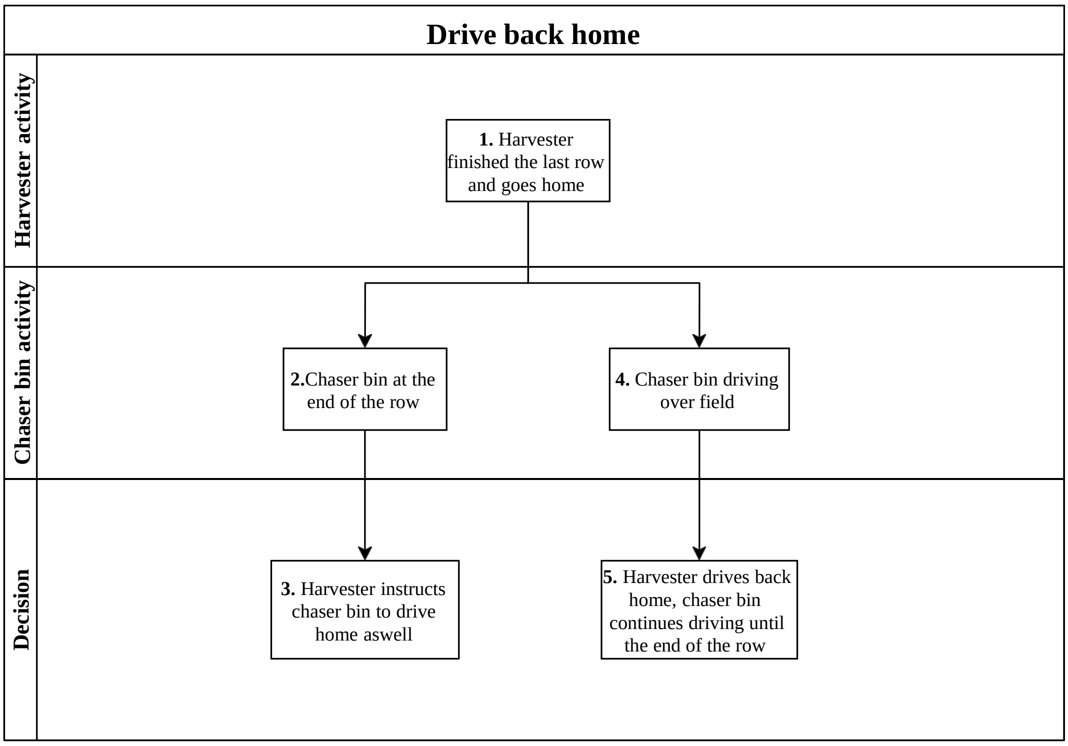


Figure 13: Harvester is driving home, chaser bin activities and decisions

4.2.5. Selecting a new chaser bin

The chaser bin needs to be switched when a chaser bin is full, the chaser bin loses connection to the harvester or has a mechanical failure. When the harvester fails, the entire system fails so this is not considered. **Fout! Verwijzingsbron niet gevonden.** shows the possible scenarios and activities when a chaser bin fails. A chaser bin can fail regardless of the activity of the harvester (1), but it can only reach the capacity threshold when the harvester is linked with the chaser bin, as that is the only time the chaser bin receives new crops. When the chaser bin fails (2), a new chaser bin immediately needs to take over the old chaser bin, regardless of whether it was a mechanical or connectivity failure. In this case, the new chaser bin drives to the front of the harvester via the headlands (3). The harvester has approximately enough capacity to store up to 10 meters of a crop row, so the harvester continues only when the new chaser bin has arrived.

In the case that the old chaser bin has reached a threshold that a new chaser bin needs to be selected (4), the harvester drives to the row that is approximately where the switch takes place (5). How this approximate row is chosen was specified in Section 4.1.2. When the threshold is reached that the old chaser bin is full, the old and the new chaser bin switch. How this switch takes place is specified in the next section.

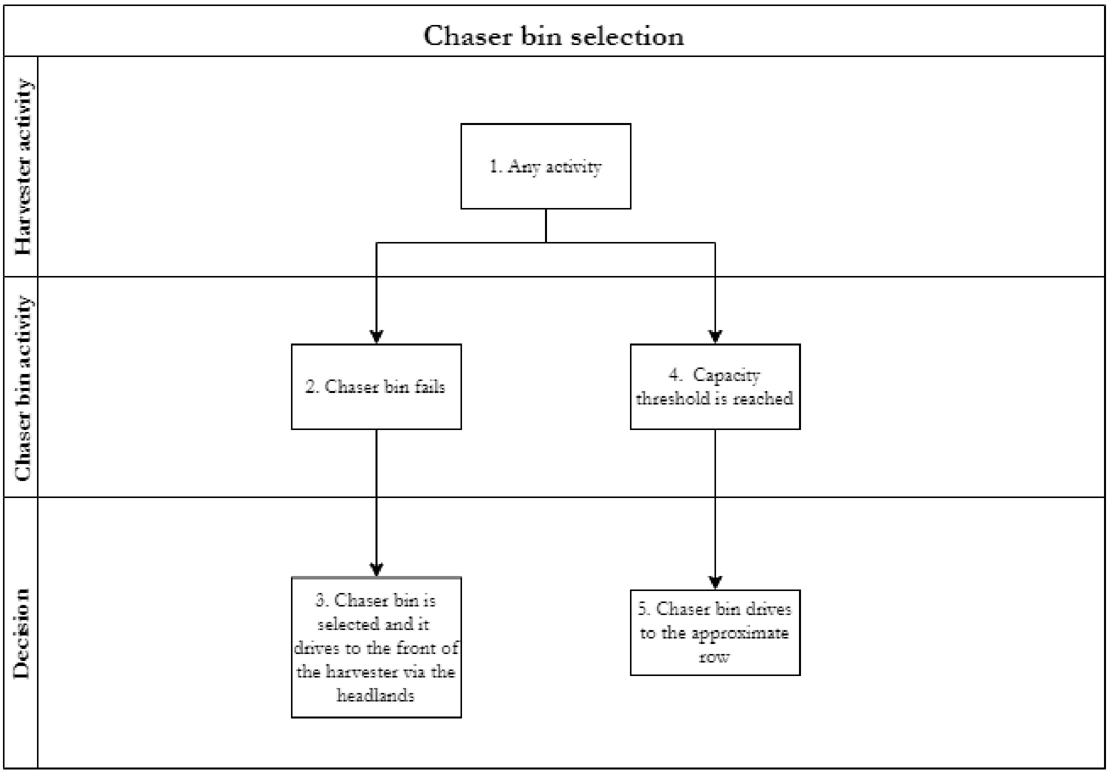


Figure 14: Chaser bin selection

4.2.6. Switching chaser bins

Fout! Verwijzingsbron niet gevonden. shows the possible scenarios and activities when a chaser bin fails. A chaser bin can fail regardless of the activity of the harvester (1), but it can only reach the capacity threshold when the harvester is linked with the chaser bin, as that is the only time the chaser bin receives new crops. When the chaser bin fails (2), the new chaser bin immediately needs to take over the old chaser bin, regardless of whether it was a mechanical or connectivity failure. In this case, the new chaser bin drives to the front of the harvester via the headlands (3). The harvester has approximately enough capacity to store up to 10 meters of a crop row, so the harvester continues only when the new chaser bin has arrived. In the case that the old chaser bin has reached a threshold (4), the harvester drives to the row that is approximately where the switch takes place (5).

First, the harvester sends a signal to the new chaser bin where to go to for the switch. The actions required for the switch depend on whether the "old" chaser bin is linked to the harvester or not (see Figure 15). If the switch takes place when the harvester and the chaser bin are not linked, the chaser bin can seamlessly take the place of the old chaser bin. This is done at the beginning of a new row, where the chaser bin is instructed to drive back home. The new chaser bin instead drives to this next row, and the harvest continues.

When the harvester and chaser bin are linked, the actions that need to be taken are more complicated. The first thing that needs to be determined is if the new chaser bin approaches the linked harvester and chaser bin from the front (where the harvester is driving towards) or from the back (where the harvester just was). Another possibility is that the chaser bins are so close to each other, that it might be more advantageous to make the switch on the headlands, so the chaser bin does not need to cross the entire row.

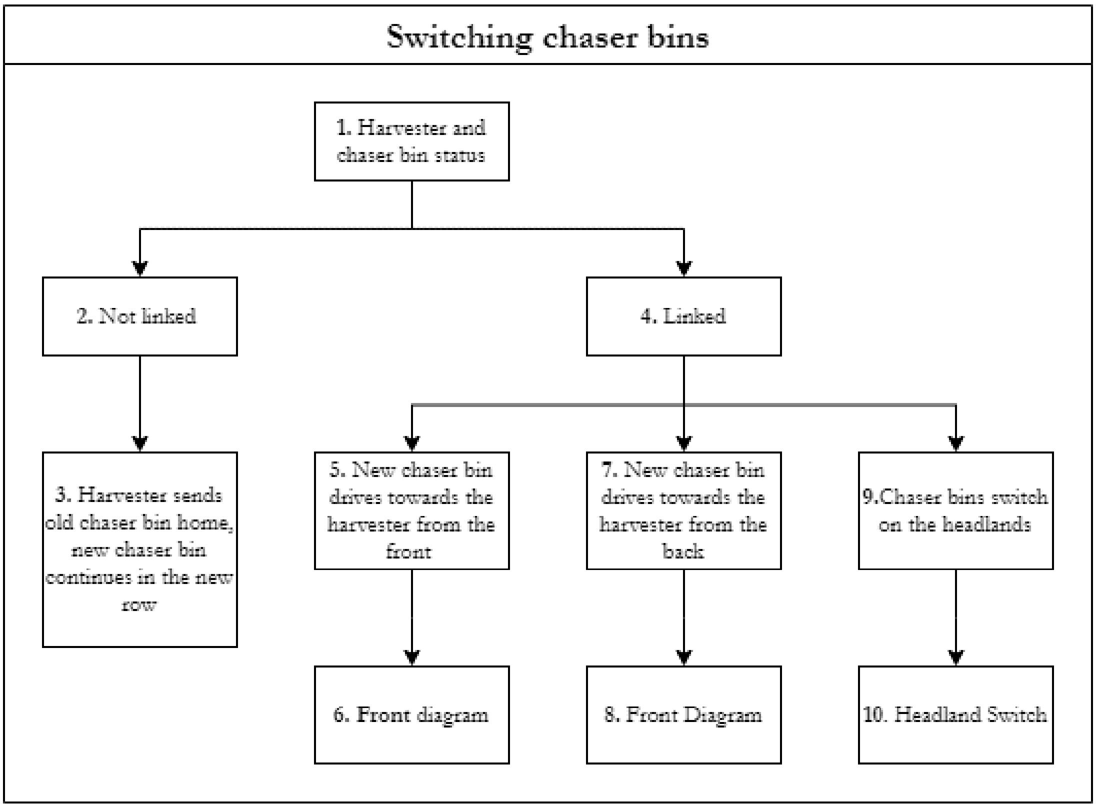


Figure 15: Decision tree for linked and unlinked vehicles.

Front

If the new chaser bin approaches from the front, the actions for the switch are made when the new chaser bin is in the proximity of the harvester (see Figure 16). Proximity here means that the old and the new chaser bin are close enough that no crops fall onto the ground when switching chaser bins. When the vehicles are close enough, both chaser bins stop, and the harvester continues the harvest as usual (6.2). Once the harvester is solely handing over the crops to the new chaser bin, the new chaser bin reverses direction (6.3). This is possible because both ends of the chaser bin are identical, so it does not have a front or a back end like the harvester. When the switch has been successfully made, the old chaser bin is sent home (6.4). Here, Dijkstra's algorithm is used to find the quickest route from its current position back to the unloading and charging stations.

Headland switch

Another option is to change at the headlands. Switching the chaser bins on the headlands can reduce soil compaction if both vehicles are close to the same edge of the field. For instance, when the old chaser bin needs to be switched at the beginning of a row and the new chaser bin is also close to this point. In the previous method, the old chaser bin would have to drive all the way to the end of the row to be able to drive home. In this method, it only needs to go to the beginning of the row where it is already close to and let the new chaser bin pass. When the chaser bin is close to the harvester (7.1), the old chaser bin can be switched. The old chaser bins drives to the headlands (7.2) and lets the new chaser bin pass so it can drive to the harvester (7.3). The old chaser bin can then return to the unloading point and the new chaser bin quickly catches up to the harvester. The downside of this method is that during the switch, the harvester is stopped so the utility goes down. Therefore, the choice when to use the headland switch or another switch needs to be closely considered. Section 5.4. goes further into the scenarios that are used to consider when to use what switch method.

