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Route optimization of primary and service units in agricultural harvesting operations

Infield routing accounting for spatial variation in susceptibility to soil compaction

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Abstract

In agriculture, soil compaction is a problem with severe consequences for soil quality, leading among other things to lower yields. Optimization of infield routes based on predefined paths is one of the methods to reduce induced soil compaction during agricultural harvesting operations. Previous work has failed to address how to determine an optimal route for a capacitated agricultural harvesting operation with discrete spatial variation of the soil (e.g. sites susceptible to soil compaction and wet spots). In this thesis, we introduce an objective function returning so called weight meters (m * kg) that integrates the collaboration of primary and service units, turning manoeuvres and wet spots. A weighted graph abstraction function is the basis on which the objective function and a heuristic optimizer (Tabu search algorithm) were applied. The method is demonstrated on three fields for which the results are compared to conventional harvesting routes. Up to a 10.45% reduction in traversed weight meters was obtained. Therefore, the method is successful in reducing the weight meters while considering weight variation, wet spots, variation in soil compaction and restrictions regarding driving patterns.

Keywords:

Precision agriculture, graph theory, soil compaction, Tabu search algorithm, service unit, heuristic optimizer, primary unit, wet spot, agricultural field, capacitated arc routing problem

Contents

List of definitions

Important words and their definitions to understand during this research paper.

Arc	A link between two nodes, representing a path or turn in an agricultural field. Similar to an edge.
Depot	A location where unloading of the service unit occurs and operations start and end.
Edges	A link in a graph between two nodes, representing a path or turn in an agricultural field. Similar to an arc.
Curvature	Curvature indicates how sharp a circle can bend and is therefore comparable with the turning rate of a unit.
Field path	A path with the width equal to the operational width of the primary unit in which agricultural operations are executed.
Headland	Area at the far ends of an agricultural field, where turning operations and movements towards the depot occur.
Main field	Area between both far ends of an agricultural field, entire field minus the headlands. The main field contains the field paths.
Nodes	A point in a graph, representing paths starts or ends, depot locations and start and endings of wet areas in an agricultural field.
Primary unit	A unit performing the main working task, an example of a primary unit is a harvester.
Route primary unit	The route which a primary unit follows during the agricultural harvesting operation. Route starts at the depot, where after all field paths are harvested and after completion of all field paths returns to the depot.
Route service unit	The route which a service unit follows during the agricultural harvesting operation. Every service unit route starts at the depot, where after the service unit is loaded until the maximum carrying capacity is reached and it returns to the depot.
Service unit	A unit supporting the primary unit, an example of a service unit is a tractor with a transport cart.
Spray paths	A higher intensity traversed path with the width equal to the operational width of the primary unit in which agricultural operations are executed. Often used for spraying operations.

List of symbols

Symbols, their corresponding units and definitions used in this research paper

CW	[kg]	Current weight
CW_s	[kg]	Current weight of the service unit
CW_p	[kg]	Current weight of the primary unit
D	[m]	Distance in meters
DP	[m]	Dubins path distance in meters
F_{dn}	[-]	Multiplication factor of dry normal path
F_{ds}	[-]	Multiplication factor of dry spray path
F_{hf}	[-]	Multiplication factor of headland field
F_{wn}	[-]	Multiplication factor of wet normal path
F_{ws}	[-]	Multiplication factor of dry normal path
HF	[m]	Distance in headland field
JSU	[m*kg]	Objective function service unit in weight meters
JPU	[m*kg]	Objective function primary unit in weight meters
k	[-]	Index for the number of already performed depot visits
K	[m^{-1}]	Curvature
k_{max}	[-]	Index for the total number of depot visits
l	[-]	Distance traversed since last depot visit
l_{max}	[-]	Sum of distances traversed
MF	[m]	Distance in main body of the field
MF_d	[m]	Distance in dry area of the main body of the field
MF_{dn}	[m]	Distance in dry normal paths in the main body of the field
MF_{ds}	[m]	Distance in dry spray paths in the main body of the field
MF_w	[m]	Distance in wet area of the main body of the field
MF_{wn}	[m]	Distance in wet normal paths in the main body of the field
MF_{ws}	[m]	Distance in wet spray paths in the main body of the field
N_{depot}	[-]	Node IDs representing the depot node
N_{funo}	[-]	Node IDs representing the full-nodes
N_P	[-]	Node IDs representing the primary nodes
N_{wet}	[-]	Node IDs representing the wet nodes
R	[m^{-1}]	Radius of curvature
W_{empty}	[kg]	Weight when the primary or service unit is empty
W_{funo}	[kg]	Weight at the location when a full node is created
W_{inra}	[kg]	Harvest rate of the primary unit

List of abbreviations

Abbreviations used in this research paper

ARP	Arc Routing Problem
CPP	Chinese Postman Problem
CTF	Controlled Traffic Farming
CARP	Capacitated Arc Routing Problem
CVRP	Capacitated Vehicle Routing Problem
TSP	Traveling Salesman Problem
VRP	Vehicle Routing Problem
VRPTW	Vehicle Routing Problem with Time Windows
GAOS	Geo-spatial Arable Field Optimization Service

1 Introduction

1.1 *Context and background*

1.1.1 Soil compaction

Compaction of the soil is one of the major problems faced in the agricultural sector (Hamza et al., 2005). This issue has severe impacts when it comes to the agricultural productivity and is seen as one of the most difficult to remediate types of land degradation (Shah et al., 2017). Soil compaction can result in loss of quality of the atmosphere, soil resources, surface and ground water (Soane et al., 1995). This is because soil compaction causes strong modifications to the structure and porosity of the soil (Pagliai et al., 2003). These modifications in the structure and porosity of the soil make the soil less suitable as a growth medium, which leads to negative consequences for the growth and development of the crop and as a result reduced yields (Shah et al., 2017; Weisskopf et al., 2010). Agricultural soil properties are under constant change of conditions because of different management practices, weather conditions and biological activities (Bronick et al., 2005; Hartge, 1994).

Soil compaction has many dimensions. In this thesis, decision was made to focus on human induced part of soil compaction. Worldwide 38% of the agricultural fields are affected by human-induced soil degradation (Oldeman, 1992). It is mostly caused mostly by agricultural vehicles traversing fields. Approximately 95.3% of the total field area is traversed by a machine at least once a year when conventional tillage is used (Kroulík et al., 2009). The vehicles traversing the field are becoming larger and heavier; for example in Denmark the average weight of a tractor has increased from 2.6 tons, in 1970 to 6.6 tons, in 2000 (Bochtis et al., 2012; Høj, 2011). This development has resulted in increased pressure on the soil and can lead to a potential increase of the severity of compaction problems (Sivarajan et al., 2018).

A single passage by a wheeled and or a rubber tracked tractor leads to a significant decrease in the porosity of the surface layer (0-10 cm), while after four passes a further decrease was found in the porosity of the surface layer (Pagliai et al., 2003). A quite similar result was found for the 10-20 cm layer. However, for a test in which a rubber tracked tractor was used, no significant decrease in the soil porosity was measured. If annually one or more wheeling's occur over a single path, the soil is not able to fully recover from the passage (McHugh et al., 2003; Tullberg et al., 2007). Therefore, it is important to minimize the load and the number of passages, to minimize the effects of soil compaction on the soil as growth medium.

Although soil compaction is mostly caused by agricultural vehicles, other factors like soil moisture content also influence soil compaction (Bochtis et al., 2012). After periods with prolonged rain under fallow conditions or when a crop is non active (e.g. potatoes prior to harvest), the subsoil will remain moist for a long period of time, because of the physical properties of the soil (Bakker et al., 1995). If the soil moisture content is above 60% of the field capacity, travelling across the field results in excessive soil compaction (Raper, 2005). Therefore, spots with a higher soil moisture content should be avoided if possible.

Another consequence of soil compaction is related to the increased amount of energy that is needed for agricultural operations (Bochtis et al., 2012). Together with the aforementioned issues regarding soil compaction, soil compaction is of large influence on the soil quality. Therefore, it is important to minimize the effects of soil compaction in the field.

1.1.2 Controlled traffic farming

One of the methods to reduce soil compaction is controlled traffic farming (CTF). CTF is a management practice in which farmers maintain the field paths at the same position for several years (Bakker et al., 1995). Field paths are in most cases unplanted, compacted areas which are primarily used for driving over the field. The layout of these field paths are designed to gain efficiency and allow effective drainage (Tullberg et al., 2007). The efficiency of the field paths design can also be assessed by comparing the environmental impacts of CTF against the effects of conventional farming. CTF shows significant reductions for nitrous oxide and methane emissions, water runoff and leaching of pesticides (Gasso et al., 2013). Combining the environmental benefits together with increased yields and increased gross margins results in a win-win situation for both the environment and the farmers (Chamen et al., 2014).

During agricultural operations, the field is often not traversed optimally; overlap and unnecessary manoeuvres at the headlands result in inefficient driving patterns (Palmer, 1984; Palmer et al., 2003). Traversing a field in a more optimal way and using more efficient driving patterns will result in less soil compaction.

In this study, a multiple unit output material flow (e.g. harvesting) operation is examined. An output material flow indicates that material is gained during the field operation and is transported to another location. In output material flow operations often, multiple units are involved. The units involved are primary units (e.g. harvesters) and service units (e.g. tractor and wagons). In addition, in these kinds of operations there have to be made considerations regarding the scheduling and operational planning. Scheduling is related to the allocation and commitment of used resources while operational planning is related to the decisions which are made during the operation regarding turning, routing, unloading and loading (Bochtis & Sørensen, 2010; Sørensen et al., 2010). For optimization of the field traffic minimizing turning time leads to more efficiency gain than to minimize unloading time (Taylor et al., 2002). Because of this, optimization of turning should be prioritized over optimization of the unloading process.

A method to create a more optimal route to traverse a field is based on the vehicle routing problem (VRP), which was first introduced by Dantzig et al. (1959) as the "Truck Dispatching Problem". The truck dispatching problem can be seen as an generalization of the "Traveling Salesman Problem" (TSP) where a person has to visit all customers (Bochtis et al., 2009).

A VRP determines multiple least costs routes from one depot to a set of geographically dispersed points. In the routes that are generated each point is visited only once and by not more than one unit. Furthermore, all routes start and end at a depot. This is to verify that the total demand of all points does not exceed the capacity of the vehicle (Bochtis et al., 2009). Harvesting operations are characterized by capacity limitations of involved vehicles. Therefore, a capacitated element is added to the VRP. The problem can then be formulated as a capacitated vehicle routing problem (CVRP) (Bakhtiari et al., 2013). For the CVRP a graph needs to be created where a set of nodes are to be visited. In this research an arc based variant of the CVRP was implemented, where paths within a field are presented by arcs, also known as edges. This so-called capacitated arc routing problem (CARP) allows to determine the minimum cost for traversing all or a subset of the edges in the graph (Corberán et al., 2009).

A CARP is classified as a NP-hard problem (Hirabayashi et al., 1992). When a problem is NP-hard no solution can be found in polynomial time. Since a CARP cannot be solved optimally within reasonable time, a meta heuristic is commonly used. A meta heuristic is able to generate a near optimal solution. Examples of meta heuristics capable of solving a CARP are the Tabu search algorithm and the hybrid genetic algorithm (Chu et al., 2005).

When the maximum capacity is reached, the operating unit needs to return to the depot, before it can continue (Bakhtiari et al., 2013). However, in intensive farming systems such as mostly used in Europe, a so-called on-the-go scenario is common practice (Bakhtiari et al., 2013). In such a system, a service unit follows the primary unit until the primary unit is ready for unloading. After the unloading is executed, the primary unit can continue harvesting while the service waits for the next time the primary unit needs to be unloaded or it returns to the depot depending on its remaining capacity.

1.1.3 Past research

In research conducted by Sørensen et al. (2004), the objective was to create a planning framework for autonomous field operations. They wanted to optimize the driving pattern by implementing corresponding restrictions for multiple implements and field characteristics. In the implementation of this framework capacity is not considered. The optimization routing was done through a graph abstraction.

de Bruin et al. (2014) created a geo-spatial arable field optimization service called GAOS. The objective of GAOS was to optimize the location of tracks within farmer their fields. This was done my maximizing the efficiency by avoiding inefficient turns and discontinuous swaths. The service resulted in reduced expenditures on time and wasted resources. Also support for the planning of spraying paths was integrated but routing was not considered.

Bakhtiari et al. (2013) developed a method for generating an optimal field coverage plan for harvesting operations based on B patterns. The optimization focussed on reducing the non-working distance and optimizing the harvester route. In this method both unloading in the field and in a facility outside the field were examined. The result of the implementation in an ant colony optimization showed reductions in the non-working distance between 19.3% and 42.1% in the field.

PhD work of Jensen at Aarhus University focused on coverage planning for capacitated field operations. One of the objectives was to identify non-productive activities in capacitated field operations and to minimize these (Jensen, Nørremark, et al., 2015). This work demonstrated the potential efficiency gains that can be made by reducing non-productive activities. During the implementation trade-offs between the different activities have to be made. In a second paper, the objective was to create an optimized coverage planning algorithm for capacitated field operations (Jensen, Bochtis, et al., 2015). This was done by reducing the non-productive distance based on the non-productive activities of the other paper. For the liquid fertiliser application that was examined, reductions between 15.7% and 43.5% were found for non-productive distance while reductions between 5.8% and 11.8% were found for the total distance traversed.

Another relevant paper by Jensen et al. (2012) presents a route planning method for service units in cooperation with primary units in agricultural operations for infield and inter-field transport. This study found that switching between optimization criteria led to differences between the resulting routes. These differences were in the range of 2 to 10%, indicated that selecting appropriate criteria for the specific conditions of the operations is important.

Brandão et al. (2008) performed a study on the implementation of a deterministic Tabu search algorithm for a CARP. The results indicated that a Tabu search produces high quality solutions within a reasonable computing time for a CARP.

Mijnheer (2018) conducted a study aiming to determine an optimal route for agricultural operations with predefined tracks and spatial variation in soil compaction (e.g. wet spots). The total cost of the route was calculated by implementing a weighted sum of soil compaction presented in weight meters (m*kg), where the optimal route was the route with the least weight meters. However, this work considered a single-unit operation as opposed to a multi-unit harvesting operation as is the case in this research. Another result of the research was that a Tabu search algorithm was deemed the most suitable optimization algorithm for the search of a near-optimal route.

1.2 Problem Definition

Human induced soil compaction has severe effects on the soil as growth medium, especially when the soil has a high moisture content. Methods such as CTF that avoid soil compaction are important for achieving higher. To optimally make use of CTF, a route for traversing the field is needed. Routes minimizing soil compaction should include factors such soil moisture content and weight of the machine. Since harvesting operations involve multiple capacitated vehicles operating together, it is necessary to find an optimal balance between the vehicles to minimize the soil compaction.

Over the previous decades, multiple studies regarding optimization of field traffic in capacitated harvesting operations have been conducted. However, most of these studies focussed on efficiency and minimizing the distance while soil compaction was mostly disregarded. Therefore, this thesis research aims to address how an optimal route within an agricultural field can be determined, depending on minimization of the soil compaction whilst accounting for spatial variation (e.g. areas with a higher soil moisture content) in a capacitated harvesting operation with both primary and service units. The focus will be on finding an optimal balance to minimize the total soil compaction that is generated by the primary and service units.

1.3 Research objective and questions

The objective of this research is to determine an optimal route for a capacitated agricultural harvesting operation with discrete spatial variation of the soil (e.g. soil compaction and wet spots).