Back

If the new chaser bin approaches from the back of the vehicles, the switch is made once the new chaser bin is near the linked harvester and chaser bin (see Figure 16, 8.1). Only this time, neither vehicle needs to stop. Now, once the chaser bin is near the linked vehicles, the old chaser bin is instructed to go home (8.2). This chaser bin then drives away at full speed than the harvester (8.3.). The new chaser bin simultaneously matches this speed so the gap between the two vehicles remains the same (8.4). Once the new chaser bin is next to the harvester, it decelerates to match the speed of the harvester (8.5).

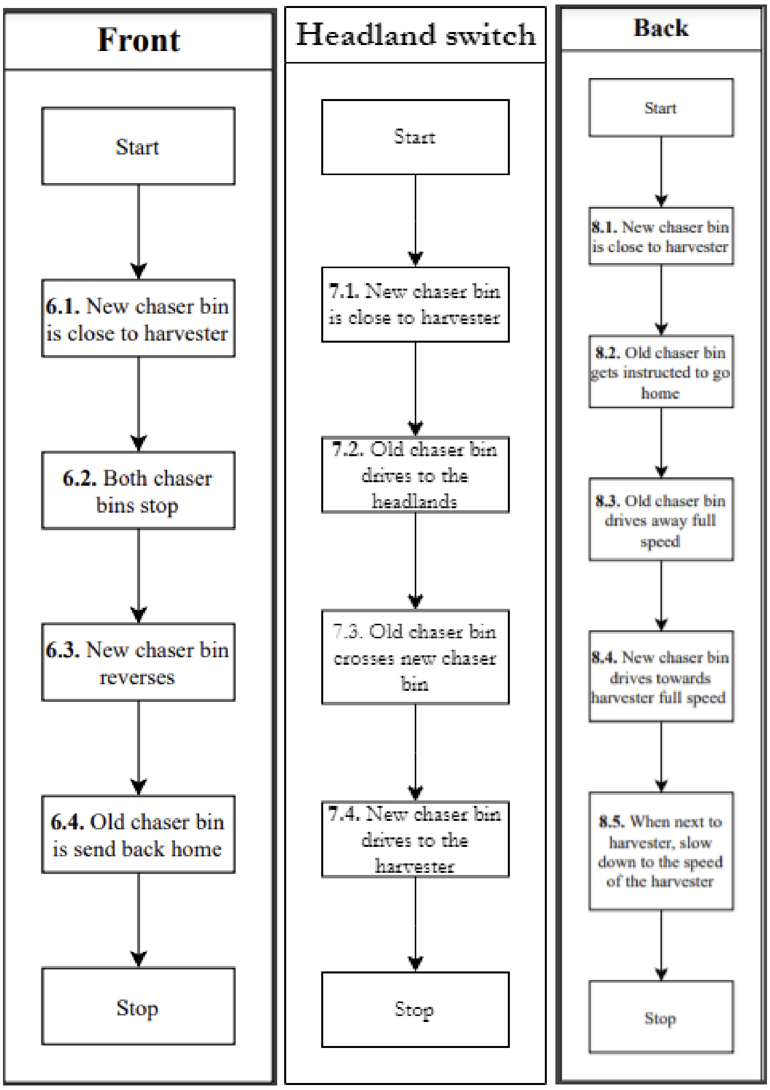


Figure 16: Possible switches the chaser bins can make. From left to right: New chaser bin approaches from the front, Chaser bins switch at the headlands and the chaser bin approaches from the back

4.3. Conclusions

This chapter answered the research question: *"How should the operational logic of the EOX tractors be designed?"*. This question was first divided into several subquestions:

a. How should the sequencing of harvesting rows be determined?

The sequencing of the harvesting rows should minimise the travel length over the headlands, as the more time spend travelling the headlands, the more time it takes to harvest the entire field

b. What activities of the harvester and chaser bins should be supported by the operational logic?

The harvester should be able to harvest when it is linked to a chaser bin, it needs to be able to go to new rows over the headlands and detect when it has reached the end of a row or the field. Furthermore, it needs to be able to detect where the chaser bin is in order to link to it. The chaser bin needs to be able to do the same things as the harvester, but alongside this it needs to be able to switch when required with another (empty) chaser bin.

c. How can these activities be translated into operational logic?

The activities can be translated with the use of a master slave principle, where the harvester is the master and commands the chaser bin to follow it during a harvest. Several decision trees were made to show how these actions can be translated into the operational logic.

Chapter 5. Evaluation model

This chapter focuses on the quantitative model that is used to evaluate the performance of the solution design described in Chapter 4. As discussed in Section 3.1.4, the choice is made to use a simulation model for these measurements. Section 5.1. describes the conceptual model that is used. This conceptual model is used to convey the concept and ideas behind the model. Section 5.2. then describes the inner workings of the model in more detail. Then, the model is verified and validated in Section 5.3.

5.1. Conceptual model

For the conceptual model, the often-cited framework of Robison (2008) is used. This author defines a conceptual model as "a non-software specific description of the computer simulation model (that will be, is or has been developed), describing the objectives inputs, outputs, contents, assumptions and simplifications of the model. The key requirements of a conceptual model are that it should be valid, credible, feasible and have utility. This means the model should:

- Produce sufficiently accurate results for the purpose at hand (*valid*)
- Be believed by the clients (*credible*).
- Be *feasible* to build within the constraints of time and available data.
- Have *utility,* that is, sufficiently easy to use.

Figure 17 Figure 17: A framework for conceptual modelling from Robinson (2008) shows a framework for conceptual modelling that Robinson (2008) proposed. The remainder of Section 5.1. describes the objectives, inputs, outputs, contents, assumptions, and simplifications, as described in this figure.

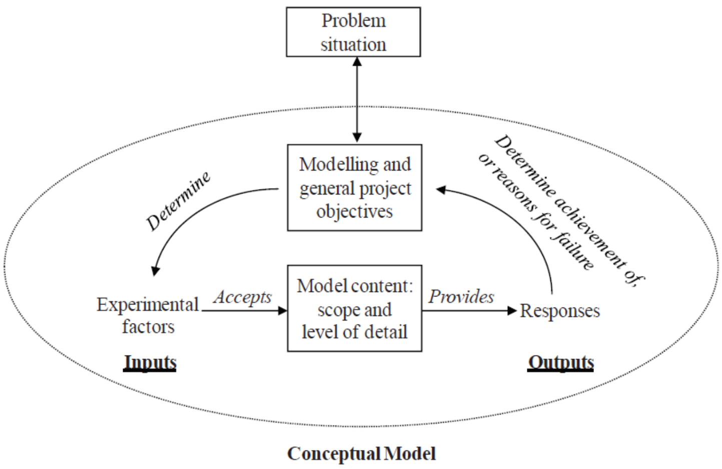


Figure 17: A framework for conceptual modelling from Robinson (2008)

5.1.1. Problem situation

The conceptual model is now coupled back to the information provided in previous chapters. This is done with the use of the key requirements for the conceptual model, as stated in the previous section. The model in the H2Trac case should:

- Provide sufficiently accurate insight into the performance potential buyers can expect with regards to the level of soil compaction and the utility of the harvester with a specified number of chaser bins (valid).
- H2Trac and other stakeholders in the DurableCASE must have confidence in the model (credible).
- Be *feasible* to build within the constraints of time and available data.
- Have *utility,* that is, sufficiently easy to use with multiple scenarios in mind, flexible in the variables and the shape and size of the fields, visually appealing to the stakeholders, and quick to run.

5.1.2. Modelling and general objectives

The objective of the model is to accurately assess the performance of the operational logic described in Chapter 4. Therefore, the fields described in Section 2.3 need to be presented accurately enough so the operational logic can be evaluated accurately.

5.1.3. Model inputs

The model inputs can be split into four categories: row network, farm data, harvester data and chaser bin data. Table 2 shows the categories and the corresponding units where applicable.

Row network	**Units**
- Coordinates of the edges of the field	Latitude, Longitude
Farm data	
- Distance between rows	Meters
- The area reserved for the headlands	Meters
- Orientation of the rows	Does not apply
- Soil information	Soil type, soil Elasticity, soil coefficients A-D (See section 2.1.4).
- Crop type	Does not apply
- Crop yield	kg
- Crop volume	m^3
- Deadweight gathered during harvest	Percentage
Harvester data	
- Speed of the harvester	m/s
- Weight of the harvester	kg
Chaser bin data	
- Capacity	m^3 and kg
- Speed	m/s
- Initial weight	Kg

Table 2:Model inputs split into four categories with the corresponding units

5.1.4. Model outputs

The model outputs can be split into two categories:

Outputs (to determine achievement of objectives)

- Mean, standard deviation, minimum and maximum bulk density of the soil
- Mean, standard deviation, minimum and maximum number of passes over a row
- Harvester utilisation

These outputs are used to find out if the goals of the model are met. The first goal is to minimise the level of soil compaction. This is measured in the bulk density of the soil. The higher the bulk density, the more soil compaction has taken place. Different soils have different types of initial bulk density. Therefore, it is important to look at the percentual change in bulk density. Each row will also be passed at least two times, once by the harvester for the harvesting of the crops and once by the chaser bin to collect the crops when the chaser bin is driving in the adjacent row. It is interesting to see if crop rows are passed more than others, or if all crop rows are passed exactly twice.

Outputs (to determine reasons for failure to meet objectives)

- Bar charts utilisation harvester
- Cumulative percentage vehicle utilisation

These outputs show when the harvester utility or the chaser bin utility takes a dip. This information can be used to find out potential failures in the system so they can be resolved.

5.2. Overview of functions and data flow in the model

Now, the functions and the data flow in the model are discussed. The model was implemented in the software of Tecnomatix Plant Simulation. The main functions and the data flow throughout the model are now discussed. Figure 18 shows main functions and the data flow of the model. Appendix D shows an enlarged version of this figure.

The main functions and a brief description of their purpose:

- **Init_markers:** This function reads the KML files for the coordinates of the edges of the map and creates an outline of the map.
- **Init_Grid:** This function uses the outline created in Init_markers, the farm data on the distance between the rows, the area of the headlands, the row orientation and the soil information as input. Then it fills the outline of the map with the rows, completing the Metric Map.
- **Create_Offline:** In the Create_offline fuction, the distance matrix is generated for the offline planner described in section 4.1.
- **Decision_Center:** The decision center function entails the online operational logic described in Chapter 4.
- **Harvest_crops:** This model uses the location of the harvester and the chaser bins as input, as well as information on the "actual crop data" to harvest the crops.
- **Predict_Dispatch:** This function uses the information on the status of the chaser bin. If a dispatch is required, the decision center is called to decide where to go.
- **Calculate_Performance:** This function calculates and stores the level of soil compaction and the harvester utility.