The objective is achieved by answering the following questions:

1. What is an optimal route for service units operating alongside a harvester with regards to soil compaction and wet spots within a field?
2. How can an agricultural harvesting operation including headland turns and wet spots be represented by a graph abstraction?
3. Which are suitable meta parameters for a heuristic optimiser applied to the CARP?
4. How do test-cases of an implemented system compare to conventional harvesting routes of capacitated agricultural operations?

2 Methodology

This section gives an explanation which methods were applied to reach the research objectives. Each subsection addresses a part of the methodology regarding either about a research question or the implementation.

2.1 Harvesting operation and overview methodology

A harvesting operation is an agricultural operation taking place on a field consisting of pre-defined paths in which primary as well as service units operate, see figure 1. Because farmers have different methods for harvesting the areas at the end of a planted field path also referred to as headlands, only the main body of a field is considered in this research. The primary units are the harvesters. These primary units store the harvest temporarily in their bunker. A primary unit is able to harvest until the maximum capacity of the bunker is reached. When the maximum capacity of the bunker is reached, a primary unit has to unload the harvest onto a service unit. Due to the construction of the machine, a primary unit can typically only unload onto the right. Therefore, the service unit must be able to get on the right side of the primary unit to make unloading possible, see figure 2. The objective of the service unit in this operation, is to manoeuvre from the depot to the primary unit, to transport the harvest from the primary unit location to the location of the depot, where the harvest is stored. This depot location is in most cases located outside the field. In a harvesting operation a service unit is not able to drive on all paths in the field, because some of these paths are normal not yet harvested paths. A service unit is not able to traverse those paths, because otherwise crops will be damaged. Therefore, the primary unit has to take a route for which it is possible for the service unit to reach the primary unit location.

Figure 1: A primary unit (right) harvesting and unloading onto the service unit (left). A second service unit (background) is waiting idle to take over the unit in the centre.

Figure 2: A primary unit (right) unloading onto a service unit (middle) and another primary unit harvesting (left).

When a primary or a service unit has reached the end of a path it has to manoeuvre from one path to another path. This is done by the implementation of a turning manoeuvre. For this problem a method is worked out further on in the methodology chapter.

Based on the situation in an agricultural harvesting operation, a methodology scheme was composed. This scheme is shown in figure 3 and gives an overview of the methodology used during this study. The scheme is based on the research questions presented in section 1.3 and shows the overall steps that were performed to obtain the answers to the research questions.

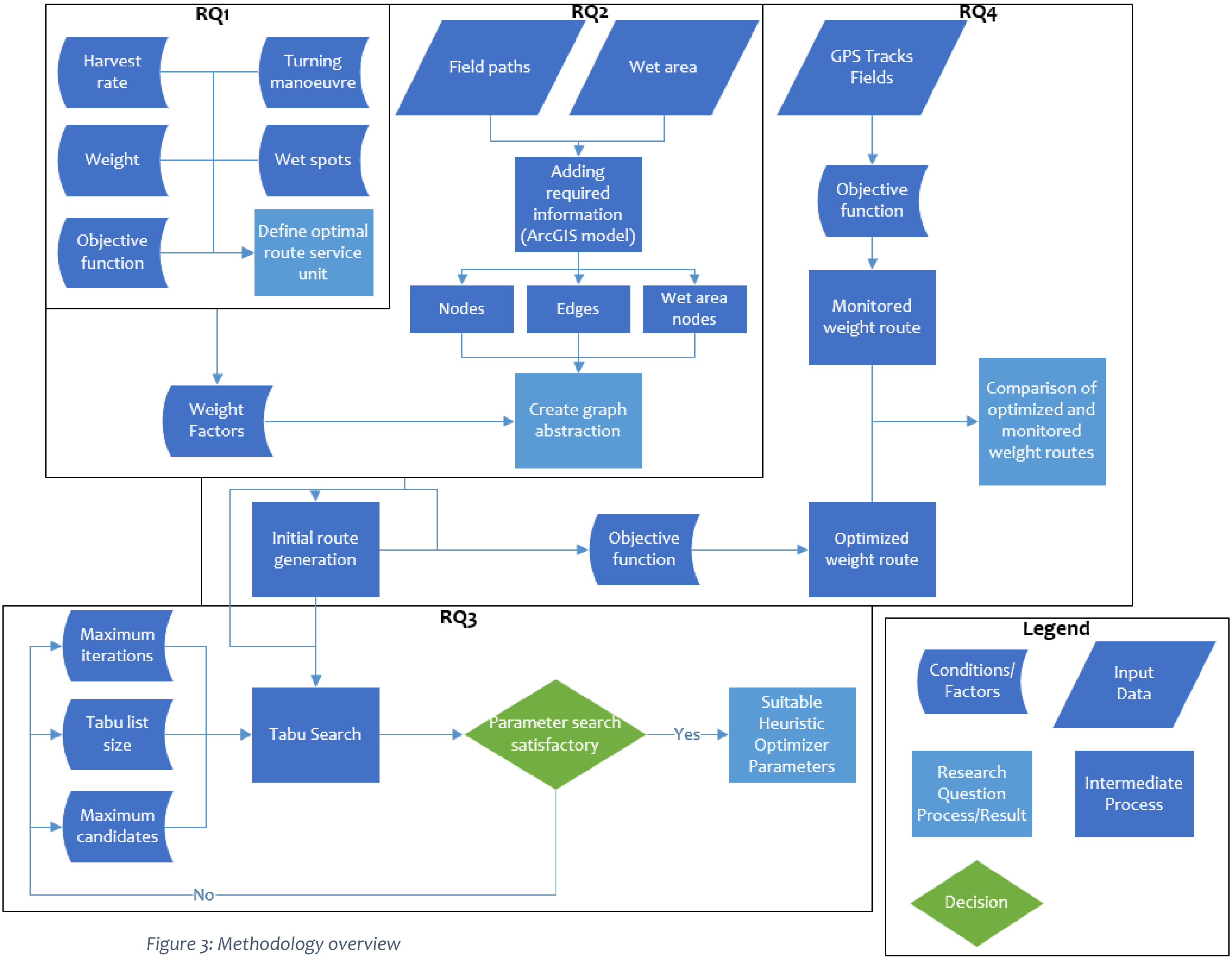


Figure 3: Methodology overview

2.2 *Optimal route service unit*

2.2.1 *Objective function*

Since the primary and service unit operate under different constrains, some parts of the objective function are presented twice with only minor differences.

In this study, the decision was made to focus on finding an optimal route for the main body of an agricultural field. Accordingly, the headlands were disregarded in the route optimization. This decision was made because farmers have different approaches for how they handle the headlands. However, that does not mean that no actions occur on the headlands. Headlands are used for manoeuvres such as turning and entering or leaving the field.

The objective is to create a route with minimal induced soil compaction. Mijnheer (2018) proposed calculating the total cost of a route by implementing a weighted sum of soil compaction presented in weight meters (m*kg), where the optimal route was the route with the least weight meters. His proposal was adopted in the current thesis. The weighted sum of soil compaction involved several cost factors. These cost factors were divided into two categories with the weight as overarching factor for both categories. The first category consisted of the actions occurring in the headlands of the field. The cost factors related to the headlands were the turning manoeuvres and the driving from and to the depot. The second category consisted of the movements that take place in the main body of the field. The following cost factors were considered for the main body of the field:

- Normal paths (lower intensity traversed paths)
- Spray paths (higher intensity traversed paths, used during spraying operations)
- Wet spots (an area in the field classified as wet)
- Dry spots (an area in the field classified as dry)

Each of these factors was assigned an unique cost factor, as explained later in section 2.3.2.

Figure 4 presents a schematic overview of the objective function. The figure shows the cost factors and their relationships for the primary unit as well as the service unit. Figure 4 provides the basis for defining the equations to calculate the total amount of weight meters of the primary and service units. The objective functions have to be calculated separately, because the service unit has to return to the depot to unload, after the maximum capacity is reached. In contrast, the primary unit unloads at the location where the maximum capacity is reached. Furthermore, the primary unit receives additional weight each meter traversed in a previously not traversed path, while the weight of the service unit only changes at locations where the primary unit has reached its maximum capacity or at the depot. The objective function of the service unit is represented by equation 1.

$$JSU = \sum_{k=0}^{k=k_{max}} \left(\int_{l=0}^{l=l_{max}} \left(CW_s * (MF + HF) \right) \right) \text{ [m*kg]}, \quad (1)$$

where k indicates an index for the number of already performed depot visits, k_{max} indicates the total number of visited depots, l is the distance traversed since the last depot visit, while l_{max} is the sum of the distances traversed between the returns to the depot. The latter distances were calculated with Dijkstra's algorithm. Dijkstra's Algorithm calculates the least cost routes between nodes on a graph (Dijkstra, 1959). This makes the algorithm suitable for the service unit distance calculation. Another part of the equation is the current weight (CW). The service unit weight only changes during the unloading of the primary unit onto the service unit and after a depot has been visited, which only occurs after the max capacity of the service unit has been reached.

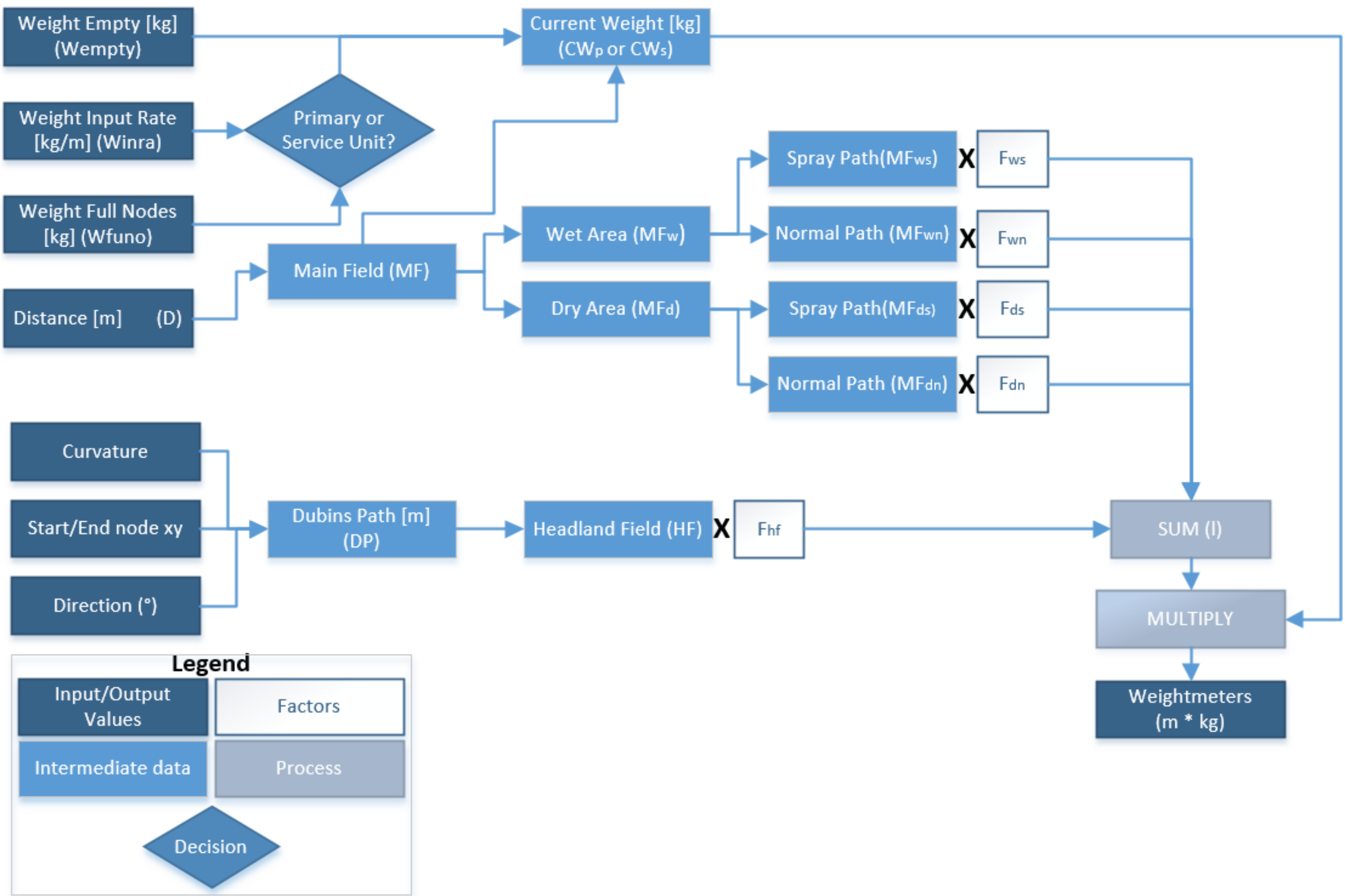


Figure 4: Schematic overview objective function

The objective function for the primary unit (equation 2) is similar. Except for k and k_{max} which are, absent because a primary unit does not have to return to the depot. However, the primary unit unloads at the location where the maximum capacity is reached. Afterwards the primary unit can continue harvesting with the current weight set to the empty weight plus the weight of any harvesting remaining in the bunker.

$$JPU = \int_{l=0}^{l=l_{max}} \left(CW_p * (MF + HF) \right) \text{ [m*kg]}, \qquad (2)$$

where CW_p is the Current weight of the primary which has to be calculated for every meter traversed by the primary unit travelled while harvesting. For this calculation an arc based approach is used, because information about the edge is required every meter. The current weight is then calculated with equation 3.

$$CW_p = W_{empty} + D * W_{inra} + R \text{ [kg]}, \qquad (3)$$

Where W_{empty} is the empty weight of the primary unit. W_{inra} is an input rate of harvest kilograms per meter and D is the distance, since the last time the primary unit was unloaded. When the maximum capacity of the primary unit is reached, the harvest in the on-board bunker of the primary unit is unloaded to the service unit. The service unit receives as much harvest as the remaining capacity of the service unit allows. If a service unit is not capable of receiving the entire load, a part of the load remains in the primary unit's bunker (R).

Equation 4 concerns calculation of the current weight of a service unit.

$$CW_s = W_{empty} + \sum_{k=0}^{k=3}(W_{funo}) \text{ [kg]}, \quad (4)$$

Where W_{empty} is the empty weight of a service unit, k is the number of full-nodes which were visited and W_{funo} is the weight received from the primary unit during the unloading. Full-nodes are the location where the maximum capacity of the primary unit is reached. The service unit is able to take up to the capacity of the service unit divided by the bunker capacity of the primary unit number of loadings, the max k is therefore 3. When the maximum capacity of the service unit is reached, the service unit has to return to the depot.

Equation 5 and 6 presents the calculation of the distance travelled in the main field and the distance travelled in the headlands multiplied by the corresponding susceptibility to soil compaction factors.

$$MF = F_w * (MF_{ws} * F_{sp} + MF_{wn} * F_{np}) + F_d * (MF_{ds} * F_{sp} + MF_{dn} * F_{np}) \text{ [m]}, \quad (5)$$

where MF_{ws} and MF_{wn} are distances traversed in spray paths and normal paths in a wet area, while MF_{ds} and MF_{dn} indicate the distances traversed in the spray paths and normal paths in a dry area, F_w is a multiplication factor in wet areas, while F_d is a multiplication factor for dry areas, F_{sp} presents the spray path factor and F_{np} is a factor for normal paths. In figure 4 these factors are combined and represented with respectively F_{ws}, F_{wn}, F_{ds} and F_{dn} (e.g. F_{ws} represents the factor for a wet area in which a spray path is located). Resulting in the total factored sum of distances traversed in the main field.

For the headlands, no distinction was made between wet and dry areas, because of the large variety in turning patterns, dependent on the circumstances of the turn. Section 4.3 explains how the distances of the turning manoeuvres were calculated.

$$HF = F_{hf} * DP \text{ [m]}, \quad (6)$$

where F_{hf} is the factor for traversing in a headland and DP is the total distance of a Dubins path. Resulting in the factored distance in the headlands.

Several simplifications were made, to set boundaries for the researched system. The first simplification made in this study was that only in-field traffic is considered. Field traffic occurring outside the field to the storage location was not considered. As a result, after a service unit has reached the maximum capacity, it heads for the exit of the field. The exit location is considered the depot location. In other words, the distance that the service unit traverses between the exit of the field and the storage location is not taken into consideration in this research. A second simplification was that the factor time is omitted. Accordingly, a new service unit spawns at the depot when required.

2.2.2 *Input parameters*

For the objective function, multiple input parameters are required. The first input parameter is the harvesting width. Based on the harvesting width, the paths in the field were generated. In this thesis a harvesting width of three meters was used. This number is in line with the path width in most agricultural fields, which is a result of the machinery used. The harvesting width of the harvester used in the examined operations was also three meters.

For the primary and service units, parameters regarding the weight and capacities have to be defined. The weights and capacities of these units were based on the units of Novifarm and Loonbedrijf Breure that were used during a monitored harvesting operation in the Hoeksche Waard. The weights and capacities of these units are given in table 1. Based on table 1, a primary unit was assigned an empty weight of 23500 kg and a bunker capacity of 8000 kg. In total, the primary unit can maximally weigh 31500 kg. The service units empty weight was set to 15800 kg, which considers both the tractor and the wagon. The total capacity of the wagon was 21000 kg, leading to a maximum weight of 36800 kg.

The values used for the factors mentioned in section 2.2.1 are given in section 2.3.2.

Table 1: Used farm equipment and GPS trackers

Vehicle	Type	Empty weight (kg)	Capacity (kg)	GPS number
New Holland T7. 220 + Beco Super 2800	Service unit	7100 + 8700 = 15800	21000	21
AVR Puma 3	Primary unit	23500	8000	22
Fendt 820 + Beco Super 2800	Service unit	7185 + 8700 = 15885	21000	23
Fendt 818 + Beco Super 2800	Service unit	7021 + 8700 = 15721	21000	24
New Holland TM 120 + Beco Maxxim 200	Service unit	5250 + 5780 =11030	20000	25
AVR Puma 3	Primary unit	23500	8000	Build-in GPS

The harvest rate value was extracted from field work data. In reality there is always spatial variation in yields across the field, which affects the harvest rate, full node locations and routing of the service unit. According to Bochtis and Sørensen (2010) determining yield information a priori is very difficult. Therefore, a constant harvest rate was assumed. The unit in which the harvest rate is expressed is in kg/m. For the calculation the total yield of the field was divided by the result of the total time multiplied with the average speed. Resulting in a harvest rate of 8.185 kg/m.

2.3 Graph abstraction of a harvesting operation

2.3.1 Restrictions

During harvesting operations, the service unit has to comply with several restrictions:

(1) The service unit is only allowed to drive on the headlands, spray paths and harvested normal paths.

(2) When unloading the primary unit, the right adjacent track should be available for a service unit to drive on.

These two restrictions were taken into account during the calculation of the path planning for the primary unit and the service unit.

Figure 5 shows a service unit driving on a path towards the primary unit. The service unit traverses a spray path on the right of the service unit, which satisfies both conditions.

Figure 5: Harvesting operation in which a service unit is traversing an unharvested spray path (red lines) to get to the primary unit. The service unit satisfies both restrictions.

The primary unit has to traverse through all edges to finish its task. A service unit does not have to operate according to this condition. The service units are allowed to take the least cost route from the unloading location of the primary unit to the depot location.

2.3.2 *Graph structure*

Implementing a weighted graph abstraction of an agricultural field, allows to store all the costs of possible movements in the field. On the weighted graph abstraction, algorithmic calculations can be applied (e.g. least costs routes in agricultural fields).

A graph abstraction consists of a set of nodes and edges. The primary unit and service unit share the same set of nodes and edges. However, for the service unit additional nodes and edges were added to represent locations where the primary unit reaches maximum capacity, referred to as "full-nodes".

For both the primary unit and service unit, $N = [0,1,\ldots,N_p]$ represents the node set of primary nodes. Primary nodes (N_p) are located at the boundaries of the main field and the headlands. N is a union of N1, N2 and N3 where $N1 = [N_{depot}]$ represents the depot node, describing the node where the route starts for both the primary and service units, and $N2 = [min(N_{wet}),\ldots,max(N_{wet})$ represents the in the main field located wet nodes, describing the locations where a primary or service unit enters or leaves a wet area. For the service unit additional nodes were added, $N3 = [min(N_{funo}),\ldots,max(N_{funo})]$ represents the nodes position, where the primary unit has reached the maximum capacity these additional nodes represents.

In the graph edges are connect by two nodes. However, for the representation of a route, the two connecting edge nodes are used as identifiers of an edge. A created route has to pass through all connecting nodes representing edges. This guarantees that the entire field is harvested.

In the dictionary of the graph abstraction, unique weight factors were assigned for traversing wet spots, dry spots, spray paths, normal paths and turning manoeuvres. These actions take place either in the main field or at the headlands. The assigned weight factors were dependent on the susceptibility of soil compaction. Therefore, in table 2 three weighting scheme scenarios depending on different field circumstances are shown. This gave insight in how susceptive the objective function is for changes, for both the primary and service unit.

In the scenarios a distinction was made between the multiplication factors for wet and dry areas in the field. In the standard scenario the multiplication factor of a wet area was higher than the multiplication factor of a dry area, because a wet soil is more susceptible to soil compaction than a dry soil.

In the dry scenario, the wet areas have dried up and the entire field has become drier. Therefore, in the dry scenario the multiplication factors of dry and wet areas have been decreased compared to the standard scenario. A similar thing was done for the wet scenario. In the wet scenario, the entire field is considered wetter than in a standard scenario and as a result the multiplication factors for traversing a wet area and a dry area were increased.

For all three scenarios, similar multiplication factors were selected for traversing spray paths, normal paths and headlands. Traversing a spray path results in less induced soil compaction because spray paths are traversed more often. As a result, a lower multiplication factor was assigned to the spray paths than to the normal paths. For the headlands a multiplication factor was selected which is slightly lower than the multiplication factor for traversing a normal path. The reasoning behind this was that in general headlands are traversed more often than normal paths in the main body of the field. Therefore, resulting in less induced compaction to the soil on the headlands, in comparison to the normal paths in the main body of the field. During the research the "Standard" scenario was applied for calculations.

Table 2: Multiplication factors for various actions in different scenario's

Scenario	Wet Area (F_w)	Dry Area (F_d)	Spray path (F_{sp})	Normal path (F_{np})	Headland (F_{hf})
Standard	1.3	1	0.5	1	0.8
Dry	1	0.7	0.5	1	0.8
Wet	1.6	1.3	0.5	1	0.8

2.3.3 *Demonstration on synthetic test field*

Figure 6 shows a graph representation of a synthetic test field consisting of seven paths in total. At the far ends of each path are primary nodes (yellow dots) located. These primary nodes are used for the presentation of the route through the field. In addition, nodes are placed at the beginning and ending locations of wet spots (blue dots) in the field. The green dot at the top right represents the depot location. The values of the original nodes and edges were stored in the dictionary of the graph abstraction. Although, the shape may be different, the stored values in the dictionary were identical to the values representing the original field.

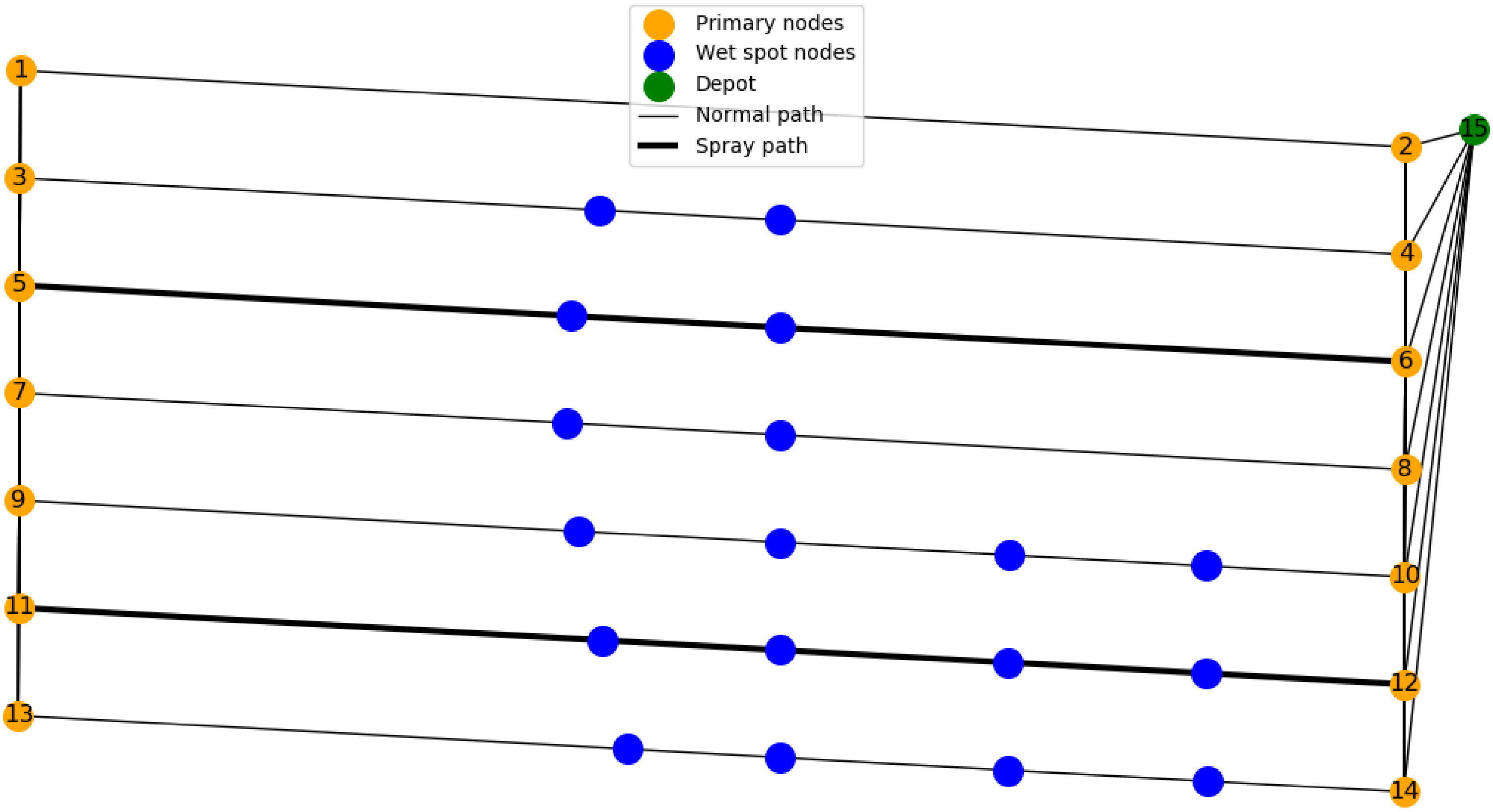


Figure 6: Graph representation of a synthetic test field visualized in Networkx

Essential parameters of the graph abstraction are the orientation and on which side of the field the depot is located, either at the side with the even node ID's (right side) or at the side of the odd node ID's (left side). These parameters had to be known for the creation of a feasible initial route. The orientation was either normal or turned. When a field was normal the lower number nodes were located on the top side of the graph while the higher number were more toward the bottom of the graph. When the orientation was turned, this was reversed, which resulted in that the higher number were on top and the lower numbers on the bottom. In figure 6 a synthetic test field is shown with a normal orientation, where the primary nodes at the top side of the figure have the numbers 1 (top-left) and 2 (top-right). However, when the numbers 1 and 2 are at the bottom of the figure, the orientation is turned.

The second parameter 'even-odd gives the algorithm information regarding on which side of the headland the depot is located. Due to the fact that all the even or odd numbers should be at one side of the headland, a depot can be connected to all the primary nodes located at that side of the headland. In figure 6 the even numbers are on the right side of the figure as is the depot. Therefore, the field is considered even and the primary nodes on the right side are connected to the depot. Knowing whether a depot is at the even or odd side of a field and its field orientation is important for creating the correct initial routes and the Tabu search algorithm.

2.3.4 Initial route

The Tabu search algorithm requires an initial route to be able to generate an optimized route. This initial route has to satisfy the earlier mentioned two conditions. If the conditions are not met, the crops will be destroyed by the service unit or the service unit has to drive outside of the field to be able to unload the primary unit. The initial route for the primary unit for the synthetic test field (see figure 6) is:

[15, 8, 7, 3, 4, 14, 13, 9, 10, 6, 5, 11, 12, 6, 5, 1, 2, 15]

For the creation of this initial route and all other initial routes of other fields, certain patterns are followed. These patterns make it possible to generate routes for all possible fields, as long as there are two clear headlands with all the even and odd numbered nodes grouped at one of the two headlands. Below an example of the patterns used for the initial generation of a route for the synthetic test field is given. The corresponding initial route nodes are added between brackets.

1. Initial node of route is the depot. (15)
2. Script determines spray path edge IDs. Spray paths in figure 6 are located at edge ID's 3 and 6.
3. Edges 3 and 6 are represented by nodes 5,6 and 11,12.
4. Traverse both edges adjacent to the spray paths in a loop around the edges represented by the nodes 5,6 and 11,12. (8,7,3,4 and 14,13,9,10)
5. Find out how many unharvested edges are between adjacent sprays paths, in this case zero due to the fact that the two edges in between have already been harvested. In general, between each pair of spray paths a number of edges is located.
6. Divide number of edges between spray paths from step 5 by two, because a single loop traverses two edges. Loop over these edges until the divided number of edges by two is reached.
7. Calculate the difference between the number of paths located at the two outer spray paths. In other words, how many edges are located next to the most outer spray paths on both sides and subtract these numbers.
8. If statement to find out, on which side of the outer spray paths more edges are located or if there is a difference at all. In this case the difference is positive and therefore, at the side of the lowest spray path (edge ID 3); an additional has to be made loop to make sure all edges are traversed.
9. Traverse all the spray paths. If the previous calculated difference is an even number, no extra action has to be taken. If the number is odd an extra movement has to be made to return at the same side of the field. In this case the calculated difference is even. Therefore, no additional loop has to be made and only the spray paths are traversed. (6,5,11,12)
10. Loop over remaining outer edges and return by traversing over the nearest spray path. (6,5,1,2)
11. After all edges are traversed, return to the depot. (15)

This initial route satisfies all conditions that have to be met and therefore, it can be evaluated by the objective function. However, for a route to be executable, there have to be at least two spray paths. Otherwise it is not possible to generate an initial route for which it is also possible to execute swaps in the Tabu search algorithm.