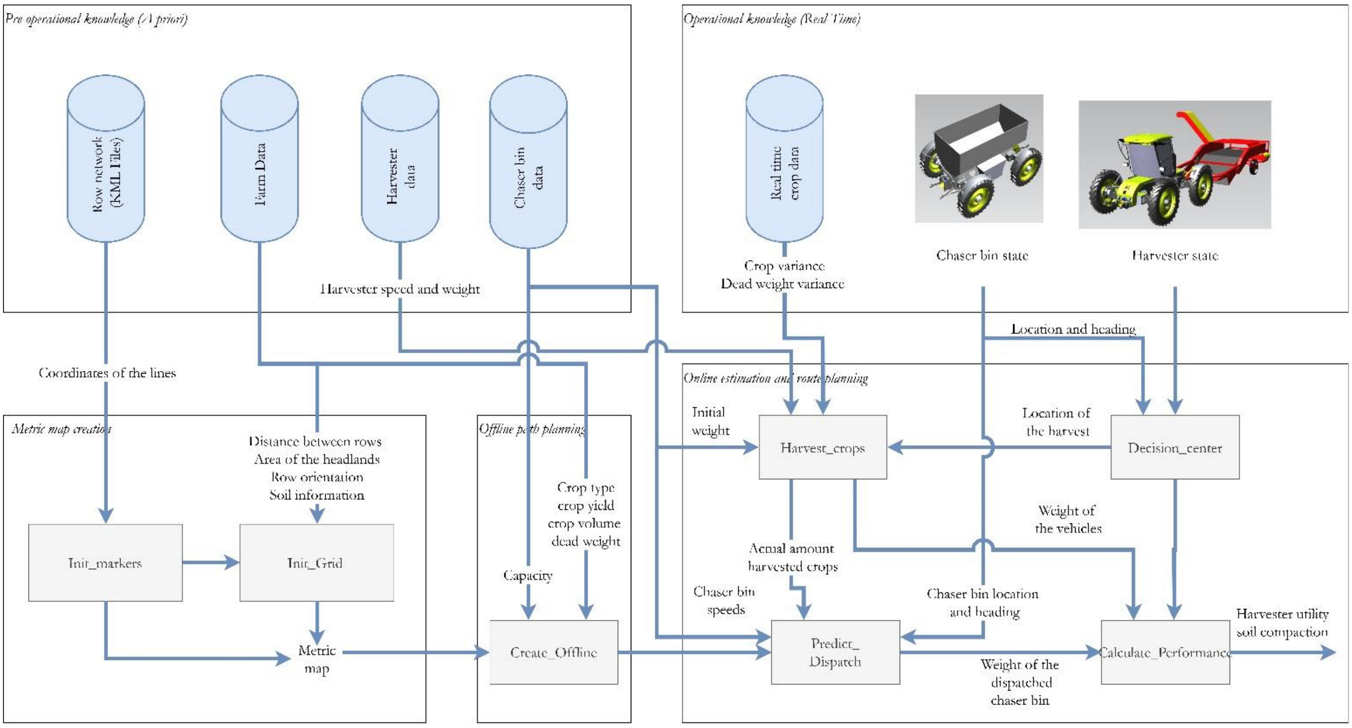


Figure 18: Overview of functions and dataflow of the simulation model. The "Metric Map Creation" and the "offline path planning" part are executed prior to the operation whereas the rest are executed online during the operation

For the metric map creation, offline path planning and the online estimation and route planning, a brief description is given on the steps that are taken. But first, the preoperational knowledge is discussed.

5.2.1. Preoperational knowledge

For the information that is given by the users of the model, a user form is made. In the user form, the user of the model can alter the data that the model uses as input for the model. The data is split into 4 tabs, corresponding to the different data inputs described in Figure 20. These tabs consider the field (contains the row network data), crops (contains the real time crop data), Farm (contains the farm data) and vehicles (contains the harvester and chaser bin data). Another tab for the advanced settings exists as well, but this tab only influences the scale of the model and is not relevant for the performance. These four tabs and what information they contain are now discussed.

5.2.1.1. Field

In the field tab, the user can change the field file and the configuration of the rows. This is done in three steps. Figure 19 shows a screenshot of the user form with the data is used in each step. In step 1, the user selects the name and the location of the file on the computer. In step 2, the user calls the function Init_grid so the user can check the map (see section 4.5.2.). In step 3, the user selects the line parallel to the rows.

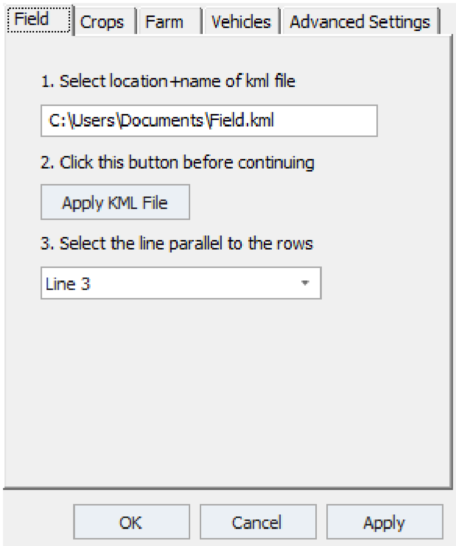


Figure 19: User form corresponding to field data

5.2.1.2. Crops

The crop tab has 4 steps, but only the first step is mandatory. This tab is to insert the crop data. In the first step, the user can define the crop type. If no other information is used other than this, generic data on that crop type is used. The user can also choose to view and alter the probability distributions by clicking the button. If this is done, the user can alter the probability distribution in step 2, the input parameters in step 3 and the amount of dead weight in kg in step 4.

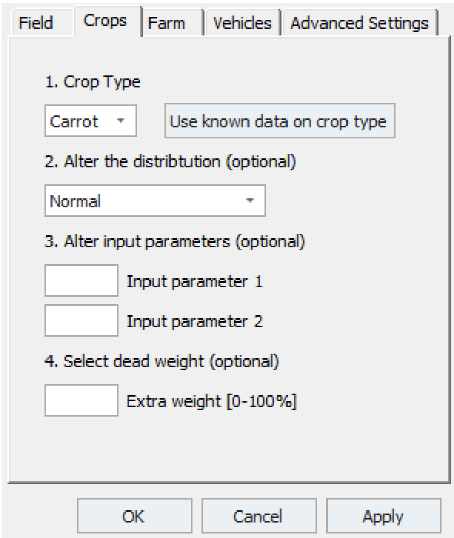


Figure 20: User form corresponding to (real time) crop data

5.2.1.3. Farm

In the farm tap the inner configuration of the field is determined. In the previously discussed field tap, uses can upload their map files and select the line orientation. This tab expands on this by specifying the crop rows and the distance between the crops. Figure 20 shows the user form of this tab sheet. In step 1, the user inputs the distance between the rows and the crops. The distance between the crops determines how often the function for harvesting crops is called. When the distance is 1, the crop yield for each cubic meter is calculated. When, for example, this distance is 3 meters, the crop yield is calculated once and multiplied by 3. This way, the speed of the model can be increased. In step 2, the user selects the headland area for the left and the right side of the field.

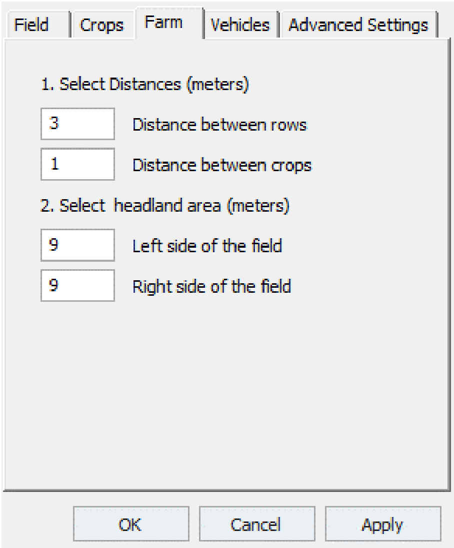


Figure 21: User form on farm data

5.2.1.4. Vehicles

In the vehicle tab, the user can input the variables for both the harvester and the chaser bins. Figure 21 shows the user form on this tab sheet. In step 1, the number of harvesters and chaser bins can be set. In this thesis, only one harvester is considered, but this way future research can also use this information. In step 2, the maximum speed of the harvester and the maximum speed of the chaser bins is selected. The assumption is made that this maximum speed is the same speed as the harvesting process. In step 3, the capacity of the chaser bins is indicated. Finally, in step 4, the user can choose the initial weight of the vehicles. Currently, the harvester has a weight of 7200 kg, and the chaser bins a weight of 2500 kg. These weights are however subject to change, as the vehicles are prototypes. Therefore, the weights need to be variable and not hidden somewhere within the model as constants.

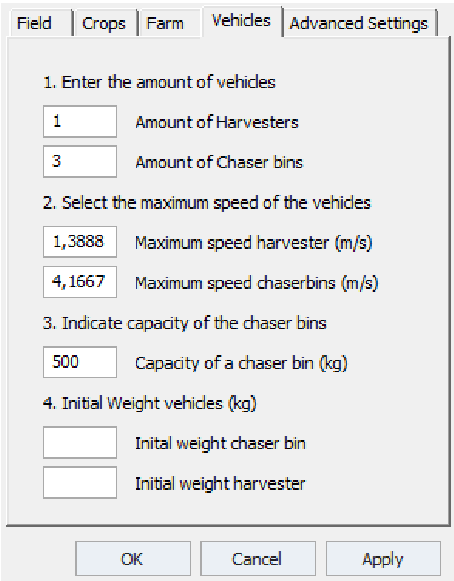


Figure 22: User form on vehicle data

5.2.2. Metric map creation

The Metric Map is a representation of the real-life field. To make the transition from the real fields to the metric map, the user first needs to upload the file with the coordinates into the model and placed in a table. This data on the longitude and latitude of the harvester is then extracted with the use of "Init_Grid". Recall that a field near Zeewolde is used to develop the model (Section 2.3.). This map consists of 19 connecting lines. The ending of one line is the starting point of another line. These coordinates of the lines are then transformed into points in the x,y plane, with the corresponding meters between each line. For the technical description of this process, see Appendix E. Once this transformation is done, the lines are drawn on a new map. Figure 23 shows the representation of both maps.

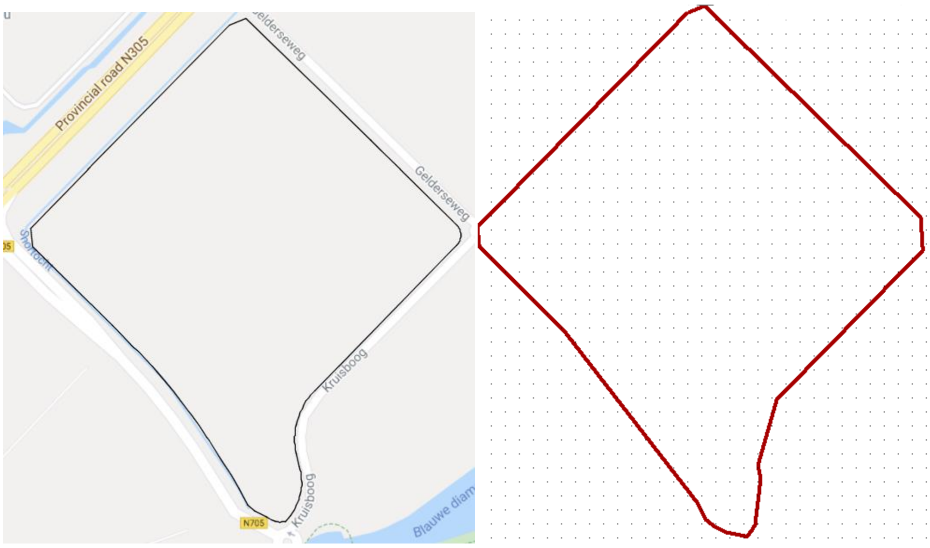


Figure 23: Real life field outline (left) and the representation of the edges (right)

Now that the outline of the map is drawn, the rows of the harvester can be generated. This is done with the use of “markers”. Markers are used to set waypoints on in the model alongside which the harvester and chaser bins can travel. These are generated with the use of the method “Init_markers”. For this part, the information that the line is parallel to is used. outline of the map that was described in the previous part is replaced with markers. Figure 24 shows the field representation that was created.

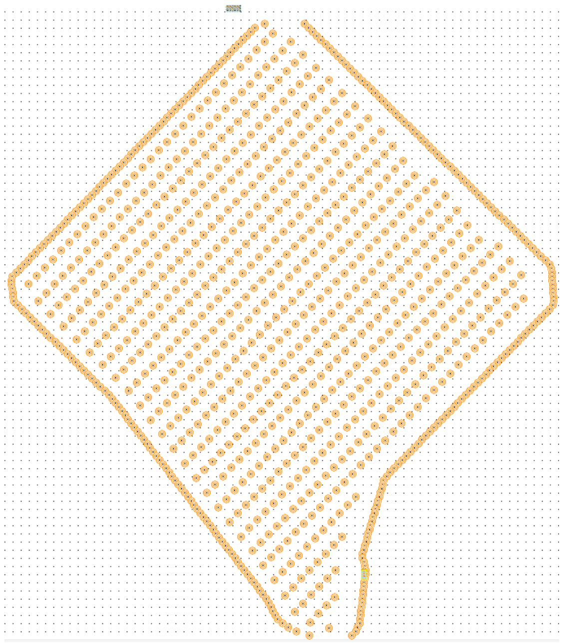


Figure 24: Field representation, including headlands and crop rows in the north east direction.

5.2.3. Online planning

Now that the harvester path and an approximation of the switches have been made, the online planning can start. First, the model is initiated with a stochastic number of crops per square meter. Then, the master-slave system is called, which was described in Section 4.4. When the harvester is driving over the field, the functions Calculate_SoilCompaction and Harvest_Crops are called. The first function calculates the bulk density of the soil under the vehicles with the formulas described in Section 2.3.2. The function Harvest_Crops looks at the exact kilograms of crops at the current position and gives this number to the chaser bin. The chaser bin in turn checks the remaining capacity, and if this capacity is lower than a certain threshold, a new chaser bin is selected to take over the tasks of the active chaser bin. The new chaser bin then gets into position close to the harvester, and the active chaser bin is switched. Then, the old chaser bin drives back to the unloading point and unloads the crops. After this, the chaser bin is charged to make sure it is ready for whenever it is called again. If there is only one chaser bin, the method is slightly different. Now, no new chaser bin is called, so the sole chaser bin needs to go to the harvester once it has charged enough.

5.2.3.1. Occasional events

There are a couple of events that only happen sporadically like the chaser bin has a mechanical failure or it loses connection to a server. These are all classified as failures. When this happens, a new chaser bin needs to come and replace the old chaser bin. The assumption is made that the harvester and the new chaser bin can guide the failed chaser bin to the headlands, where the farmer can try to resolve the issues and it does not stand in the way of the harvesting operation.

5.3. Verification

With verification, the model is checked to see if it does what it is supposed to do. Several techniques can be used to verify the model (Law, 1983). One method described by Law (1983) is by debugging the most important methods and see if it works properly. This technique was used, but it is not possible to show this properly. Another technique Law (1983) mentions that is easier to show is to run the model under a variety of settings and check if the results are reasonable. When a harvester is selected with a single chaser bin without any capacity constraints, the time to harvest the entire field should be equal to the length of the route of the harvester divided by the speed of the harvester. When a field is considered with a length of approximately 22 kilometres (see Figure 25) and a harvester speed of 3 meters/per second, the harvester should finish in approximately 2 hours. When running the model with this data, the total time to harvest the entire field is 2 hours and 26 minutes. This 26-minute discrepancy can be explained by two aspects of the model that increases the time it takes to finish. First, the harvester needs to wait until the chaser bin is linked. It had to wait 3.28% of the time (see Figure 27). This accounted for travel time from and to the headlands, as these are located at least 9 meters from both the beginning and the end of the crop row. When looking at the travel distance of the harvester, it did have to travel almost 3 kilometres extra due to this, which can be seen in Figure 25.

TotalLengthRoutes=22060.5301245182

2:26:38.3422

Figure 25: Exact length and time to harvest the entire field in the model

Another validation can be done on the number of crops that are harvested. In the field tab, a normal distribution is selected with a mean of 5 kg and a sigma of 1.5. Then, a log is kept on the crops that have been harvested and fitted in a normal distribution. With 14048 values, a level of significance of 5%, and 118 classes, the probability distribution of the model was observed as normal with a mean value of 5.010 and a sigma of 1.502 (with a Chi statistic value of 131.96 and a chi value of 141.03). This falls in line with the input of the model with a mean of 5 and a sigma of 1.5. Figure 26 shows the observed crops that have been harvested with the desired amount of crops. Because of this, the assumption is made that the harvesting process is valid.

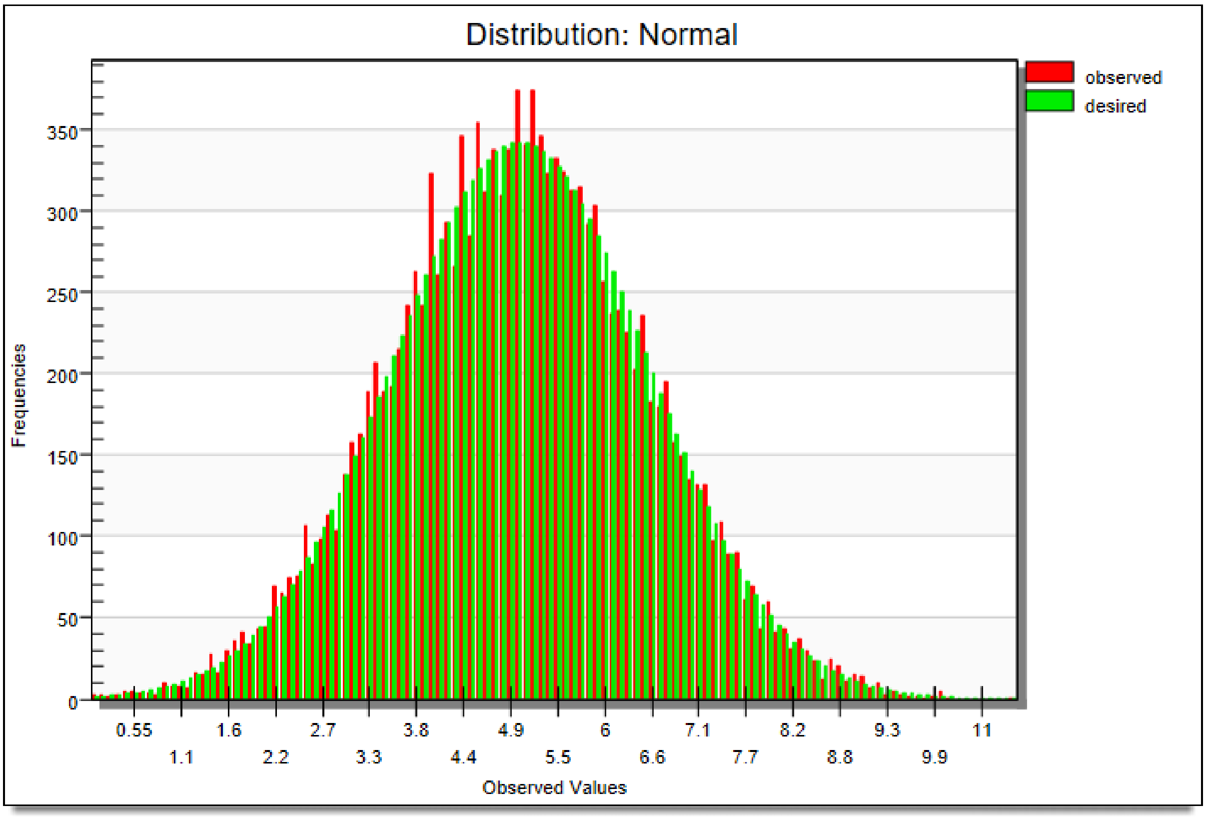
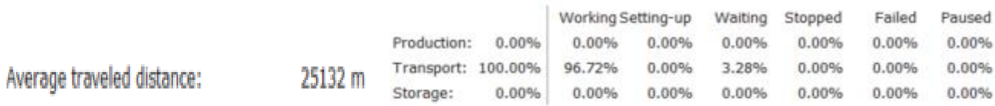


Figure 26: Distribution of harvested crops



Average traveled distance: 25132 m

		Working	Setting-up	Waiting	Stopped	Failed	Paused
Production:	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Transport:	100.00%	96.72%	0.00%	3.28%	0.00%	0.00%	0.00%
Storage:	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Figure 27: Distance travelled by the harvester and the percentages it was doing certain events.

5.4. Validation

First, the creation of the maps is validated. Validation is the process of determining whether the simulation model is an accurate representation of the system. To do this, a harvest was attended near Zeewolde. Here, some measurements were done on the current situation of the harvest. During the harvest, the chaser bin and the harvester need to stop approximately 2-3 times per row to ensure that the vehicles are linked. When they are not linked, the chaser bin reverses until they are close enough to each other again. Another thing that was observed was that the harvester did not drive precisely in the crop rows. This meant that even half a lane was completely run down during the harvest, and this crop row was ruined. The harvester and the chaser bin drove at most 4.5 meters per second during the harvest. The chaser bins only switched with the use of a driving switch. This switch was done without any foresight on how much of the row was still left to harvest, so the new chaser bin drove almost the entire length of the field to get to the harvester, greatly increasing the soil compaction.

As discussed in the technical specifications for the metric map in Appendix E, the GPS coordinates are converted into points on an X, Y plane. Table 3 shows a comparison between the GPS line length and the length between the X, Y coordinates. From this table, no difference in length can be perceived, therefore, the model is assumed to be valid.

Line	GPS line length (meters)	X, Y plane line length (meters)
Line 1	262	262

Line 2	27	27
Line 3	428	428
Line 4	29	29
Line 5	168	168

Table 3:Comparison of the length of line 1-5 in meters between the GPS and X,Y coordinates

For another part of validation, a field of

5.5. Number of replications

The number of replications is the number of times a certain setting is run to ensure the results are statistically valid in α percent of the time (the confidence level). To calculate the number of replications, the formula $\delta(n,\alpha) = t_{n-1,1-\alpha/2}\sqrt{S_n^2/n}$ is used, with t being the student's t- distribution and n-1 degrees of freedom, n being the number of replications, α the confidence level and S^2 being the sample variance. To find the required number of replications, an alpha of 5 % is used, so the formula becomes $\delta(n, 0.05) = t_{9,0.975}\sqrt{S_{10}^2/n}$. If this value falls below a value of gamma', more replications are required. Appendix F shows the experiments and the results for a run with 40 replications. From these experiments it is shown that a minimum of 3 replications are required. However, since the model runs quite fast, the decision is made to use 10 replications to ensure all results are statistically significant (with 95% confidence).

5.6. Conclusion

This chapter gave answer to the research question *"How can performance of the operational logic be evaluated?"* . To answer this question, several sub questions needed to be answered first:

What does the conceptual model look like?

The conceptual model was described in section 5.1. using the framework from Robinson (2017). Here, the situation, objectives, inputs and outputs were described.

What is the data that is required, and how does this data flow through the system?

Section 5.2. describes the functions of the model, what data they require and how the functions use this data to generate new data.

Does the quantitative model what it is supposed to do? (verification)

The model was verified with the use of two methods. First the model was debugged to find out if it did what it was supposed to. Although this was successful, it was not possible to show this method properly. Therefore, another technique was used. Here, the model was run with input for which the outcome was predicted by hand. The discrepancy between the estimation and the outcome was 26 minutes. This discrepancy turned out to be caused by a misjudgement of the predicted outcome, since it did not take waiting time and travel time from and to the crop rows into account.

Does the quantitative model accurately represent reality? (validation)

The model was validated by comparing the length of the edges of the field with real-life data. No discrepancy was found between the generated field and the real-life field length. Therefore, the model is deemed valid. When a field near Zeewolde was visited during the harvest, the actions of the harvester and the chaser bin were shown to be the same as in the real field, although it should be considered that the harvester and chaser bin need to stop frequently because of failures by the operators.

Chapter 6. Experimental design and results

This chapter considers the experimental design and the results. First, Section 6.1 gives the experimental design then Section 6.2 shows the performance of the offline route planning. Then, Section 6.4 gives the results of the Then, Section 6.4 gives a sensitivity analysis and the Chapter is concluded in Section 6.5.

6.1. Experimental design

This section goes over the experiments that will be run to determine the performance of the operational logic. The experimental design was made with the help with the HAN and a farmer connected with the DurableCASE. This was required to make sure the goals of the project coincided with the goals of the DurableCASE goals. The goal of these experiments is to find out four things:

1) Find out the shortest route for all three fields
2) Find out the most optimal types of switches
3) Recommend the amount of chaser bins and their capacity for a field
4) Find out the performance of the system, when compared with the old system

The first row concerns the offline route that is generated in Python. For all three fields, the shortest route is calculated. This is done with the use of the savings algorithm, simulated annealing and a tabu search. The solutions to these three methods is compared to one another in section 6.2.

The second goal is to examine the driving switch, headland switch and the hybrid switch (combination of driving and a headland switch) to find out which one, if any, performed better than the other ones. For the hybrid switch, comparison is also made between having the switch at 10, or 25 percent.

The third goal is to find out and recommend the amount of chaser bins and how much capacity they should have for any of the three fields. With this goal the comparison is made between the three fields to find out if any of them outperforms the others.

The final goal is to find out the performance of the new EOX tractors with the use of the operational logic, when compared with the old system. As stated earlier, in the traditional system two drivers need to drive simultaneously to make sure all crops are placed correctly in the chaser bins. This does not go without error in reality. For the comparison, the evaluation model is used to give it a fair comparison. Here the assumption is made that the traditional system is also able to use the operational logic so the performance of the eox versus that of a traditional system can be examined properly.

With these goals in mind, the experiments can now be drawn up. First, the settings that are used as variables are shown in table 5, and then in table 6 the constant factors are shown.