The service unit route is based on the number of full-nodes in the field. In this particular case, a service unit has to visit to three sequenced full-nodes (e.g. 34,35 and 36) before the maximum capacity is reached. The full-nodes are picked up in sequence to follow the order in which the full-nodes are created, and as result follow the. The service unit route is generated in a similar fashion as that of the primary unit. Since the synthetic test field route results in only one full node, for the sake of illustration the harvest rate presented in figure 7 is multiplied by 10 producing 14 full-nodes. Some of the full-nodes are very close to each other, this is the result of the directions in which the adjacent edges were traversed. An example of a sequenced service unit route is given below based on figure 7:

- Initial node of the route is the depot (15)
- Set route towards initial full node (34)
- Use shortest path function between 15 and 34. Result contains the nodes in between (15,6,19,34)
- Go to second node from first node in sequence (35)
- Use shortest path function between 34 and 35. Result contains the nodes in between (34,18,35)
- Go to third node from second node in sequence (36)
- Use shortest path function between 35 and 36. Results contains the nodes in between (35,5, turn at headland,18,19,36).
- Set route towards the depot (15)
- Use shortest path function between 36 and 15. Result contains nodes in between (36,6,15)

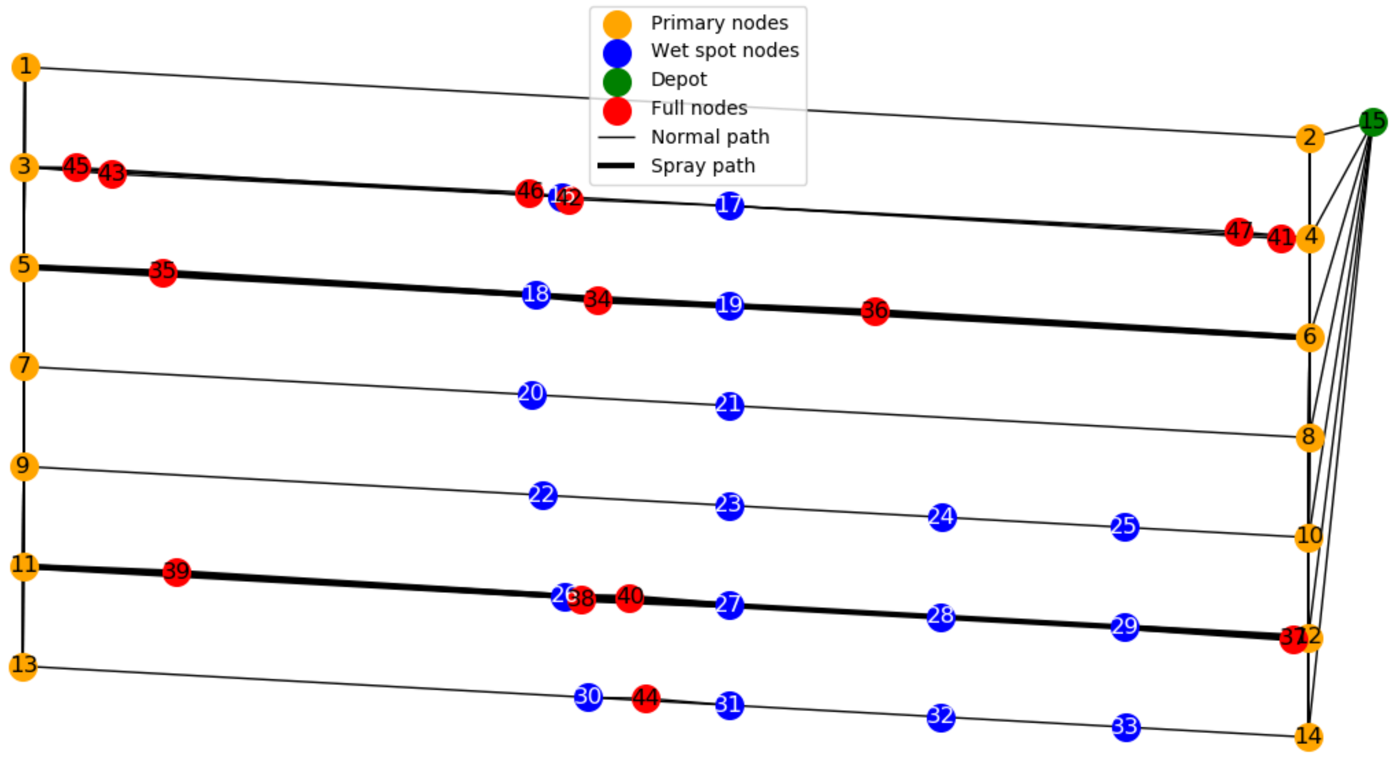


Figure 7: Service unit graph abstraction, harvest rate multiplied by a factor 10.

2.3.5 *Dubins path*

When a path has been fully harvested, a unit has to navigate from one edge to another edge. This action was performed by the implementation of a turning manoeuvre. In this study Dubins path (Dubins, 1957) was used for that purpose. Dubins path is a method to calculate the minimal curve between two points in a 2d plane. Dubins path results always in of one of the six following types: RSR, RSL, LSR, LSL, RLR, LRL, where each letter represents an action: R is a turn the right, S implies a straight segment and L is a turn to the left. Figure 8 gives an example of a Dubins path. The curve in figure 8 starting at point a consists of a curve towards the right, followed by a straight segment and another curve to the right (RSR).

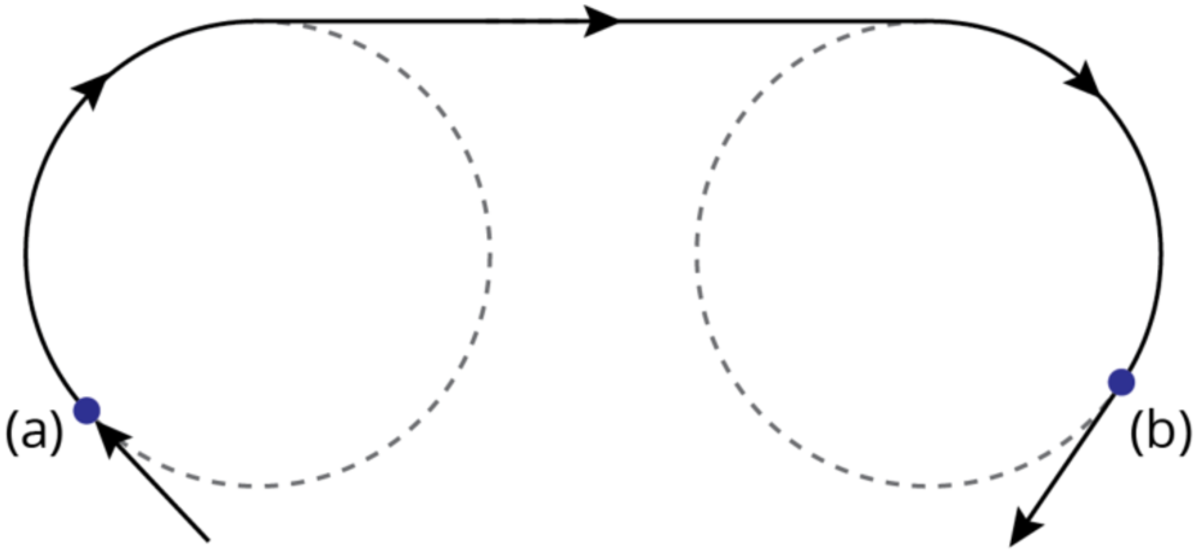


Figure 8: RSR Dubins path Source: Versleijen, J. based on Dubins path

In this study, Dubins paths are used for deriving the length of curves based on a list of pairs of x and y coordinates. For the calculation of the total length, the Euclidean distance between each pair of two coordinates is calculated and summed. Depending on the smoothness of the curve and the number of xy coordinates representing a turn, variation in length can occur. Therefore, the decision was made to check for multiple turning degrees the total distance. Table 3 shows that when the turning degree was decreased the length of the xy coordinate list increases. However, this had a minimal effect on the total distance of the Dubins path (no differences with three decimals precision). Figure 9 shows for two different turning degrees the Dubins path curve. A turning degree of 3° results in a smooth turn, while a turning degree of 30° results in a bumpy turn. The decision was made to implement the Dubins path with a turning degree of 3°.

Table 3: Distances in meters and length of list with various turning degrees as input for a turn between node 13 and 3 of the synthetic test field of figure 6

Turning degree	Length of xy list	Total distance
30°	14	21.054
5°	44	21.054
3°	68	21.054
1°	188	21.054

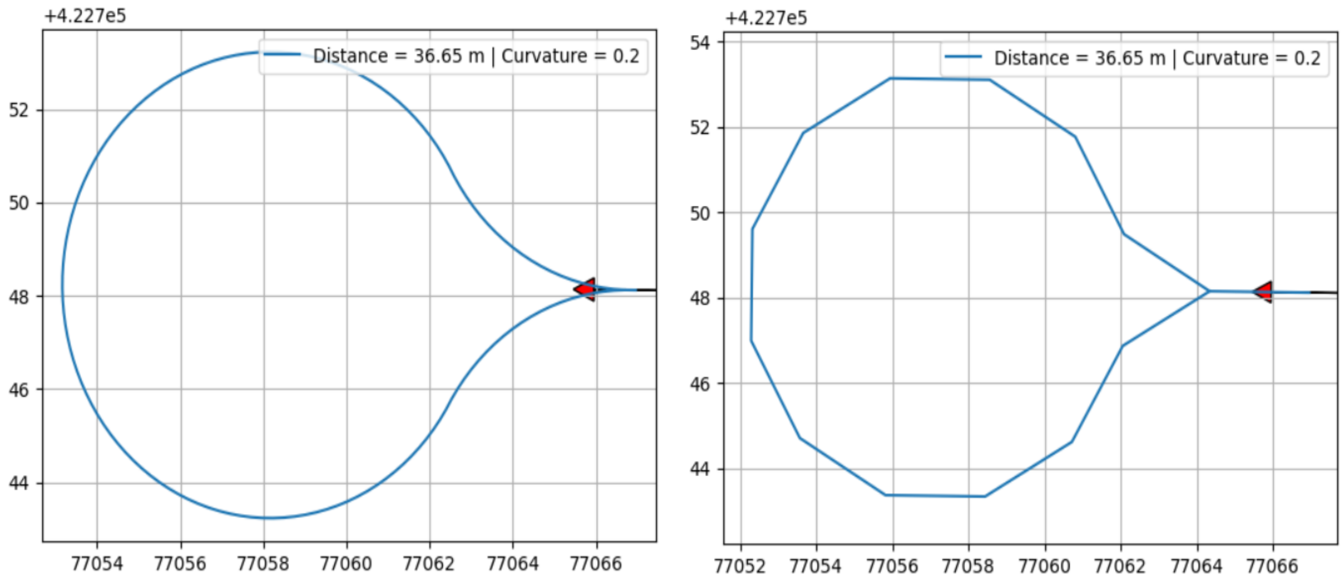


Figure 9: Dubins path for 3° turning degree (left) and 30° turning degree (right)

Another variable required for the calculation of Dubins path is the curvature value. The curvature of a Dubins path indicates how sharp a curve bends. A small circle will therefore, have a higher curvature value and a larger circle will have a lower curvature value. The curvature is similar to the rate at which the curve is turning (Lady, n.d). For the calculation of the curvature equation 7 is used.

$$K = \frac{1}{R}\ [m^{-1}], \tag{7}$$

where R is the radius of curvature. The radius of curvature is the radius of the circle approximating the curvature. For the calculation of the radius of the curvature equation 8 is used.

$$R = \frac{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{3/2}}{\left|\frac{d^2y}{dx^2}\right|}\ [m^{-1}], \tag{8}$$

where the derivative is based on formula y = f(x).

Figure 10 shows a Dubins path curve for eight different curvature values. For each Dubins path in figure 10 the same node pairs and directions were used. Between the two nodes was a distance of approximately three meters. Figure 10 shows that a higher curvature value results in a shorter total distance and a smaller curve. A lower curvature value results in a larger total distance. For the implementation of the turning manoeuvres it was necessary to select a curvature value, which is representative for the maximum rate at which primary units and service units are able to make turns. As can be seen in figure 10, a curvature value of 0.2 results in a turn of in total 32.88 meters, which was found a satisfying approximating of the turning distance in reality.

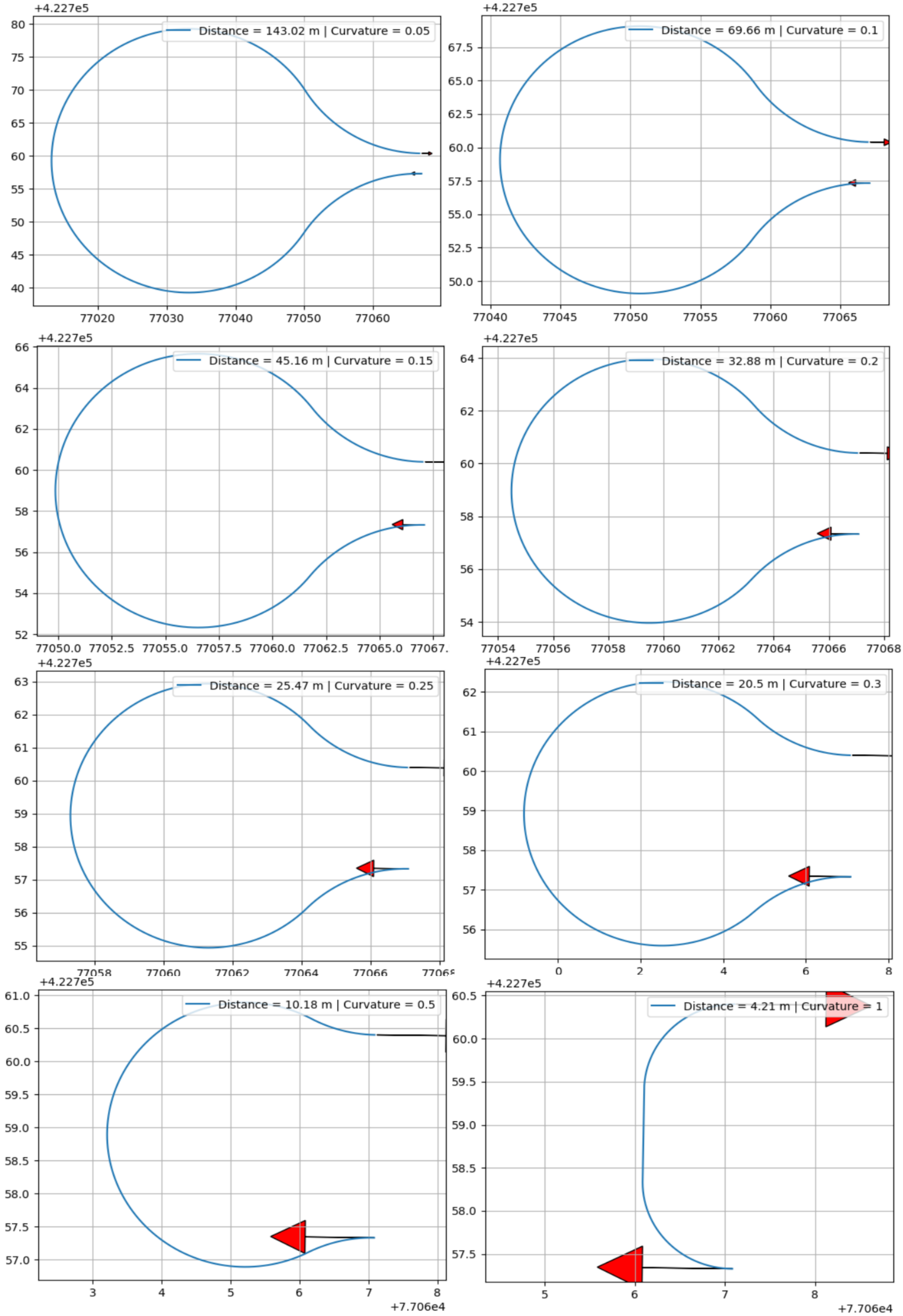


Figure 10: Dubins path for various curvature values

2.4 *Choice meta parameters optimization CARP*

The papers by Mijnheer (2018), Brandão et al. (2008) and Greistorfer (2003) showed that the Tabu search algorithm is capable of providing high quality solutions for a CARP within a reasonable time period. Another advantage of the Tabu search algorithm is the reproducibility (Brandão et al., 2008). Therefore, a Tabu search algorithm was implemented to optimize the CARP. A Tabu search algorithm requires an initial solution which also has to be feasible. Otherwise, situations would occur which are incompatible with the harvesting constraints detailed in section 2.3.1.

For the Tabu search algorithm a short-term memory approach was adopted. The short term memory stores recent route proposals in a so-called Tabu list and avoids that future proposals undo these routes (Brownlee, 2011) As a long as a route remains in the Tabu list.

In addition, a Tabu search algorithm requires a method for exploring the entire search space (Glover et al., 1998). According to the results of Sarmady (2007) adopting a long term strategy (swapping method) as strategy to explore the search space does not result in faster convergence towards the optimal solution as compared to a free random swap. Therefore, a free random swap was implemented. A free random swap indicates that a randomly chosen edge is swapped with another edge in the field. For the sake of this research, the swap must be ensured to generate a feasible solution. Therefore, it is to be examined in advance which are suitable options for, a random swap.

Brownlee (2011) identified three tuning parameters of a Tabu Search algorithm, i.e., maximum number of iterations, length of the Tabu list and the maximum number of candidates. In the current research, these three parameters were examined to see how and with what values they can contribute to the optimization process. Because of computational limitations the decision was made to run the Tabu search forty times. This is not to be confused with the maximum number of iterations. Running a Tabu search forty times and averaging the result lead to a more consistent value in comparison to situations when the Tabu search algorithm had not fully converged yet. The used parameters values are given in table 4. The suitability of the parameter values were judged on the weight meters and the total calculation time.

Before a near-optimal solution could be found for a specific problem. It was essential to set suitable values for the meta parameters of the optimization heuristic. This was because the quality of the solution of the heuristic optimization algorithm is strongly dependent on the input values. Completely manually executing this task is a time-consuming task, which requires a lot of expertise and knowledge, therefore, the decision was made to test only for a couple of input values to optimize the CARP.

Table 4: Tabu Search Parameters input values

Unfixed parameter	Parameter values	Number of runs Tabu search
Maximum number of iterations	5, 10, 20, 40, 80, 250	40
Tabu list size	5, 10, 20	40
Maximum number of candidates	5, 10, 20, 40,80	40

2.5 *Comparison tests case*

To measure how effective the route optimization algorithm was, a comparison was made between the route optimization algorithm and three conventional harvesting routes. For one of the three fields the author conducted field work; hereafter it is referred to as the Novifarm field. During the fieldwork, data was collected of the movements of a harvesting fleet, consisting of two primary units and four service unit, harvesting a partly harvested field.

For collecting the data, Garmin Etrex 30 receivers were mounted on the roof of each participating unit, except for one harvest unit having a build-in GPS. The settings that were used for tracking the units are shown in table 5. The recording interval was set at 20 seconds, to make sure the GPS unit collected enough data, while also making sure that the batteries did not drain too fast. The coordinates collected in WGS 84; positions were subsequently projected to the Dutch grid (RD New).

Table 5: Settings Garmin Etrex 30 during tracking

Function	Setting
Recording interval	00:00:20
Recording Method	Time
Distance and Speed	Metric
Map datum	WGS 84
Map spheroid	WGS 84

Two harvesters were used. Because the algorithm developed in this thesis research assumes a single harvester, it was decided to consider one harvester GPS track and double the capacity, harvest rate and weight values of that harvester.

Two other GPS tracks of harvesters were received from Jacob van der Borne. The received GPS tracks consisted of the route the harvester traversed during a harvesting operation. The format in which the data was acquired was identical to the build-in GPS unit of the primary unit on the Novifarm field. For all three GPS tracks the unnecessary columns were removed. Next, the traversed paths by the primary units were manually matched with the paths in the field. Based on the sequence in which the primary units traversed the field a so-called monitored route was created. This route represents the followed route by the primary units. The costs for traversing a part of the field are identical for both the optimized route and the monitored route in the comparison.

During the fieldwork, it was observed that service units made turns in the middle of the field on multiple occasions. This behaviour is considered sub-optimal, because the service units traverse a part of the field outside the paths or headlands. Therefore, turns inside a field were not implemented in the algorithm.

For the creation of a monitored route, the locations the full-nodes locations of the primary unit would have to be known. From the primary unit data, it was not possible to identify these locations. And as a result, the correct weights could not be assigned to the primary and service units. Therefore, in the comparison the service unit tracks were disregarded and only the primary unit track was considered for the calculation of the total amount of weight meters in practice. The service unit routes were based on the full-nodes generated by the primary unit route.

2.6 *Python implementation Graph abstraction*

The algorithm was implemented in Python 3.6.5. For the implementation of the graphs the NetworkX package was used. This is a Python package for the creation, manipulation and study of the structure, dynamics and function of complex networks such as graphs (NetworkX, 2014).

In ArcGIS pro the shapefiles consisting of the paths were pre-processed. The ArcGIS model adds information to the nodes, edges and nodes wet area datasets. These outputs are required as input for the graph abstraction.

On the results of the ArcGIS pro a manual visual review has to be performed to check if the even and odd numbered nodes were located at the correct side of the field. All the even-numbered nodes should be at one side of the field, while odd-numbered nodes are at the opposite side. If this was not the case, the numbers of nodes at opposite sides of the edge were swapped.

The initial graph contains the basic information like primary nodes, wet area nodes, the depot node and the edges between the primary nodes. To expand towards a complete graph, edges between the depot and the nearest side of the field were created. In addition, edges between all primary nodes on the depot side of the field and the depot were inserted.

For adding the wet area edges, there has to be verified if the wet area node has the same edge ID as the primary nodes have. If correct, between the closest nodes were created edges, just as between the wet area edges. The ID's of the wet area nodes were used to confirm that if there were multiple pairs of wet nodes with the same edge ID's the edges were correctly inserted in between the nodes.

Another step was to connect all the primary nodes within one headland with each other. The primary nodes were connected by calculating the individual distance via Dubins path for every combination of primary nodes. Several implementations of Dubins path are available online, most of which are written in C++ or other programming languages and not in Python. Fortunately, Sakai (2019), wrote a Python implementation of the Dubins path for the PythonRobotics library. This implementation made it straightforward to understand how to implement Dubins path. Small adaptations were made to the script of Sakai (2019) to make it applicable for calculating the distance between the primary nodes.

For the creation of the full-nodes a route is required, because based on a route the locations for the full-nodes are calculated. When a primary unit is not able to traverse another meter before the maximum capacity of the bunker is reached, a node is created on the right side of the primary unit. For the placement of the node, the direction of the primary unit has to be known. This to verify that the node is placed at the correct side of the primary unit. When all the full-nodes are placed, it becomes possible for the service unit to create a route as is discussed in section 2.3.4.

2.7 *Python Implementation Tabu Search Algorithm*

Various Python implementations of the Tabu search heuristic were found. One of these implementations was made by Panyam (2011) and is based on the Ruby implementation of Brownlee (2011), available in the book Clever Algorithms: Nature-Inspired Programming Recipes. The Python script made it easier to adopt the Tabu search algorithm into the script of the author.

The basic structure of the script by Panyam (2011) functioned well, however, some changes were implemented to adapt it for the problem of this research. Therefore, a function was integrated which searched for all possible swaps depending on a random first edge. If, no possible solutions are found, a while loop is initiated to select a random first edge until one or multiple swaps are possible. Next, a random second edge is selected based on the possible swaps. The two randomly selected values with their corresponding neighbour nodes were swapped from position and if necessary reversed to make sure that the resulting sequence was possible. Reversing was sometimes necessary to ensure that the original order was kept. For example, if a unit is at a headland on one side of the field before the swap, after the swap the unit has to remain at the same headland(e.g. if route sequence before is [23,24,82,81] a swap should result in [81,82,24,23] and not in [82,81,24,23])

Figure 11 shows the basic structure of the Tabu search algorithm. First, an initial route is generated, and it is assigned a cost value using the objective function. Next, for a maximum number of iterations a while loop is initialized, which for each loop generates a number of candidates (dependent on the input number). For each candidate, a new route sequence is determined with the corresponding weight meters. The candidate with the lowest weight meters is selected and compared to the currently considered best solution. If the solution of the candidate has less weight meters than the best solution, the best solution is replaced by the candidate. The candidate route solution is also added to the Tabu list. Therefore, it is not possible for the candidate solution to be generated again, as long as the sequence is in the Tabu list.

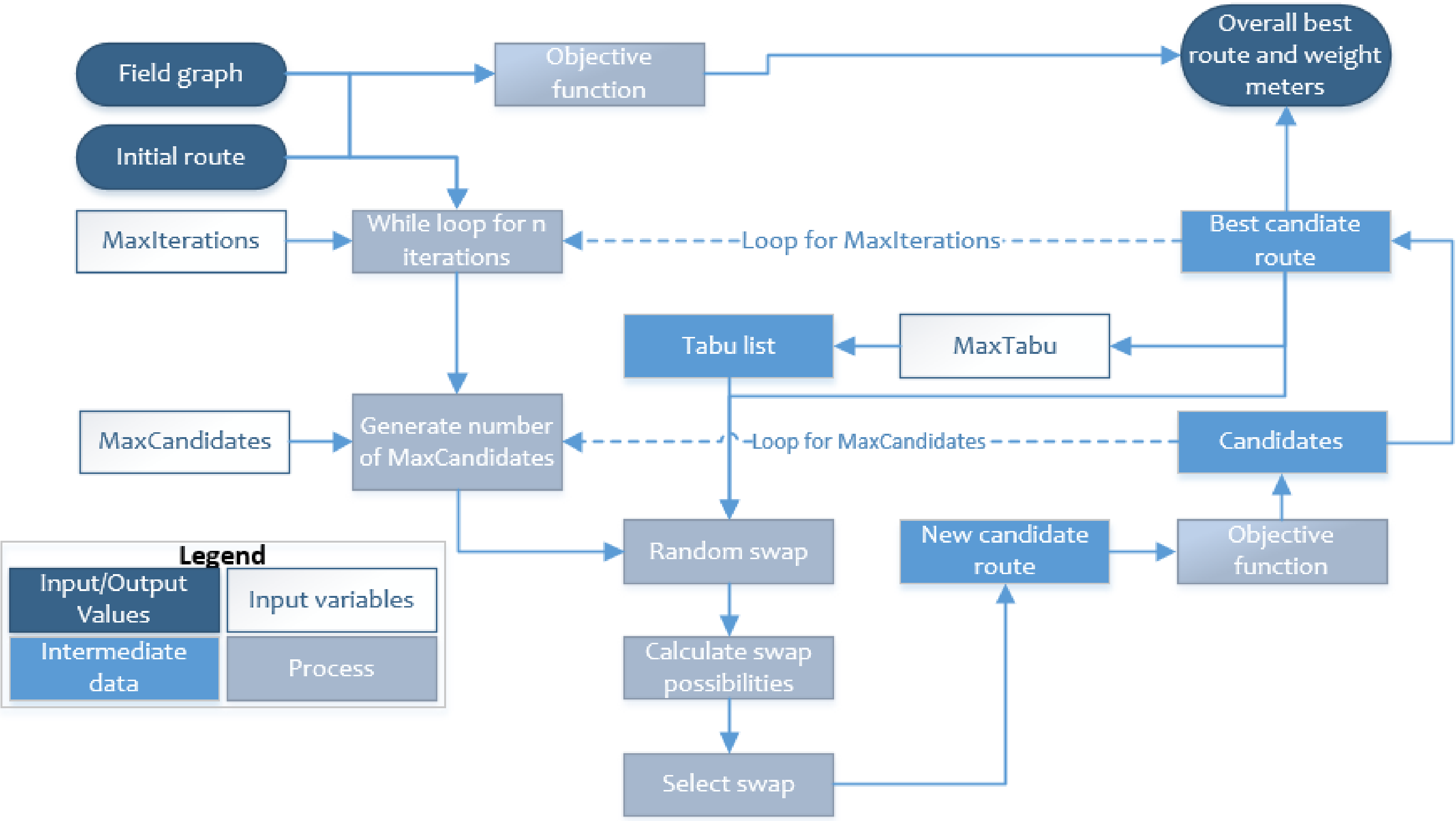


Figure 11: Tabu search algorithm structure

2.8 Test fields

Several test fields were used for testing of the objective function and, the Tabu search algorithm and for comparing optimized routes against monitored routes. Initially, a synthetic test field was constructed as was previously shown in figure 6 in section 2.3.3. This field was constructed for testing purposes during the development of the algorithms. After the development was completed, both algorithms were ready to be applied on larger fields. Five fields were selected for that purpose, three were retrieved from the GAOS database and two were provided by from Jacob van der Borne, who also supplied GPS tracks of a harvesting operation. The selected fields received the names Novifarm, Goudswaard, Oudekreek, Hans Houbraken Spiegroot and Obroek Proefveld. For the selected fields, the field and corresponding graph abstractions are shown. The graph abstractions are the graphs used for the routing of the primary unit. Fictive wet areas were digitized within the fields. The shapes of these polygons range from relatively simple to more complex.

The Novifarm field is shown in figure 12. For the transformation of the paths to a graph several incomplete paths were removed. These paths did not extend until the headlands and stopped somewhere in the middle of the field.

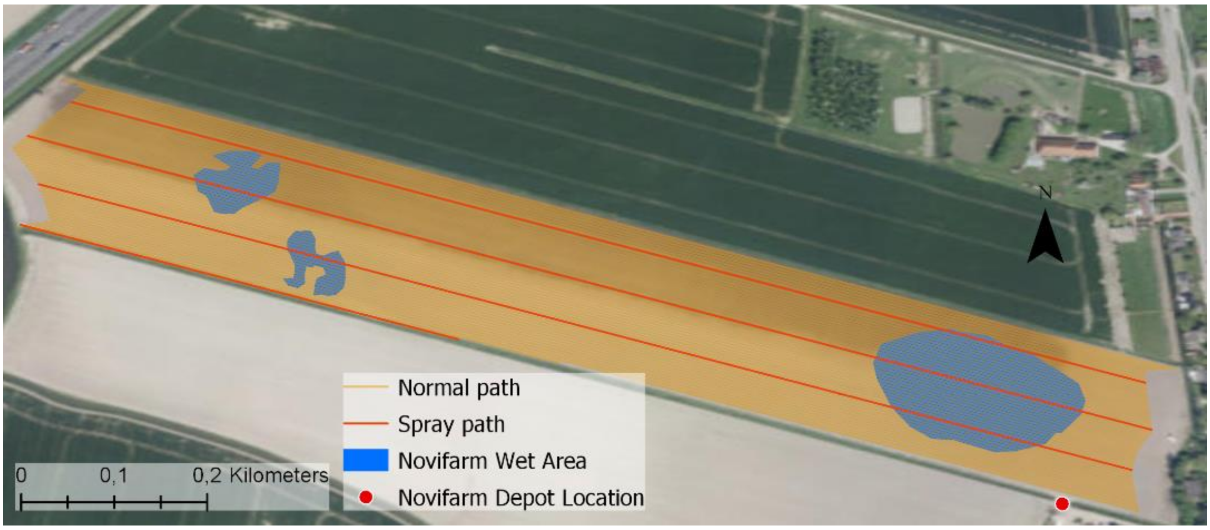


Figure 12: Novifarm field

Figure 13 shows the graph abstraction of figure 12. On the headlands there are many connections between nodes. Therefore, this area looks darker on the figure, however, this is only caused by the density of the edges between nodes. For the comparison, a subfield was created of the Novifarm field which only contained the paths that were used during the harvesting operation that occurred during the data collection on October 11, 2018.