Table 5 shows experiments that are run in the evaluation method, as well as the names given to them to identify them later on in the results. For the first experiments, the switchtypes are examined. All other experimental factors and inputs are set to the values in table 6. The variance of the crops is set to zero, so it is deterministic and does not interfere with these experiments. Experiment 2 concerns itself with the performance of the system, and varies the amount of chaser bins and their respective capacity to see what effect it has on the performance. Finally, in experiment 3 the best setting of experiment 2 is compared with the traditional setting to see how they stack up.

Experiment number	Name	Amount of chaser bins	Capacity Chaser bins
1.1	Switchtype_ Driving	3	4200
1.2	Switchtype_ Headland	3	4200
1.3	SwitchType_Hybrid_ 10	3	4200
1.4	SwitchType_Hybrid_25	3	4200

2.1	Performance_2_2100	2	2100
2.2	Performance_3_2100	3	2100
2.3	Performance_4_2100	4	2100
2.4	Performance_2_2800	2	2800
2.5	Performance_3_2800	3	2800
2.6	Performance_4_2800	4	2800
2.7	Performance_2_4200	2	4200
2.8	Performance_3_4200	3	4200
2.9	Performance_4_4200	4	4200
3.1	Traditional_2_8400	2	8400

Table 4: Experiments and their input values

Table 5 shows the other input values that have been selected. These values remain the same throughout these experiments. The distance between the rows is set to 3 m as this was the distance between the rows as described in Section 2.3. The harvested number of crops is calculated every 10 meters. The carrot was selected with a value of 12 kg of crops per meter as average (Agrifarming.in, n.d.). The assumption is made that the amount of crops per square meter follows a normal distribution with a standard deviation of 20%. Section 6.4 looks further into this assumption in the sensitivity analysis. The information on the harvester and the chaser bin was provided by H2Trac. Harvesting occurs at a speed of 1,38889 m/s and the chaser bins have a maximum speed of 6 m/s. The initial weight of the harvester is 7200 kg for the EOX tractor, and another 5000 kg for the harvesting tool, resulting in a combined total of 12200 kg. The initial weight of the chaser bin is 5000 kg for the EOX chaser bins and 10000 kg for the traditional chaser bin, as this needs to be pulled by a tractor aswell

Input:	Value	System unit
Distance between rows	3	meter
Distance between calculations for crop values	10	meter
Distance to headlands	9	meter
Crop type	Carrot	-
Average amount of crops	12	Kg/m^2
Speed of the harvester	1,38889	meters / second
Speed of the chaser bin	6	meters / second
Initial weight of the harvester	12200	Kilogram
Initial weight of the EOX chaser bin	5000	Kilogram
Initial weight of the current chaser bin	10000	Kilogram

Table 5: Constant input variables for the evaluation model

These experiments are done on all three fields described in Section 2.3. Now that all information is given, and the experiments are defined. But before they can be run, the offline routing needs to be made to ensure that the harvester takes the shortest route over the field.

6.2. Results offline routing

As stated in Section 4.1, the offline planning was made in Python with the use of the OR-Tools library developed by Google. This library allows quick selection for developing an initial solution and iterating on this solution using a local search. The initial solutions that are used are the savings algorithm, the cheapest arc insertion and an automatic solution, which was automatically picked by the library. Then, the cheapest arc and the automatic solution were used as input for a simulated annealing algorithm and a tabu search algorithm. The results of these actions can be found in Table 6.

Initial solution	Local search algorithm	Field 1 results (meters)	Field 2 results (meters)	Field 3 results (meters)
Savings algorithm		2805	2811	3936
Cheapest insertion		2805	2811	3936
Cheapest insertion	-	2805	2811	3936
Cheapest insertion	Simulated_annealing	2805	2811	3936
Cheapest insertion	TABU_Search	2805	2811	3936
Automatic	-	2805	2811	3936
Automatic	Simulated_annealing	2805	2811	3936
Automatic	TABU_Search	2805	2811	3936

Table 6: Results Offline route planning

Here, all methods for all fields yield the same exact solution. The reason for this is that these problem instances are not exceptionally large, with a maximum of 300 rows that all lay in a sequential order. Therefore, the initial solution already found the optimal solution to these problems, and the local search algorithms could not make these solutions better.

6.3. Results online planning

Here the results of the experiments described in table 4 are discussed. With first the results of the best types of switches, then the best overall settings for the systems and finally the comparison with the traditional system

6.3.1. Results types of switches

As can be seen in Figure 28 and the corresponding table 8, the accumulative weight that is driven over the entire field is largest in the driving experiment. This is because the old chaser bin needs to drive over areas that it has already driven over. The headland switch has the lowest weight for the vehicles driving over the field. Both the hybrid cases perform in between the performance of the headland case and the driving switch.

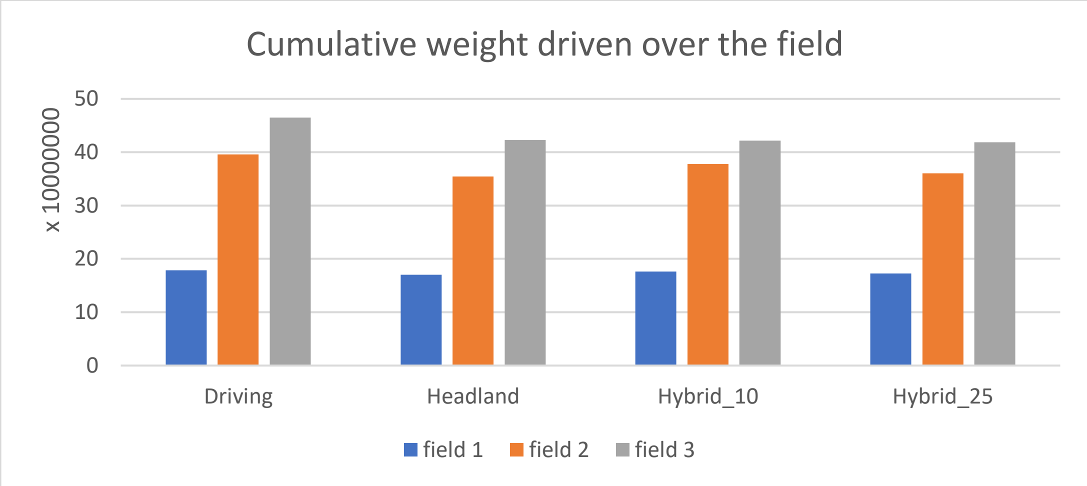


Figure 28: Cumulative weight driven over the field

	Cumulative weight (x10^8)		
	Field 1	**Field 2**	**Field 3**
Driving	1,78	3,96	4,65
Headland	1,70	3,54	4,23
Hybrid_10	1,76	3,78	4,21
Hybrid_25	1,72	3,61	4,19

Table 7: Cumulative weight driven over the field table

When the harvester utilisation is also considered, a different picture is drawn. Figure 29 and Table show that the harvester utilisation of the different types of switches. Here it can be seen that the driving switch significantly outperforms the other switches in the utilisation. The headland switch performs the worst on the harvester utilisation, as the harvester needs to stop until the old chaser bin is at the headlands so the new chaser bin can pass. The figure and table also reveal that, on average, the Hybrid switch where the first and last 25% of the field are headland switches outperforms the experiment where only the first and last 10 percent of the field are headland switches. Therefore, in conclusion the hybrid switch with the first and last 25% of the field as headlands and the remaining 50% as driving switches is chosen as the best solution.

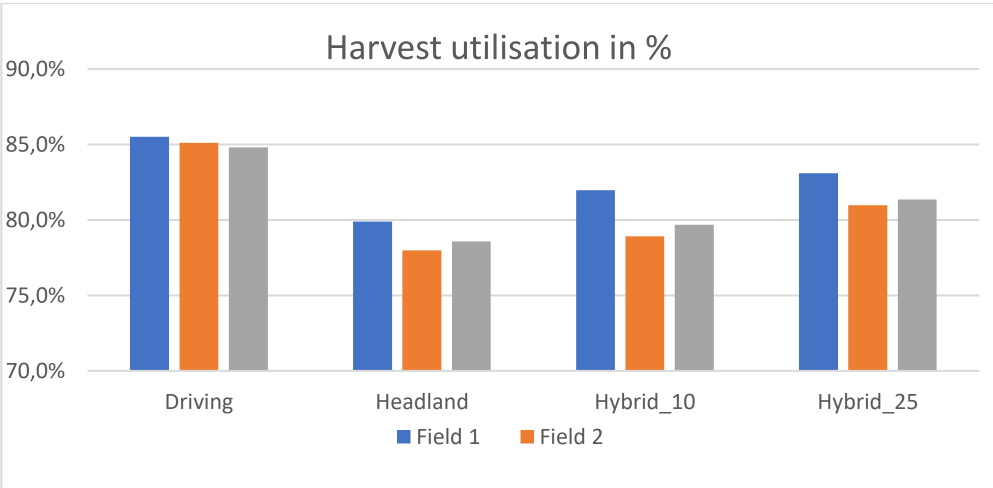


Figure 29: Harvester utilisation different types of switches (%)

	Field 1	Field 2	Field 3
Driving	85,5%	85,1%	84,8%
Headland	79,9%	78,0%	78,6%
Hybrid_10	82,0%	78,9%	79,7%
Hybrid_25	83,1%	81,0%	81,4%

Table 8: Harvester utilisation different types of switches (rounded to 3 decimals)

6.3.2. Results performance with different settings chaser bins

Figure 30 and Table show the harvester utilisation of the different settings in percentages The harvester utilisation here means the amount of time the harvester is actually driving over the land, and not standing idle because it has to wait for a new chaser bin. What is immediately obvious from the observations from the experiments with 2 and 3 chaser bins with a capacity of 2100 the performance is very low (<60% in all cases). The reason for this is that this number of chaser bins with this capacity is insufficient to make sure a new chaser bin is available in time when a linked chaser bin is full. With 4 chaser bins with a capacity of 2100 kg, the utilisation of the harvester is already better for field one (>80%), but for field 2 and 3 it remains low. The reason for this is that these are bigger fields than field 1, so the travel time from and to the harvester becomes larger, which means sometimes a new chaser bin is not available in time. When the remaining results are examined for the harvester utilisation, the performance of 4 chaser bins with a capacity of 2800 kg and 4200 kg stand out. These have approximately the same utilisation on the bigger fields, and on field 1 the experiment with a capacity of 2800 kg outperforms the experiment with a capacity of 4200 kg. The reason for this can be that the switches of the chaser bin happened closer to the headlands, where the harvester utilisation takes less of a hit. Section 7.4 goes further into the discussion on these results, and more specifically on what possible options there are for increasing the harvester utilisation of field 3.

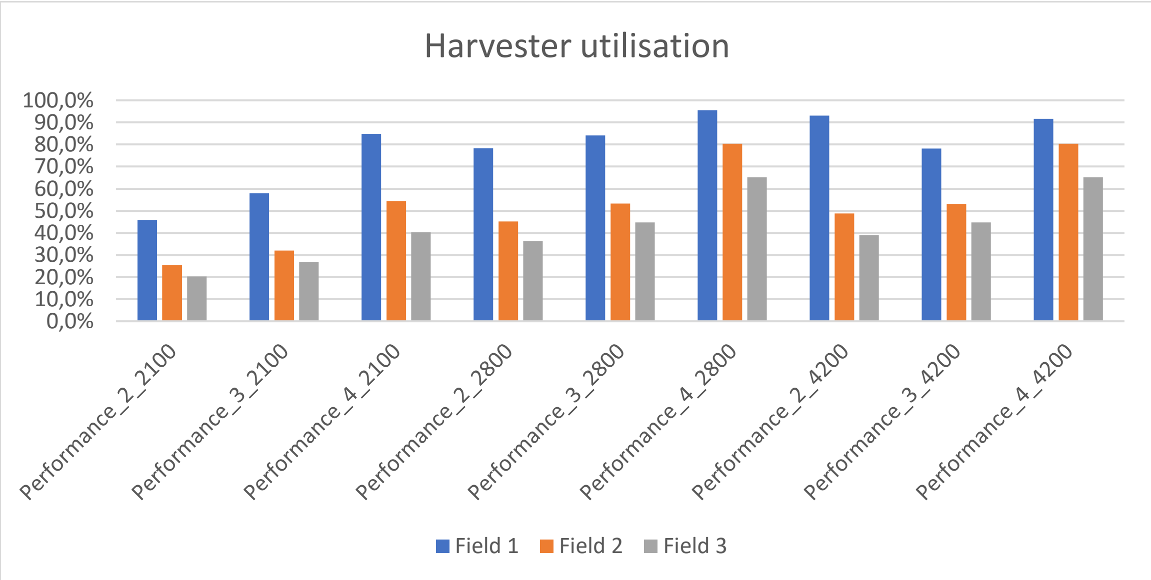


Figure 30: Harvester utilisation performance different chaser bin settings

	Field 1	Field 2	Field 3
Performance_2_2100	45,9%	25,5%	20,3%
Performance_3_2100	57,9%	32,1%	26,9%
Performance_4_2100	84,8%	54,5%	40,2%
Performance_2_2800	78,3%	45,2%	36,3%
Performance_3_2800	84,1%	53,2%	44,8%

Performance_4_2800	95,6%	80,3%	65,2%
Performance_2_4200	93,1%	48,7%	38,9%
Performance_3_4200	78,1%	53,2%	44,8%
Performance_4_4200	91,7%	80,3%	65,2%

Table 9: Harvester utilisation performance different chaser bin settings

When looking at the soil compaction of these experiments, it might be surprising that the first experiment with 2 chaser bins with a capacity of 2100 kg performs poorest by a long shot. This can be explained by that, although these have a low capacity, they need to switch many times and therefore the harvester stands extended periods of time on the field without moving, increasing the soil compaction further. When looking at the best solution for the soil compaction, the experiment with 4 chaser bins and a capacity of 2800 kg and 4200 kg shows the most promise. They have approximate same performance for field 2 and 3, suggesting that 4 is enough chaser bins for these fields. Since the experiment with 4 chaser bins with a capacity of 2800 kg further outperformed the experiment with a capacity of 4200 kg on the harvester utility, the recommendation is made to use these settings in fields of these sizes.