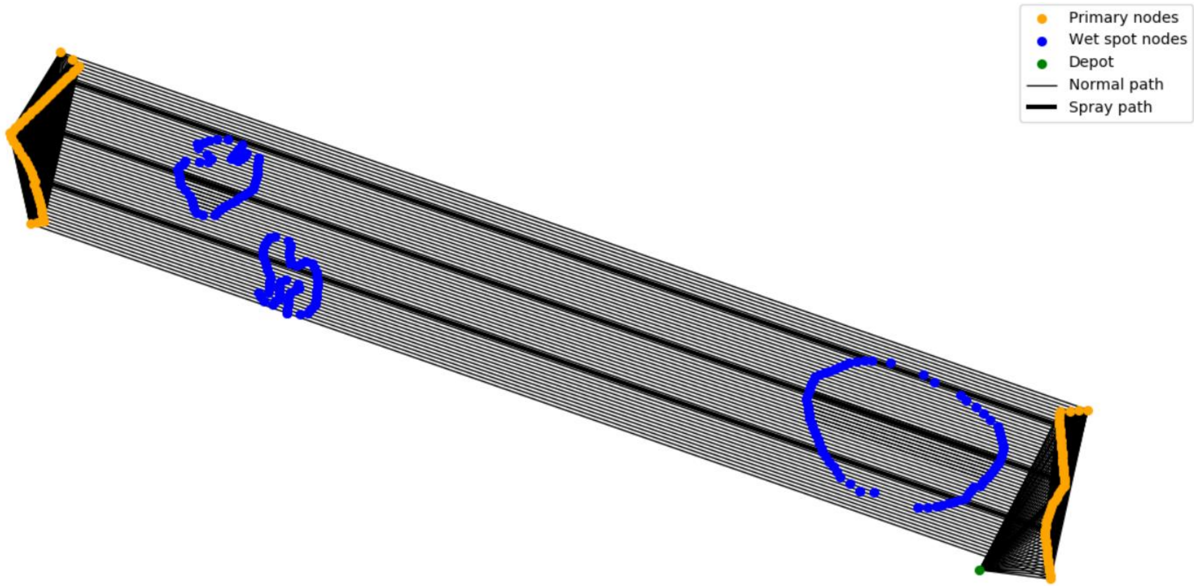


Figure 13: Graph abstraction of Novifarm field

The Goudswaard field shown in figure 14 is a field located near the village of Goudswaard and was taken from the GAOS database. Figure 15 shows the graph abstraction of figure 14.

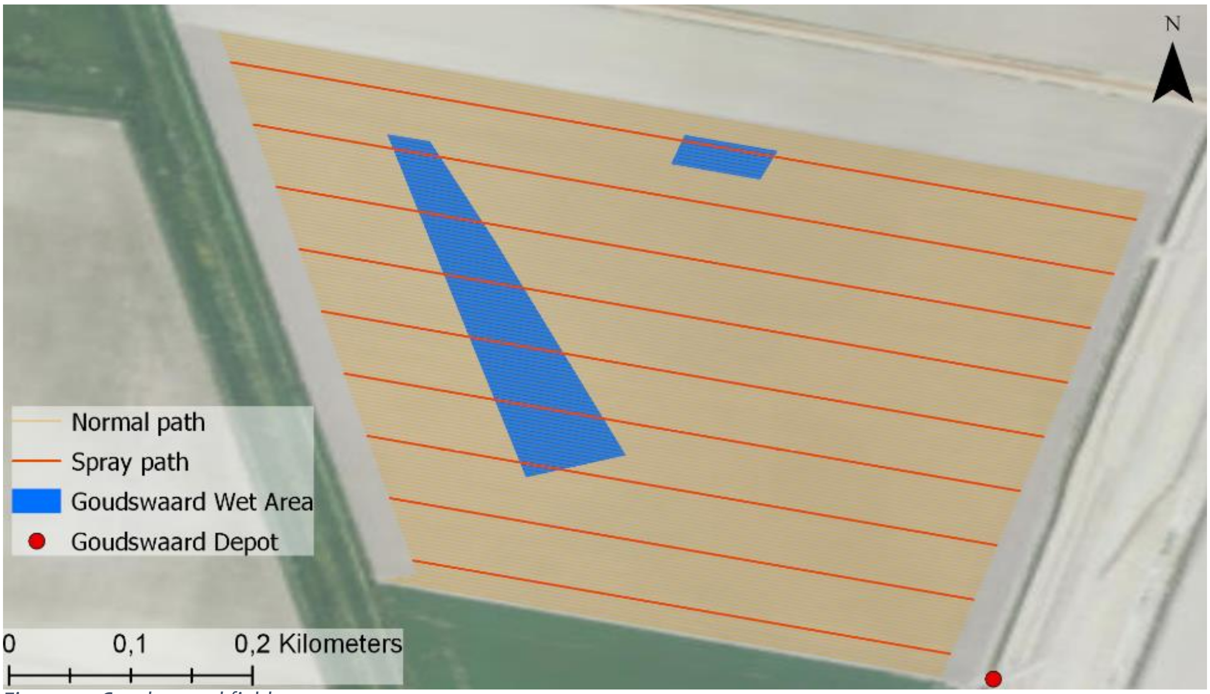


Figure 14: Goudswaard field

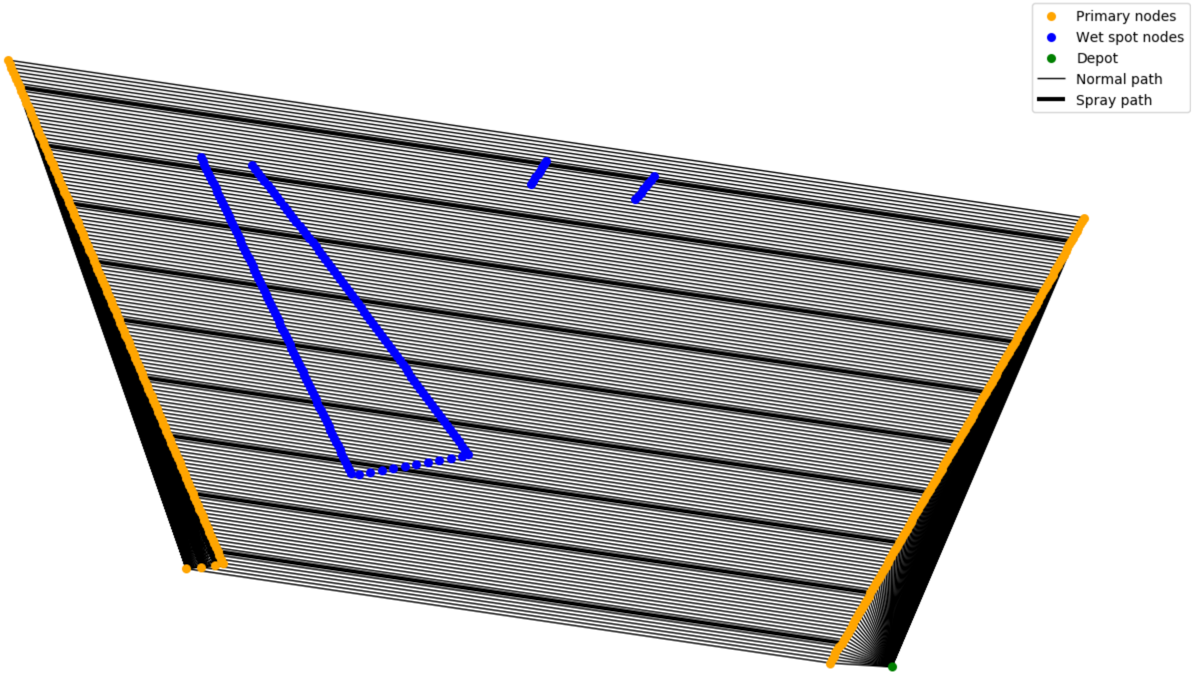


Figure 15: Graph abstraction of Goudswaard field

The third field used in this research was the Oudekreek field shown in figure 16. For the conversion of the input values to a graph abstraction some actions had to be performed. The field contained some additional nodes and edges near its northern boundary. These had to be removed because the length of the edges was less than one meter, and therefore not representative for real paths. The result of the graph abstraction of figure 16 is shown in figure 17. The graph abstraction of this field was mainly used for the testing of the Tabu search algorithm.

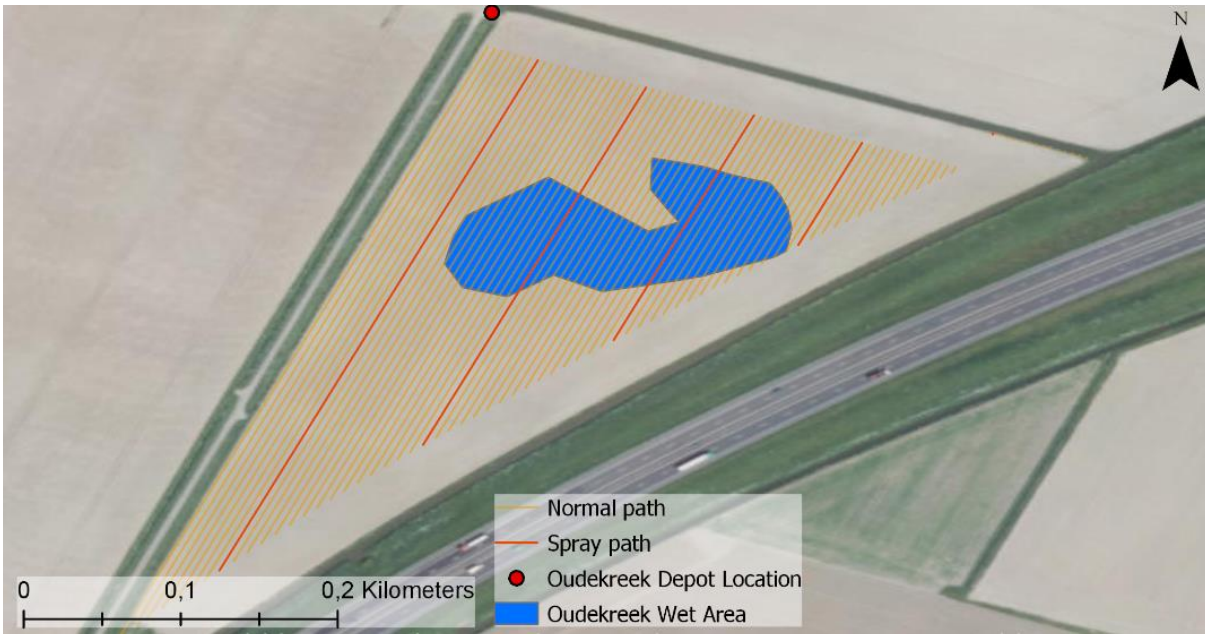


Figure 16: Oudekreek field

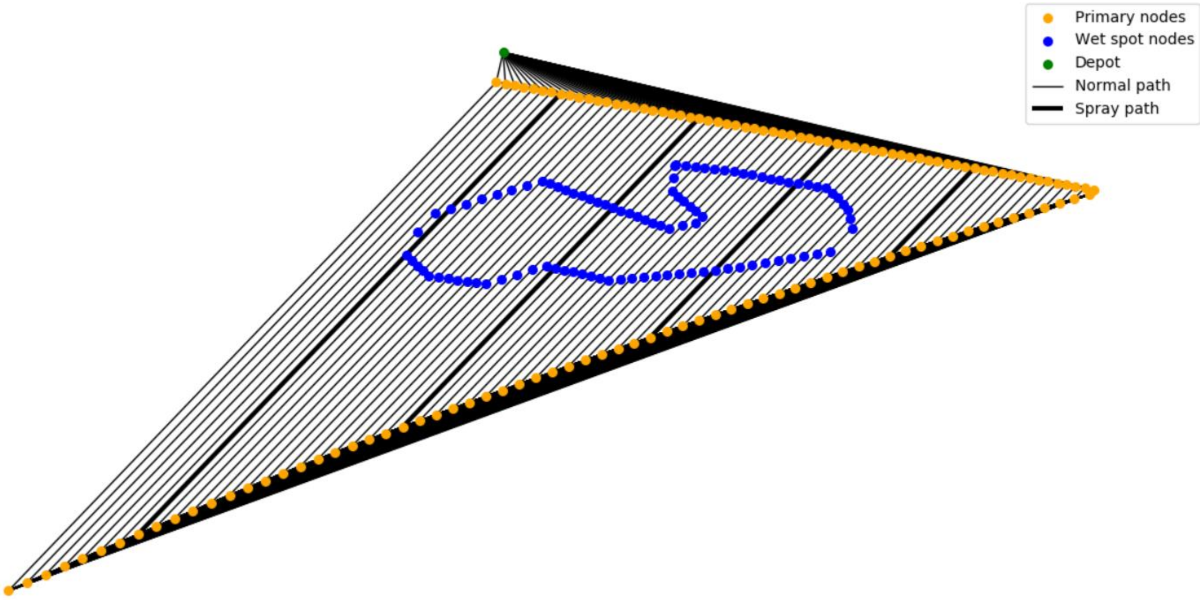


Figure 17: Graph abstraction of Oudekreek field

The fourth field was the Hans Houbraken Spiegroot field shown in figure 18. This field is the second field for which comparison data is available, the comparison data was received from Jacob van der Borne. The resulting graph abstraction can be seen in figure 19.