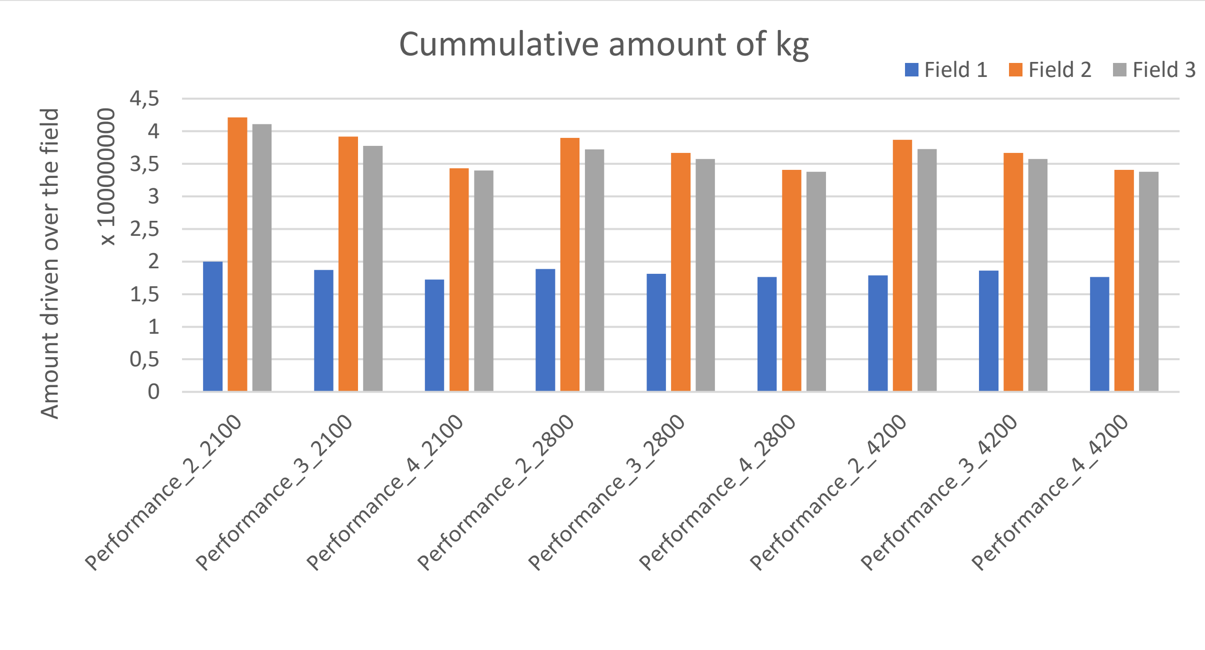


Figure 31:Cumulative kilograms driven over the field

	Kg driven over field *10^8		
	Field 1	**Field 2**	**Field 3**
Performance_2_2100	2,00	4,21	4,11
Performance_3_2100	1,87	3,92	3,77
Performance_4_2100	1,73	3,43	3,40
Performance_2_2800	1,88	3,90	3,72
Performance_3_2800	1,81	3,67	3,57
Performance_4_2800	1,77	3,41	3,38
Performance_2_4200	1,79	3,87	3,72
Performance_3_4200	1,86	3,67	3,57
Performance_4_4200	1,76	3,41	3,38

*Table 9: Approximate cumulative kilograms*10^8 driven over the field*

6.3.3. Traditional vs new situation

Table 10 shows the performance of the cumulative weight driven over the field, and table 11 shows the performance of the harvester utilisation. Here it can be seen that the new strategy and EOX vastly improves the number of kilograms driven over the field, and therefore the soil compaction. The performance on harvester utilisation decreases slightly on the first field, but the performance of 12% on the third field could be seen as significant. On the other hand, the soil compaction decreases more drastically with 26,6%. The discussion goes further into this change.

	Field 1	Field 2	Field 3
Performance_4_2800	1,77E+08	3,41E+08	3,38E+08
Traditional harvester	2,08E+08	4,79E+08	4,6E+08
Change new vs old (%)	-15,3%	-28,9%	-26,6%

Table 10: Performance old vs new chaser bin on kg driven over the field

	Field 1	Field 2	Field 3
Performance_4_2800	95,6%	80,3%	65,2%
Traditional approach	96,4%	85,5%	76,9%
performance decrease new approach (%)	-0,8%	-5,2%	-11,7%

Table 11: Harvester utilitsation and the performance decrease when compared to the traditional situation

6.4. Sensitivity analysis

This part concerns the sensitivity analysis. This is done to show how different values of the independent variables affect a particular dependant variable under a given set of assumptions. The first of the assumptions that was made in the previous section was that all the crops had a deterministic value, and that they had 20% variance. Now, this assumption is changed to 40% and 60% to see how this changes the model. Another assumption that was made that was not explicitly stated is that the new chaser bin always knows where the harvester and current chaser bin will be at the moment of a shift, so it is always able to go there in time (or, at the very least a large part of the way). This assumption is also challenged by changing the availability of this information to only available when the switch is needed and looking at what happens if the switch positions are only given at the start of a run and do not update during the run. The corresponding experiments for the sensitivity analysis can be found in table 12.

Experiment	Name	Variance of crops	type of plan
1	2.4_Update	2.4	plan is updated
2	2.4_Predefined	2.4	Predefined
3	2.4_NoPlan	2.4	No plan
4	3.6_Update	3.6	plan is updated
5	3.6_Predefined	3.6	Predefined
6	3.6_NoPlan	3.6	No plan
7	4.8_Update	4.8	plan is updated
8	4.8_Predefined	4.8	Predefined
9	4.8_NoPlan	4.8	No plan

Table 12: Sensitivity analysis changes

These experiments were run in all three fields. Note that the first experiment 2.4_Update is the same experiment as Performance_4_2800, as they have the same amount of chaser bins and capacity. From the results in Table 13 this can be seen aswell, as they have the same values. Table 13 and Table 14 shows a comparison with the old values.

	Field 1	Field 2	Field 3
2.4_Update	1,77E+08	3,41E+08	3,38E+08
2.4_Predefined	1,97E+08	3,41E+08	3,38E+08
2.4_NoPlan	1,97E+08	3,41E+08	3,38E+08
3.6_Update	1,96E+08	3,41E+08	3,38E+08
3.6_Predefined	1,95E+08	3,4E+08	3,38E+08
3.6_NoPlan	1,95E+08	3,41E+08	3,38E+08
4.8_Update	1,96E+08	3,4E+08	3,38E+08
4.8_Predefined	1,96E+08	3,4E+08	3,38E+08
4.8_NoPlan	1,96E+08	3,4E+08	3,38E+08

Table 13: Cumulative weight driven over the field (kg)

Table 14 shows that the amount by which the weight driven over the field is increased is not larger than 2.5% in all three fields. Field 2 even shows a slight decrease in weight driven over the field. This can be explained by that the new chaser bins might arrive at the wrong side of the row, which means they have to drive longer towards the harvester over the field. When comparing solutions with the same variance, the increase or decrease is negligible.

	Field 1	Field 2	Field 3
2.4_Update	0,00%	0,00%	0,00%
2.4_Predefined	2,01%	0,17%	0,03%
2.4_NoPlan	2,01%	0,02%	0,02%
3.6_Update	1,46%	-0,05%	0,03%
3.6_Predefined	1,36%	-0,24%	0,06%
3.6_NoPlan	1,41%	-0,02%	0,03%
4.8_Update	1,56%	-0,17%	0,06%
4.8_Predefined	1,55%	-0,08%	0,05%
4.8_NoPlan	1,55%	-0,14%	0,06%

Table 14: Percentage increase weight driven over the field when compared to experiment 1 (%)

Table 15 shows the harvester utilisation of these experiments. Here it can be seen that the predefined plan always (slightly) outperforms the updated plan. One possible explanation for this is that the predefined version is made with the mean number of crops. Therefore, updating the plan during the harvest might make it unnecessarily complicated and the target row can be overshot or undershot, which then decreases the harvester utilisation.

	Field 1	Field 2	Field 3
2.4_Update	95,6%	80,3%	65,2%
2.4_Predefined	96,4%	80,5%	65,3%
2.4_NoPlan	84,4%	69,9%	58,3%
3.6_Update	95,3%	79,2%	64,6%
3.6_Predefined	97,0%	79,8%	65,3%
3.6_NoPlan	84,5%	71,1%	58,4%
4.8_Update	95,6%	78,7%	64,6%
4.8_Predefined	97,2%	80,2%	65,4%
4.8_NoPlan	86,0%	70,1%	58,4%

Table 15: Harvester utilisation sensitivity analysis

6.5. Conclusion

This chapter aimed to answer the research question: *'What performance can farmers expect from buying the EOX tractor with the generated operational logic?'* To answer this question, several other questions were answered:

a. What is the best type of switch for the chaser bins?

The best type of switch depends on the KPI's that are used. If only the harvester utilisation is important, the best switch is the driving switch. If only the soil compaction is important, the headland switch works best. If both KPI's are considered, a hybrid version is best where the first and last 25 % of the field are headland switches and the remaining 50% is a driving switch.

b. What are the best configurations for the examined fields?

For all fields examined, the best solution was found to be either 4 chaser bins with a capacity of 2800 kg, or 4 chaser bins with a capacity of 4200 kg. These solutions looked very similar, as the extra switches that were required for the lower capacity of the first experiment roughly offset the extra weight that the 4200 capacity system had.

c. How does the EOX perform when compared to a traditional harvester chaser bin combination?

The EOX performed worse on harvester utilisation when compared to traditional harvester chaser bin combination with 12 crates of 700 kilo, with up to a 15% decrease. However, the soil compaction of the system was far lower than the traditional system, as the amount of crops driven over the field decreased from 15 to 30%.

d. How does the algorithm perform per scenario in the sensitivity analysis?

When comparing the variances, the increase of soil compaction was not very noticeable. This could be because a variance of 2.4 already provided enough coverage for the system, so that it did not change that much when the variance was increased. One interesting note was that the use of only a predefined route could increase the harvester utilisation very slightly in the case of field 2 and 3, and with 0,8% in field 1. This could be because the updates only happen when the plan does not work anymore, which could mean that the system sometimes overestimates the row and sometimes underestimates the required row.

Chapter 7. Conclusions and Recommendations

This thesis aimed to answer the question: "*How can robust, cooperative behaviour be developed for harvesting vehicles, assuming variable communication connection quality, a variable amount chaser bins, and a varying field size?*"

This question needed to be answered for the company H2Trac, as they are currently developing a new tractor called the EOX. This tractor can work autonomously, with the benefit that it can drive in between crop rows with an accuracy of just a couple of centimetres. However, the operational logic that makes these EOX tractors autonomous did not exist yet, which makes it impossible to give any indication on the performance to convince potential buyers to buy the EOX. Because the EOX tractors are currently not able to drive autonomously yet, an evaluation method also needed to be designed to evaluate the performance of the operational logic. The performance that was most interesting for H2Trac to share with their potential customers are the level of soil compaction, and the utilisation of the harvester. Since fields come in all different shapes and sizes, these needed to be incorporated in the evaluation and the operational logic needed to be able to use this as well.

When looking at other works in this field, they fell under three categories, which were spatial configuration, route planning and path planning. The difference between route planning and path planning is that path planning looks at creating a continuous path for a vehicle (the harvester), and the route planner looks at smaller routes (for the chaser bins). Although not required, some works suggested that creating a path for the harvester before the harvest can greatly reduce the time the harvester needs to travel. It is called offline planning whenever a decision is made before the harvest takes place, and online planning whenever a decision is made during the harvest.

The operational logic that was created used the master- slave principle. Here, the master (in this case the harvester) guides the "slave" (the chaser bin) where to go. For all activities of the harvester, a corresponding activity and decision for the chaser bin was made, alongside where a chaser bin can switch.

For the evaluation method, first a metric map is made. This is a representation of the real field, that can be imported into the model from an KML file. Then, the offline planning decisions need to be made before the harvest (is simulated). All information from the KML file and the crop row orientation is fed into an arc routing problem solver, which finds the shortest route for the harvester. This path is then put back into the evaluation model, where the approximate row of a switch is calculated. Then, the online decisions can be made by the operational logic.

7.1. Conclusions

First of all, the offline route planning can be used to find the shortest length over the headlands, but this is not a problem for regular fields. If the fields are irregular or exceptionally large, the local search within the offline route planner can be used to improve the initial solutions. Three fields were used for testing. The first conclusion that can be drawn was that, when both KPI's were used, the best solution was to use a hybrid of the two switch types at 25% of the field. Furthermore, for all fields 4 chaser bins with 2800kg capacity each was enough to harvest the fields. The EOX performed at worst 11% worse than the traditional harvester on the utilisation, but the soil compaction improved anywhere from 15 to 30%. When using a predefined route, it can slightly outperform a regularly updated route.

7.2. Recommendations & Future research

The recommendations for H2Trac are:

- Whenever possible, try to estimate the crop yield per square meter as accurately as possible. In the evaluation, the assumption was made that all crops follow a lognormal distribution, but in reality, this might be a different distribution and fields can have good areas with higher yield than usual and parts with lower yield than usual.

- Always use the offline planning before a harvest (regardless of whether this is a real harvest or a simulated one) to ensure that the harvester always takes the shortest path.
- Install sensors in the EOX to always know how full the chaser bins are.
- Make sure the unloading points are always halfway on the headlands, to ensure that harvesting happens at most half the headland away.
- If possible, remove all obstacles from a field before harvesting to ensure the least amount of soil compaction.

Future research

- Future research should focus on implementing the operational logic within a ROS system, so it can be implemented further within the DurableCASE and the EOX.
- Research needs to be done on better predicting when and where switches are required. Currently the new chaser bin is called once a certain threshold is reached, but this threshold can also be dynamic.
- Once the EOX is up and running, research can be done on how the evaluation model can be used as a digital twin.
- Research can be done on what effect hydrogen tanks instead of fuel has on the system.
- Communication failures of the vehicles need to be examined further to make the system more robust.
- Further research can be done on how to incorporate the offline route within the evaluation model.
- Research on the interaction between the weight that is driven over the field and the corresponding amount of soil compaction needs to be researched further.

Contribution to business

- The operational logic that can be further used within the DurableCASE
- An evaluation model that can be used to show audiences the benefit of smaller vehicles in the agriculture.
- An arc routing solver

Contribution to Science

- An evaluation model was provided that can serve as a decision support system for future agricultural purposes
- A master slave principle that is designed specifically for the agricultural sector.

7.3. Discussion

The initial solutions found by the offline route with the use of cheapest arc insertion and the savings algorithm proved to be sufficient for the fields and the number of rows in these fields. This was not expected, as the thought was that the local search algorithms could improve these outcomes. This was not the case, because the fields that were used all had very conventional patterns that the cheapest arc could easily find a solution for. Different, imaginary fields could be used to test the local search algorithms, but most fields in the Netherlands have the same structure as the fields described in this thesis. Therefore, the choice was made to disregard these imaginary fields, as the current cheapest insertion and savings algorithm are sufficient.

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Appendices

Appendix A.
Current agriculture process

This appendix provides additional information on the agricultural process, but is not required to understand the thesis. To get a better understanding of the harvesting process, the entire process on the field examined. The amount of steps in the agricultural cycle is different with each source (Rasheed, 2012) (FAO, 2020). This section only discusses the steps that are relevant to the farmland, the focus of this thesis. shows how these steps interact with each other. This diagram is cyclical since a farmer can reuse the field after a harvest. Now, a brief explanation is given on each step.

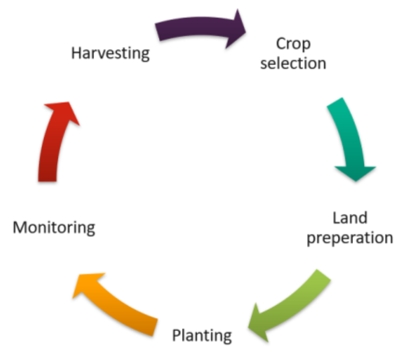


Figure 32: Agricultural Cycle

Crop selection

Before the farmer can plant seeds, the right crop needs to be selected. This process might seem straightforward, but there are many factors that the farmers need to take into account when picking the crop they want to grow and harvest in the coming season. If the farmer produces crops that use the same nutrients as the year(s) before, the field is depleted of that nutrient, and crops grow around 45% smaller than previous years (Aref & Wander, 1997). Therefore, farmers need to rotate the type of crop they grow, as different crops affect the field in distinct ways (Baldwin, 2006).

Land preparation

Once the farmer has selected the crop type, he/she prepares the field for seeding. The purpose of land preparation is to provide the necessary soil conditions that enhance the successful establishment of the young offshoots or the tissue culture plants (Klein & Zaid Date, n.d.). Generally, it involves overturning the soil (primary cultivation), then harrowing to break soil clods and levelling the field (secondary cultivation) (Greenlife, n.d.).

Planting

Now the farmer can plant the seeds. The type of technique that the farmer uses depends on the type of crop that he selected. Some crop seeds are hand sown, like grasses, and others use special equipment because the seeds need to be planted into the ground.

Monitoring

The farmer now monitors the growth of the seeds into crops and make adjustments where necessary. He does this to ensure healthy crop growth. These actions typically involve water management, weed management, deterring pests and diseases and managing soil fertility. During this time, the farmer calculates the estimated amount of crops he thinks he will harvest this season.

Harvesting

When monitoring the growth of the crops, the crops eventually reach a point where the farmer can harvest them. There are four different parts in the harvesting process, namely reaping, threshing, gathering and cleaning. With reaping, the mature panicles and straw are cut (Rice Knowledge Bank, n.d.). Then, the farmer separates the crop from the rest of the cut material with threshing. The remainder of the cut material is then "dead weight". Finally, the farmer cleans the crops, so they remove non-crop materials like sand.

This method used to be done by hand, but now farmers use combine harvesters or combine for short. As the name suggests, a combine harvester combines the techniques of reaping, threshing, gathering and cleaning. This machine allows farmers to harvest all their crops much faster, enabling them to have larger fields. In general, the larger the combine, the more the process of harvesting is sped up.

The EOX is not a combine harvester, but rather a harvesting tool is attached to the backside of the EOX tractor. The harvesting tool harvests the crops and places these in the chaser bin using a spout. This spout is situated at the right side of the tool, so the active chaser bin always needs to drive on the right side of the vehicle. Figure 33 shows a picture of this process, where the harvester (bottom of the picture) transfers the crops to the chaser bin via the spout. Note that the picture has some differences with the EOX, as this is a combine harvester where the harvesting tool is placed on the front, and the chaser bin is pulled forward by a tractor, whereas the EOX tractor has a harvesting tool at the back and the chaser bin can drive without a tractor in front.

Figure 33: Harvester and chaser bin with the spout on the right side of the vehicle

Appendix B.

Model scope

Component	Include/ Exclude	Justification
Entities:		
Crops	Include	Flow through the harvesting process, simplification: represented as points on the map
Activities:		
Harvesting	Include	Required for the objectives.
Driving to storage	Exclude	Not being modelled
Turn over crops from harvester to chaser bin	Include	Changes the mass of vehicles, so required for soil compaction
Switching chaser bins	Include	Required for soil compaction.
Making headland turns	Include	Required for harvester utilisation
Map:		
Straight crop rows	Include	Most fields have only straight rows
Curved crop rows	Exclude	Great complexity with few uses
Charging station	Include	Place where all vehicles enter from
Headlands	Include	Required to get to crop rows
Resources:		
Farmers	Exclude	Not required
Other working staff	Exclude	Same as the farmers, not required
Harvester	Include	Required for the harvester utility
Chaser bin	Include	Required for soil compaction

Appendix C.

Model level of detail

Component	Detail	Include/ Exclude	Justification
Entities:			
Crops	Quantity: 1 entity represent 1 cubic meter with crops	Include	Simplification: removes the need to model individual crops
	Quality: The quality of the crops	Exclude	Simplification: all crops have the same quality
Activities:			
Harvesting	Picking up the crop from the field	Exclude	Simplification: represented by the weight of the vehicle increasing
	Differentiating between the crops and the dead weight	Exclude	Simplification: The amount of dead weight is always the same fraction per cubic meter
Switching chaser bins	Stop filling a chaser bin and waiting for the next	Include	Impacts the harvester utility
	Harvester stops to make the link	Include	Impacts the harvester utility
Making headland turns	Vehicles avoid collision	Include	Can influence the harvester utility
Map:			
Straight crop rows	Layout of rows can be changes	Include	Required for flexibility
Charging station	Vehicles get put on the charger	exclude	This is not modelled
	Vehicle charges	Included	Assumption: vehicle charge per minute is linear
Headlands	Soil compaction modelled	Exclude	Headlands are non- working area's, so no effect on soil compaction
Resources:			
Harvester	Routing	Include	Impacts utility and soil compaction.
	Capacity	Exclude	Assumption: The harvester has enough capacity until it can link with the chaser bin
Chaser bin	Routing	Include	Impacts utility and soil compaction
	Capacity	Include	

Appendix D.

Technical explanation metric map

For the explanation of the metric map, the field near Zeewolde is used, as described in Section 5.2.2. Table 7 shows the lines, the corresponding beginning points (latitude 1 and longitude 1) and the end points (latitude 2 and longitude 2). Notice here that the end point of a line are the beginning points of the second line. This is also true for the end of line 19, which is the beginning point of line 1. Therefore, the field is entirely connected. Note that in the longitude, some slight differences in the last couple of digits behind the comma occur. This only considers a couple of centimetres in real life, and the differentiation can therefore be ignored.

LINE	LATITUDE 1	LONGITUDE 1	LATITUDE 2	LONGITUDE 2
1	52,34916	5,510342	52,35081	5,5075883
2	52,35081	5,507588	52,35072	5,5072166
3	52,35072	5,507217	52,34797	5,5028165
4	52,34797	5,502817	52,34771	5,502863
5	52,34771	5,502863	52,34666	5,5046231
6	52,34666	5,504623	52,34444	5,5074243
7	52,34444	5,507424	52,34422	5,5076226
8	52,34422	5,507623	52,34413	5,5077796
9	52,34413	5,50778	52,34405	5,5080392
10	52,34405	5,508039	52,34399	5,5084647
11	52,34399	5,508465	52,34407	5,5085763
12	52,34407	5,508576	52,34415	5,5086545
13	52,34415	5,508655	52,34474	5,5087672
14	52,34474	5,508767	52,34491	5,5087012
15	52,34491	5,508701	52,34576	5,5091057
16	52,34576	5,509106	52,34767	5,512164
17	52,34767	5,512164	52,34809	5,5121209
18	52,34809	5,512121	52,34902	5,5105784
19	52,34902	5,510578	52,34916	5,5103419

Table 7: Latitude and longitude of the lines of a field near Zeewolde

Now, these lines can be converted into points in an x,y plane. To do this, the most extreme points for the latitude and longitude are used as the 0,0 point for the model. Then, the x and y coordinates for each of the lines is measured with respect to the 0,0 line (The coordinates of the 0,0 point are from here on referred to as lat1 and lon1, and that of the point that needs to be calculated as lat2 and lon2). For the y coordinate, this is done by first converting the latitude to radians with the formula: d1=lat1*$\frac{\pi}{180}$ and d2= lat2*$\frac{\pi}{180}$, and setting lon2 equal to lon1. Then, the delta with the 0,0 point is also calculated with the formula $\Delta Lat = \frac{(lat2-lat1)*\pi}{180}$ and $\Delta Lon = \frac{(lon2-lon1)*\pi}{180}$. For the y coordinate, this means that the ΔLon is equal to zero. Now, the distance to the y coordinate can be calculated. This is done with the use of the "haversine formula": $a = sin^2\left(\frac{\Delta Lat}{2}\right) + \cos(\text{d1}) * \cos(\text{d2}) * sin^2\left(\frac{\Delta Lon}{2}\right) * \sin\left(\frac{\Delta Lon}{2}\right)$. Now, with this the angular distance in radians can be calculated with the formula $c = 2 * atan^2(\sqrt{a}, \sqrt{1-a})$. Finally, with this angular distance and the earth's radius, the y coordinate can be calculated with the formula d=R*c, with the radius of the earth used being R=6378137 meters. For the x coordinates, the same formulas can be used, only now lat1= lat2, and therefore ΔLat =0.