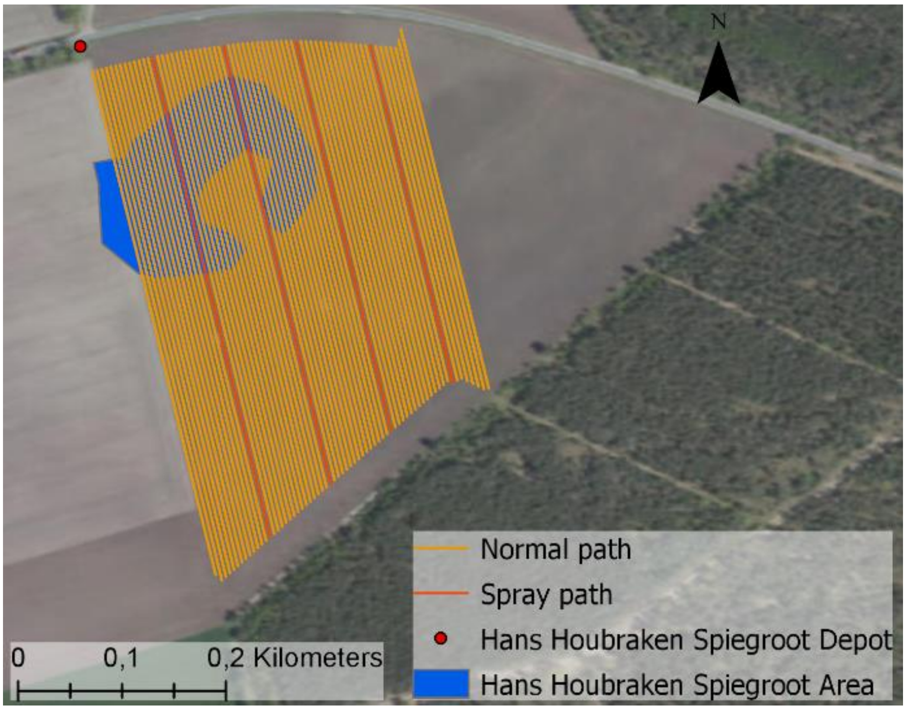


Figure 18: Hans Houbraken Spiegroot field

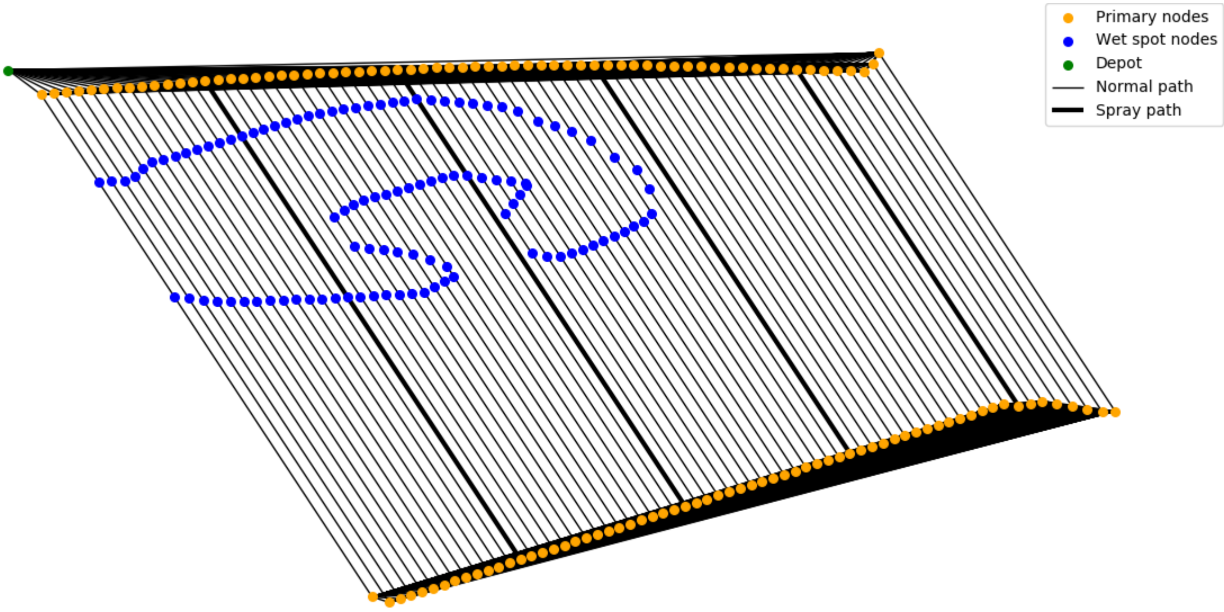


Figure 19: Graph abstraction of Hans Hobraken Spiegroot

The fifth and final field was the Obroek Proefveld shown in figure 20. For this field comparison data were received from Jacob van der Borne. The resulting graph abstraction is shown in figure 21.

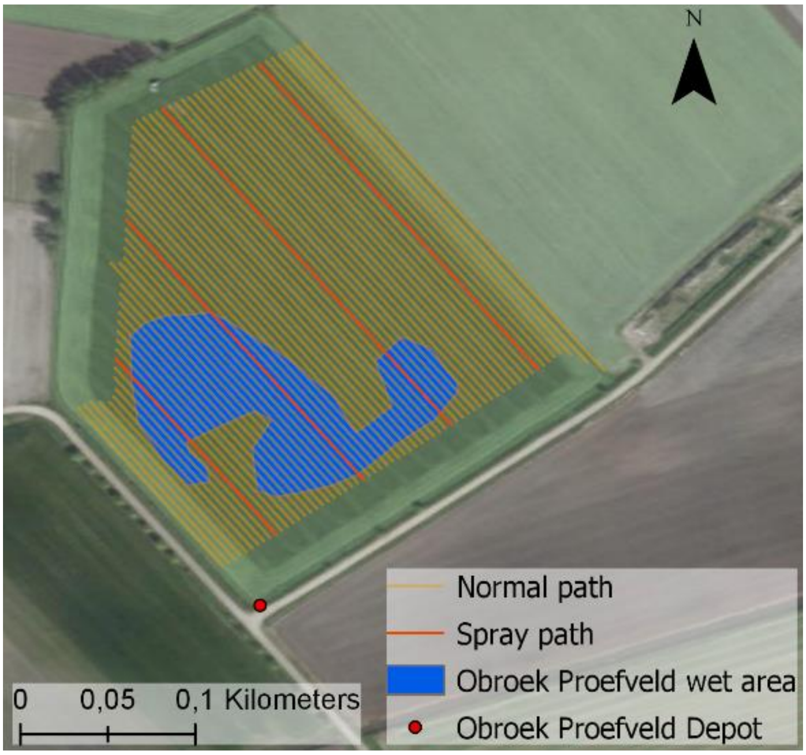


Figure 20: Obroek Proefveld field

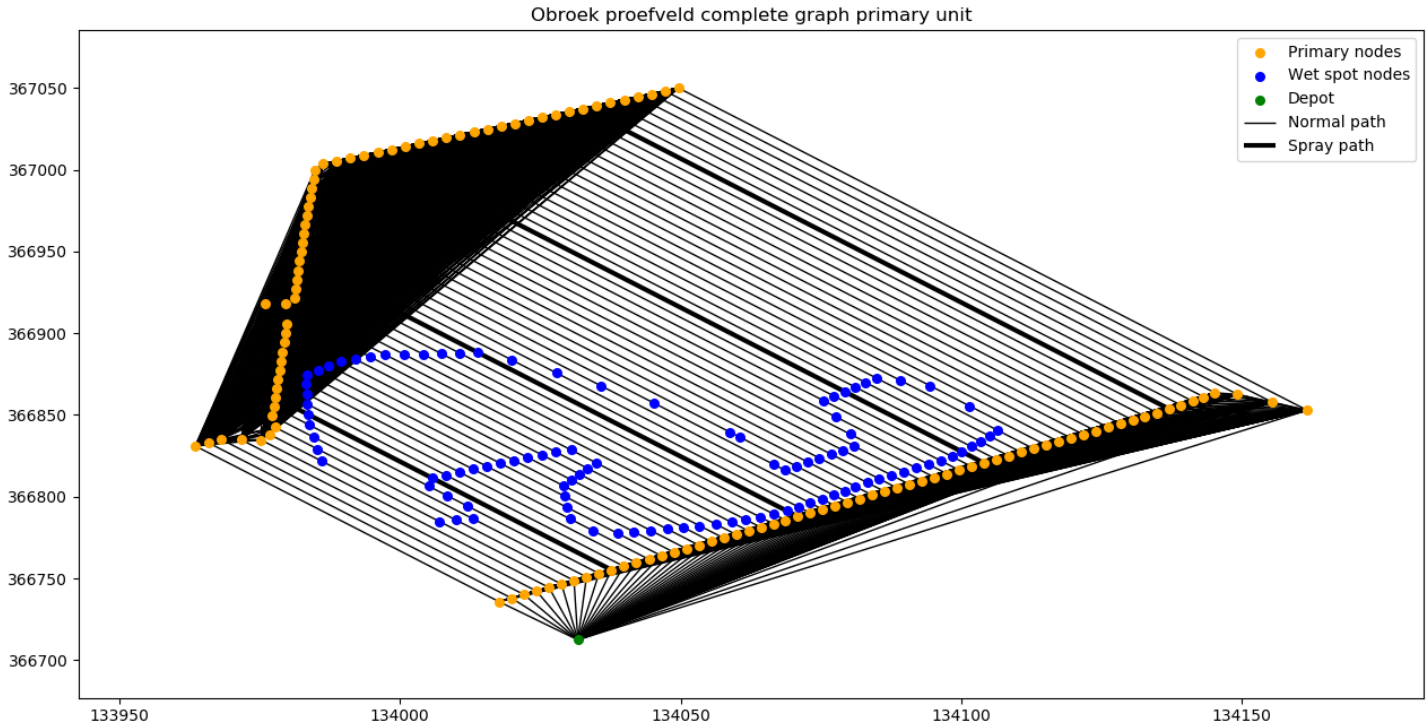


Figure 21: Graph abstraction of Obroek proefveld

3 Results

The results are presented in the order of the research questions.

3.1 *Optimal route service unit alongside a harvester*

In this thesis, an optimal route for a service unit in a capacitated harvesting operation is obtained by minimizing the total amount of weight meters (Equation 1). Because the service unit is dependent on the primary unit, the service unit has to operate optimally alongside the harvester. The developed weighting scheme (table 2) gives an indication of susceptibility to soil compaction of certain areas of the field. It is necessary to understand which operations in the field with a variation in weight, result in a minimal amount of induced soil compaction, for the creation of an optimal route. The weighting scheme consists of three scenarios; dry, standard and wet. These scenarios were applied on common field operations. Each operation is multiplied by factors, based on the susceptibility to soil compaction. For example, for traversing a wet normal path the distance is multiplied with F_{np} and F_w. For the weights an empty and a full service unit were used. This should maximize the difference in susceptibility to soil compaction.

Table 6 shows a large difference between the costs of certain operations. Mainly caused by the difference in lengths between the nodes and the difference in weight when the service unit is empty or full. The numbers in table 6 between brackets in the top row are based on operations between two nodes executed on the synthetic test field of figure 6 in section 2.3.3. Figure 22, 23 and 24 show the visualizations of the Dubins paths for a turn with a small distance (7-5), a turn with a medium distance (13-5) and a turn with a large distance (13-3). These Dubins paths are also shown in table 6.

A similar table could be calculated for the primary unit. The results for the primary unit would only differ with table 6 because of the continuous harvest rate and changed empty- and full weights. The primary unit table has been computed in the objective function, although is not shown because for the service unit table (table 6) it is easier to identify which operations are more susceptible to soil compaction in comparison to the primary unit table. This is the result of the larger difference in weight between the empty- and full weight for the primary unit and service unit.

*Table 6: Costs in weight meters of operations for the service unit in different scenarios. The empty weight of the service unit (15800 kg) and the full weight of the service unit (36800 kg) are used for the calculations. The costs are shown in in the unit 10^4 m * kg. The number in the top row present the nodes between which turns are considered.*

Scenario	Turn small distance (7-5)	Turn medium distance (13-5)	Turn large distance (13-3)	Normal path dry (1-2)	Spray path dry (5-18)	Normal path wet (16-17)	Spray path wet (18-19)
Dry (empty	41.6	22.7	26.6	194.3	38.7	36.0	20.8
Standard (empty)	41.6	22.7	26.6	277.6	55.3	46.8	27.1
Wet (empty	41.6	22.7	26.6	360.9	71.8	57.6	33.3
Dry (full)	96.8	52.9	62.0	452.6	90.1	83.9	48.6
Standard (full)	96.8	52.9	62.0	646.6	128.7	109.1	63.1
Wet (full)	96.8	52.9	62.0	840.6	167.3	134.2	77.7

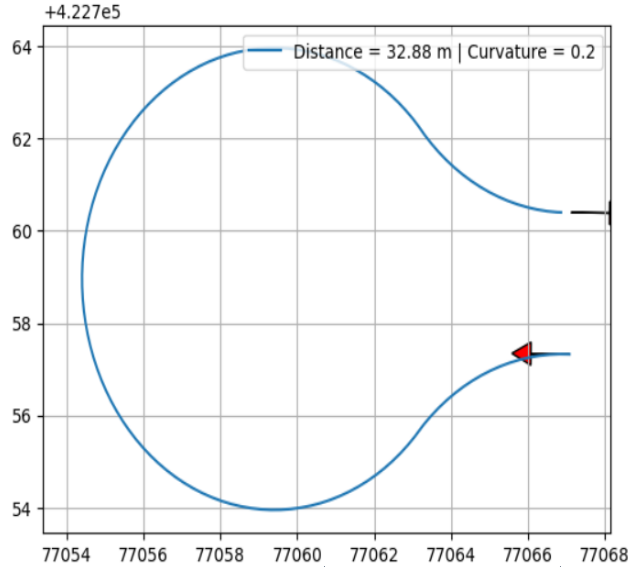


Figure 22: Turn (7-5) with small distance between two points (approximately 3 meters).

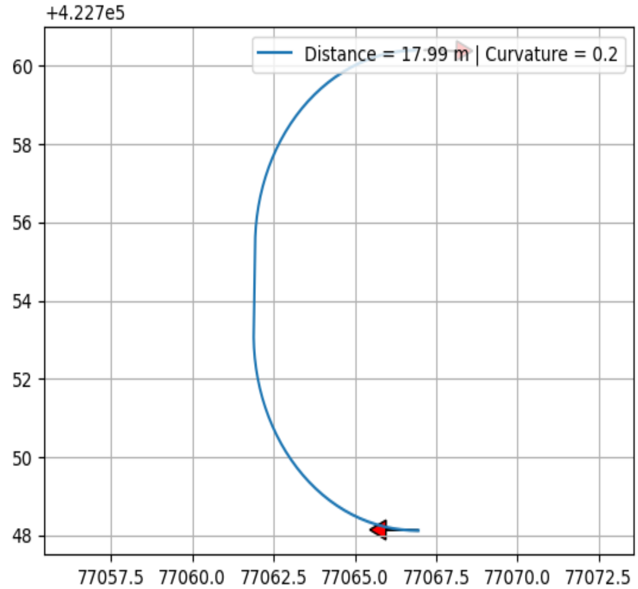


Figure 23: Turn (13-5) with medium distance between two points (approximately 12 meters).

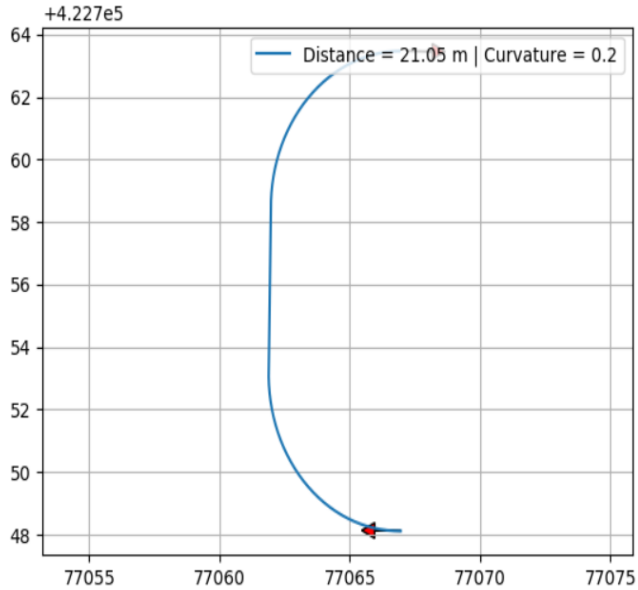


Figure 24: Turn (13-3) with large distance between two points (approximately 15 meters).

3.2 Tabu search heuristic optimizer parameter CARP

Suitable meta parameters were explored by testing multiple values for three different parameters: maximum number of iterations, length of the Tabu list and maximum number of candidates. The agricultural field that was used for testing the Tabu search algorithm was Oudekreek. During the testing of each parameter the other two parameters were set at a fixed value. For all three parameters this fixed value was 20.

Running the Tabu search algorithm 40 times with all three parameter values was necessary to receive stable results in some occasions. Because not all the results were already fully converged after the set number of iterations, length of the Tabu list and candidates. Some of the total calculation time values in tables 7,8 and 9 are unknown. This is because the script was interrupted by sleep mode of the computer or multiple process ran simultaneously, which influenced the speed of processing. As a result, the total completion time of these calculations were longer than it would have taken in an ideal situation. Therefore, these values were omitted.