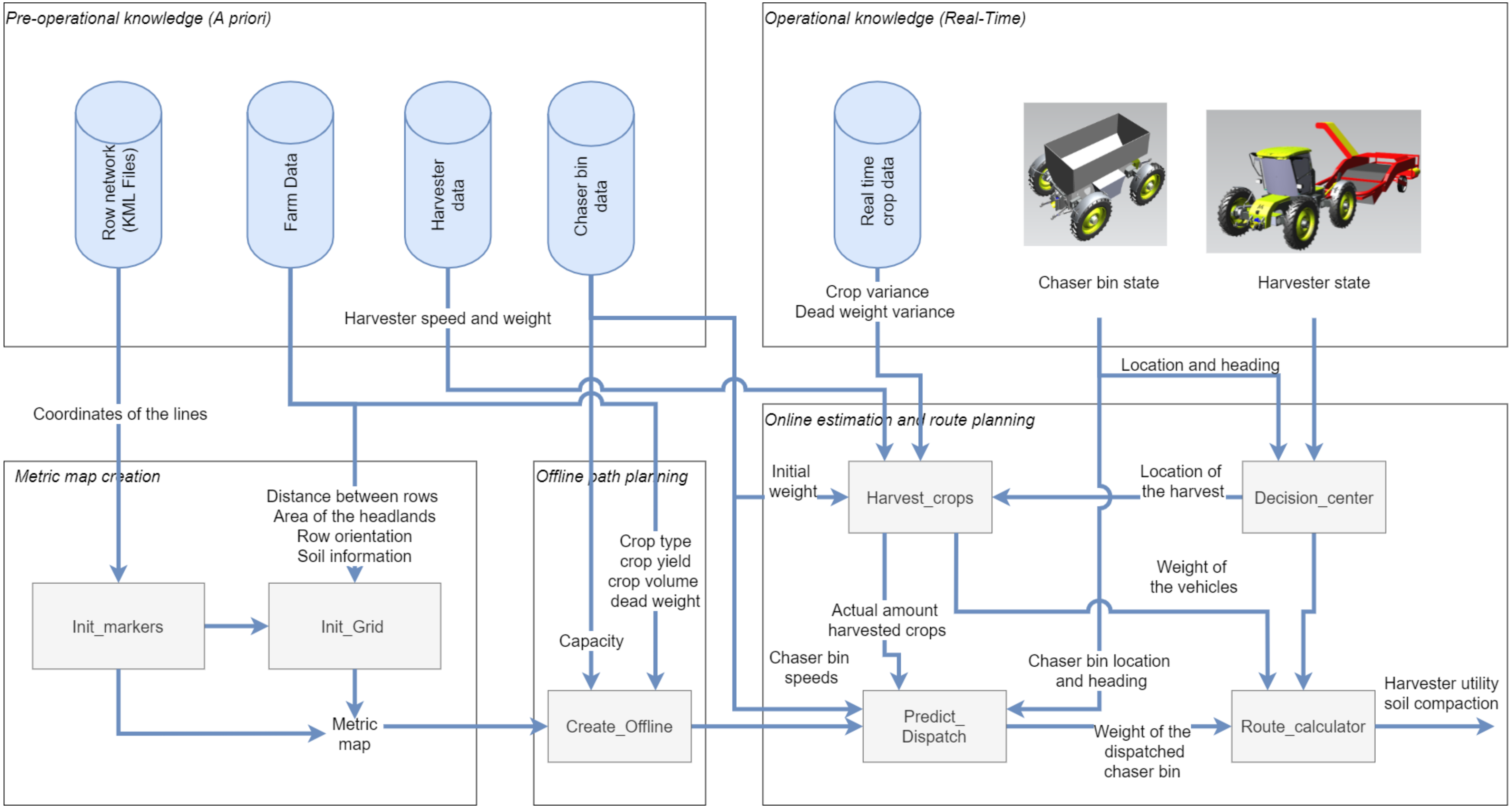
Now that the distance between all points is known, the slope of the lines can be calculated. This is done with the formulas $ChangeX = X_{end} - X_{start}$, $ChangeY = Y_{end} - Y_{start}$, and finally, if ChangeX is not equal to zero, slope $m = \frac{ChangeY}{ChangeX}$. A slope of 1 means that for an increase of 1 on the x axis, the y axis also increases with 1. Table 8 shows the coordinates from the maps converted to points in the x,y plane, including the slope of the line. Notice that due to the software used, the y points have been multiplied with minus 1. These points are then placed into sheet and the lines between them are drawn.

	Xstart	Xend	Ystart	Yend	M
Line 1	511,7	324,5	-183,6	0,0	-0,98052
Line 2	324,5	299,2	0,0	-10,1	0,39816
Line 3	299,2	0,0	-10,1	-316,6	1,02456
Line 4	0,0	3,2	-316,6	-345,0	-8,97429
Line 5	3,2	122,8	-345,0	-462,6	-0,98315
Line 6	122,8	313,3	-462,6	-709,6	-1,29640
Line 7	313,3	326,8	-709,6	-734,1	-1,81546
Line 8	326,8	337,5	-734,1	-743,3	-0,86862
Line 9	337,5	355,1	-743,3	-752,5	-0,51964
Line 10	355,1	384,1	-752,5	-758,9	-0,22277
Line 11	384,1	391,6	-758,9	-750,8	1,06942
Line 12	391,6	397,0	-750,8	-741,2	1,80252
Line 13	397,0	404,6	-741,2	-675,6	8,56915
Line 14	404,6	400,1	-675,6	-656,7	-4,19949
Line 15	400,1	427,6	-656,7	-562,5	3,42482
Line 16	427,6	635,6	-562,5	-349,3	1,02549
Line 17	635,6	632,7	-349,3	-302,5	-15,95347
Line 18	632,7	527,8	-302,5	-199,6	-0,98090
Line 19	527,8	511,7	-199,6	-183,6	-0,99820

Table 8: Coordinates from the field near Zeewolde converted to an X,Y plane and including the slope of the line

Now that the outline for the map is known, the crop rows can be drawn. This is done with the use of the slope of the line that is followed. In the model, the crop rows are parallel to line 3 with the slope of 1,02456. The formula for a general line is y=mx+b., where m is the slope of the line, and b the point of the y-intercept (if x=0, y=m*0+b=b). With the line that is considered, the formula becomes 1,02456*x+b=y. The b can be changed, as multiple crop rows need to be made. The b and m of line 3 are from here on referred to as b1 and m1 Now, the formulas for the other lines are investigated to see where they intersect with the previously mentioned line. For instance, if Line 1 is considered, the slope equals -0,98052 and the y-intercept becomes b2= Yend--0,98052*Xend. Now line 3 with some b1 and line 1 are investigated where they cross. Two lines always cross somewhere, as long as they do not have the same slope. The x- point where the two lines cross is $x = \frac{b2-b1}{m1-m2}$. If this point is higher than the lowest x point and lower than the highest x point at that y- axes point, the point is valid for a crop row. This way, all lines are considered with the same b1 point. If a crop row exist, the begin point and the end point are given as xlow and xhigh. Then, a line is drawn with the formula y=m1*xlow+b1, and then the xlow is incremented with the space between two points. Then, the crop row that has been created is placed in a table with all the routes created so fare, and the b is incremented until a stopping criterion is reached. This stopping criterion is chosen in such a way that at least the entire length of the field is considered.

Appendix E.


Pre-operational knowledge (A priori)
Row network (KML Files)
Farm Data
Harvester data
Chaser bin data
Harvester speed and weight
Operational knowledge (Real-Time)
Real time crop data
Crop variance
Dead weight variance
Chaser bin state
Harvester state
Location and heading
Coordinates of the lines
Metric map creation
Distance between rows
Area of the headlands
Row orientation
Soil information
Init_markers
Init_Grid
Metric map
Offline path planning
Crop type
crop yield
crop volume
dead weight
Capacity
Create_Offline
Online estimation and route planning
Initial weight
Harvest_crops
Location of the harvest
Decision_center
Weight of the vehicles
Actual amount harvested crops
Chaser bin speeds
Chaser bin location and heading
Predict_ Dispatch
Weight of the dispatched chaser bin
Route_calculator
Harvester utility
soil compaction

Appendix F.

Settings for determining number of replications

Exp Number	Input Parameter 1	Input Parameter 2	Extra Weight	Amount Of Chaser Bins	Capacity Chaser Bin	Capacity Call	Capacity Full	Type of Switch	PercentageSwitch	FailuresActive
1	5	2.5	0	2	2100	500	50	Hybrid	25	false

Results

n	AvgtTPtime	Avg	Var	Rel. error	OK/NOT OK
1	0,325438	0,325438	0		
2	0,320542	0,32299	5,99E-06	0,068096	NOT OK
3	0,320644	0,322208	5,22E-06	0,017612	OK
4	0,311104	0,319432	2,7E-05	0,0259	OK
5	0,325097	0,320565	2,68E-05	0,020038	OK
6	0,319933	0,32046	2,24E-05	0,015484	OK
7	0,321249	0,320573	1,92E-05	0,012654	OK
8	0,316427	0,320055	1,87E-05	0,0113	OK
9	0,320182	0,320069	1,66E-05	0,009795	OK
10	0,318213	0,319883	1,53E-05	0,008742	OK
11	0,317886	0,319702	1,42E-05	0,007925	OK
12	0,315334	0,319338	1,45E-05	0,007575	OK
13	0,322388	0,319572	1,4E-05	0,007086	OK
14	0,320252	0,319621	1,31E-05	0,00653	OK
15	0,317496	0,319479	1,25E-05	0,006123	OK
16	0,320607	0,31955	1,18E-05	0,005722	OK
17	0,320665	0,319615	1,11E-05	0,005371	OK
18	0,319603	0,319615	1,05E-05	0,005049	OK
19	0,318686	0,319566	1E-05	0,004774	OK
20	0,321683	0,319672	9,73E-06	0,004567	OK
21	0,320698	0,31972	9,31E-06	0,004345	OK
22	0,321628	0,319807	9,05E-06	0,004171	OK
23	0,318475	0,319749	8,73E-06	0,003996	OK
24	0,321411	0,319819	8,48E-06	0,003844	OK
25	0,319929	0,319823	8,14E-06	0,003682	OK
26	0,318024	0,319754	7,94E-06	0,00356	OK
27	0,319636	0,319749	7,65E-06	0,003422	OK
28	0,321387	0,319808	7,47E-06	0,003314	OK
29	0,320619	0,319836	7,23E-06	0,003199	OK
30	0,32079	0,319868	7,02E-06	0,003093	OK
31	0,322832	0,319963	7,07E-06	0,003048	OK
32	0,31832	0,319912	6,93E-06	0,002967	OK
33	0,317026	0,319824	6,97E-06	0,002926	OK
34	0,321199	0,319865	6,81E-06	0,002848	OK
35	0,328065	0,320099	8,49E-06	0,003126	OK
36	0,319231	0,320075	8,27E-06	0,00304	OK

37	0,3219	0,320124	8,13E-06	0,002971	OK
38	0,310777	0,319878	1,02E-05	0,003275	OK
39	0,316235	0,319785	1,02E-05	0,003242	OK
40	0,320183	0,319795	9,98E-06	0,003159	OK