Table 7 lists the results of the different numbers of iterations. The total weight meters of the optimized routes decreased up till 80 iterations. After around 80 iterations, the total weight meters stabilized as can be seen in figure 25, resulting in a similar total weight meters for 80 and 250 iterations runs. For the iterations for which a correct computation time was available, the time increase is steady although not linear.

Table 8 shows the results of changing the length of the Tabu list. The results indicate that a larger length of the Tabu list result in a lower total weight meters. The computation time for all the input parameter values are more or less the same.

The influence of the maximum number of candidates on the objective function is shown in table 9. The results indicate, that selecting more candidates produced on average a better result and therefore, a route with less induced soil compaction. Similar computation times were achieved for the maximum number of candidates as for the maximum number of iterations. A steady although not linear increase in the computation time is visible.

The maximal reduction achieved for the total weight meters compared with the initial route is for the maximum number of iterations set to 80 while the Tabu list size and maximum number of candidates were both set to 20. The reduction in weight meters achieved with those parameter values for Oudekreek amounted to a reduction of 10.45%. In addition, a trace plot was generated for these values of the maximum number of candidates and Tabu list length. A trace plot (figure 25) was generated to assess convergence of the Tabu search algorithm. The weight meters decreased until around 80 iterations, where after the weight meters became stable and no further decrease in the weight meters was obtained.

Figure 26 shows a trace plot of a Tabu search algorithm for the lowest tuning parameter values of tables 7,8 and 9. The weight meters decreased in figure 26 until around 18 iterations, where after the weight meters became stable and no further decrease in the weight meters was obtained. Further on in this research, the optimal values of all three tuning parameters were used as input.

*Table 7: Tabu search for various number of maximum iterations. Average weight meters route is expressed in 10 ^{6} m * kg and was summed and divided by the number of iterations. The total calculation time is expressed in seconds and is for the number of iterations that were ran.*

Number of Maximum iterations	Initial Route	5	10	20	40	80	250
Average weight meters route	755.83	730.51	710.57	686.18	682.48	676.84	676.86
Total Calculation Time	-	1861.19	3458.62	11720.43	17064.52	-	
Number of runs Tabu search algorithm	-	40	40	40	40	40	40

*Table 8: Tabu search for various lengths of the Tabu list. Average weight meters route is expressed in 10 ^{6} m * kg and was summed and divided by the number of iterations. The total calculation time is expressed in seconds and is for the number of iterations that were ran.*

Length of Tabu list	Initial route	5	10	20
Average weight meters route	755.83	698.87	689.07	686.18
Total Calculation Time	-	8684.07	8911.46	11720.43
Number of runs Tabu search algorithm	-	40	40	40

*Table 9: Tabu search for various number of maximum candidates. Average weight meters for the route expressed in 10 ^{6} m * kg and was summed and divided by the number of iterations. The total calculation time is expressed in seconds and is for the number of iterations that were ran.*

Number of Maximum candidates	Initial route	5	10	20	40	80
Average weight meters route	755.83	709.78	697.73	686.18	681.74	677.09
Total Calculation Time	-	1642.62	4823.59	11720.43	14518.24	-
Number of runs Tabu search algorithm	-	40	40	40	40	40

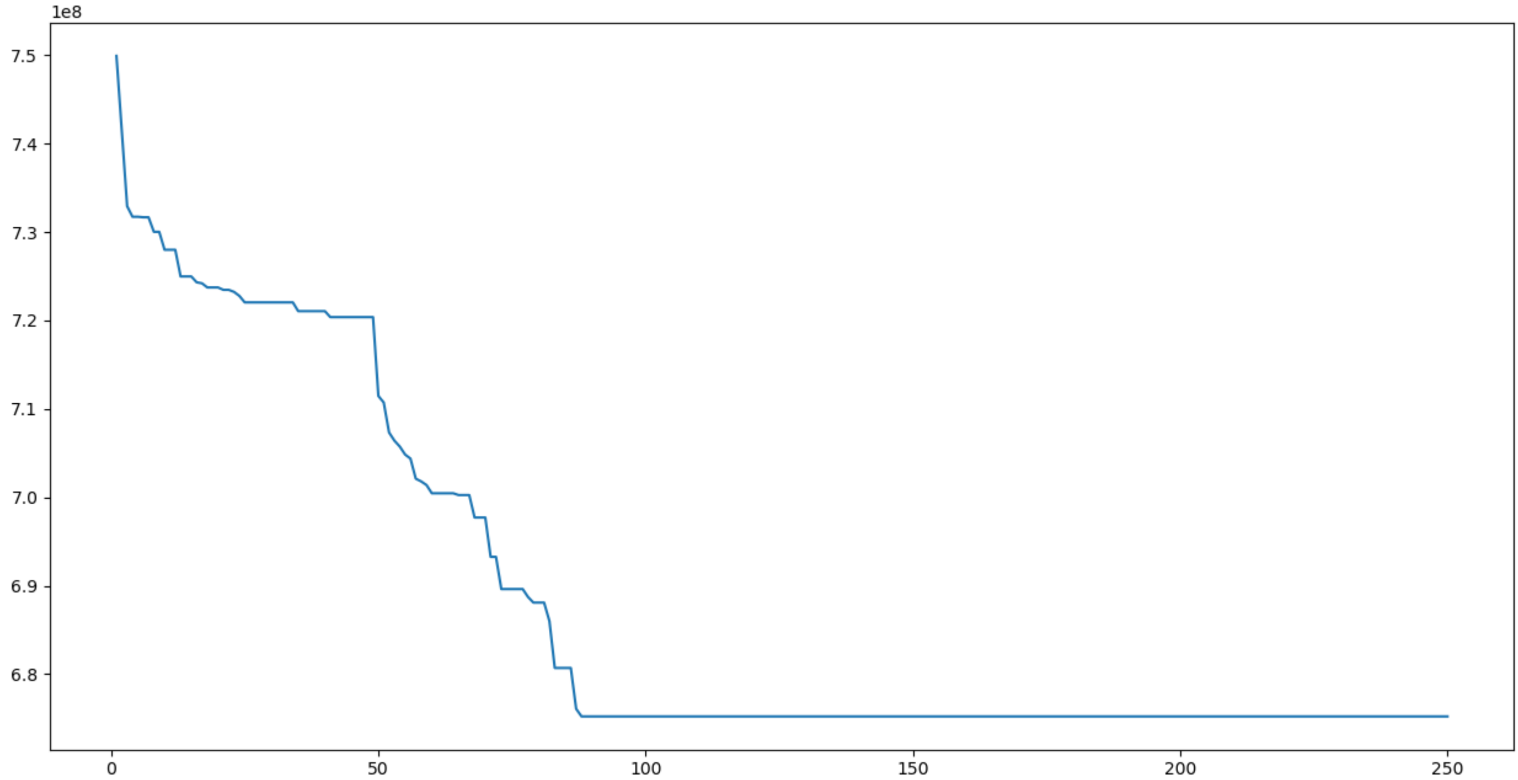


*Figure 25: Trace plot of Tabu search algorithm. Values on x axis indicates the iteration number, value on y axis indicates the weight meters in 10^8 m * kg. For the Tabu search algorithm the maximum number of iterations was set to 250, the Tabu list size to 20 and the candidates to 20.*

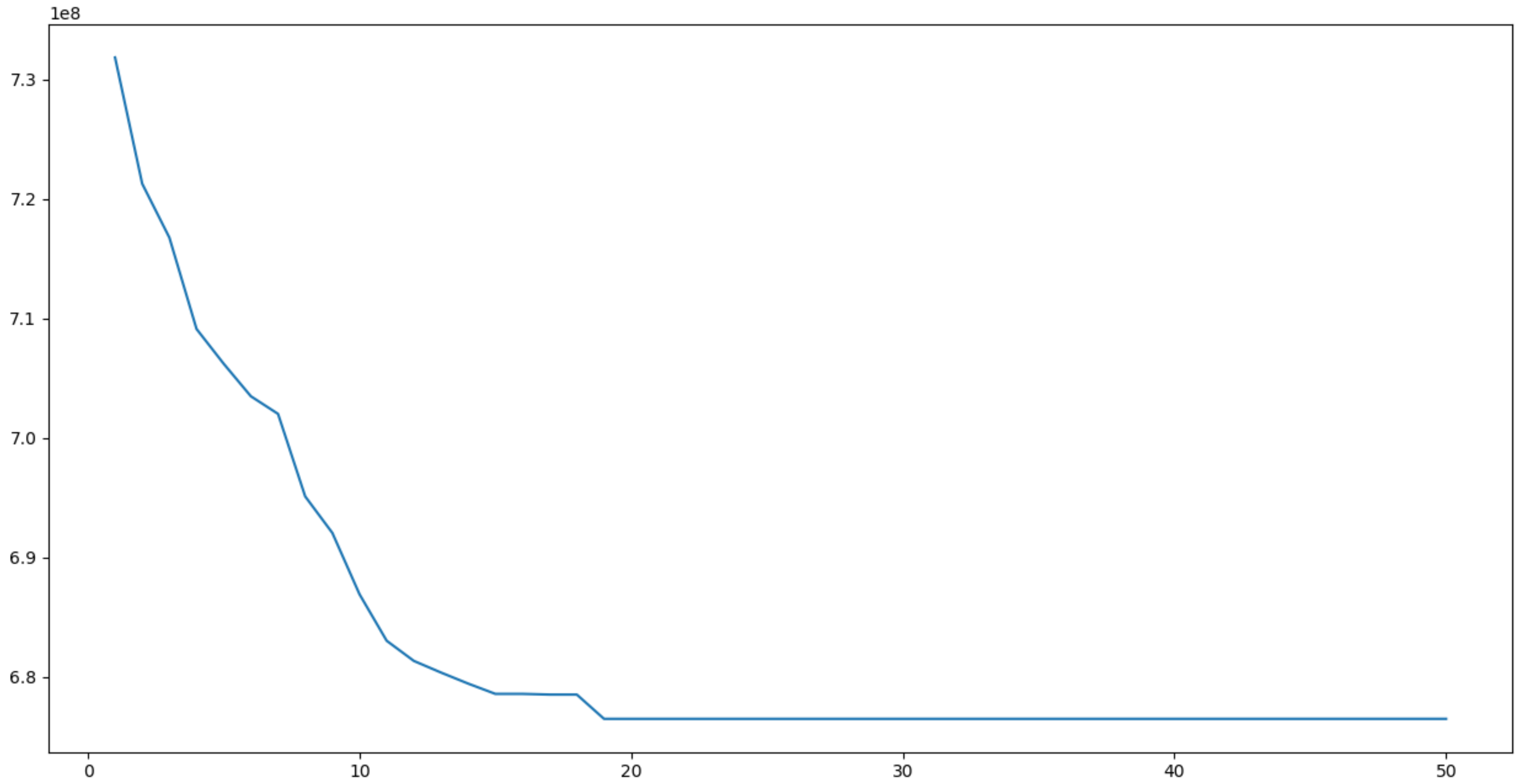


*Figure 26: Trace plot of Tabu search algorithm. Values on x axis indicates the iteration number, value on y axis indicates the weight meters in 10^8 m * kg. For the Tabu search algorithm the maximum number of iterations was set to 50, the Tabu list size to 20 and the candidates to 80.*

3.3 Comparison

For the comparison research question, comparisons between the optimized and monitored routes for three different fields; the Novifarm field, Hans Houbraak Spiegroot field and Obroek proefveld field were made. For these three fields the weight meters of the primary unit, service unit and the sum of the primary and service unit are shown in table 10,11 and 12.

For the Novifarm subfield, some modifications were made to make the collected data comparable to the developed algorithm as mentioned before in section 2.5. The results of the comparison for the Novifarm subfield are shown in table 10. Table 10 shows also the weight meters for the initial route. The initial route values were included to illustrate improvements made by the Tabu search algorithm upon the initial route. The values of table 10 indicate that the monitored route had 17.65% less weight meters than the optimized route. When the optimized route of the Novifarm field is compared with the initial route, the main reduction was achieved for the service unit. For the primary unit there was even a slight increase in the total weight meters compared to the initial route

*Table 10: Displays for the Novifarm subfield initial, optimized and monitored routes for the primary unit, service unit and summed the weight meters. The weight meters are expressed in 10^6 (m*kg)*

Novifarm subfield	Total weight meters route primary unit	Total weight meters route service unit	Total weight meters route
Initial route	957.41	1931.90	2889.30
Optimized route	959.09	1794.31	2753.40
Monitored route	923.71	1347.65	2267.48
Percentage difference monitored versus optimized routes	3.69%	24.89%	7.65%

The second field for which a comparison was made is the Hans Hobraken Spiegroot field, the results of this field are shown in table 11. The optimized route had 5.44% less weight meters than the monitored route. This reduction is mainly achieved by a decrease in weightmeters for the service unit, for which a reduction of 12.65% weightmeters was achieved for the optimized route compared to the monitored route. On the contrary, the primary unit of the optimized route had 2.62% more weight meters than the monitored route. When the optimized route is compared with the initial route, a reduction for both the primary and service unit in the weight meters is achieved. The reduction for the weight meters of the primary unit is relatively small. The larger part of the reduction is achieved for the weight meters that a service unit traversed.

*Table 11: Displays for the Hans Hobraken Spiegroot initial, optimized and monitored routes for the primary unit, service unit and summed the weight meters. The weight meters are expressed in 10^6 (m*kg)*

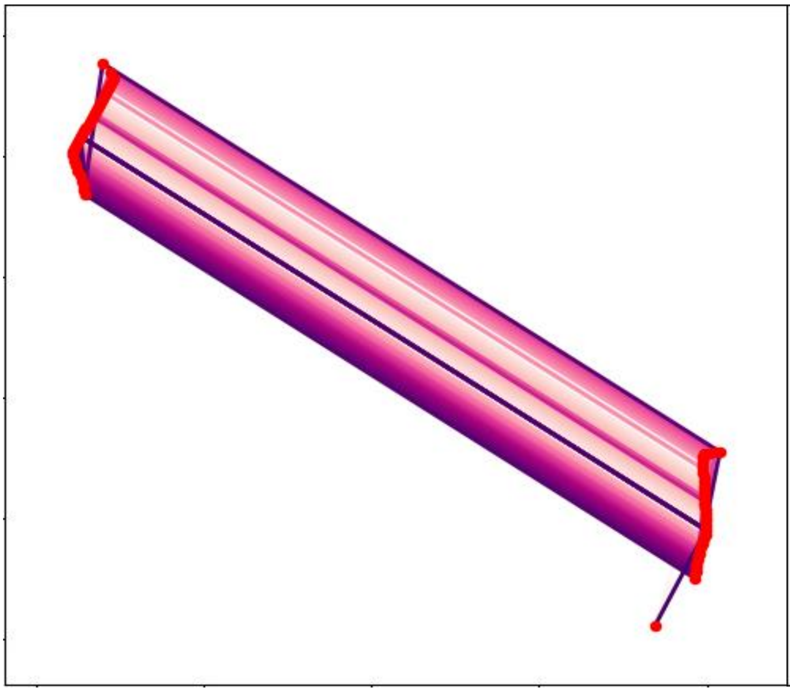
Hans Hobraken Spiegroot	Total weight meters route primary unit	Total weight meters route service unit	Total weight meters route
Initial route	942.88	1082.28	2025.16
Optimized route	937.56	892.53	1830.09
Monitored route	913.61	1021.83	1935.45
Percentage difference monitored versus optimized routes	2.62%	-12.65%	-5.44%

The last field for the comparison was the Obroek Proefveld. For this field the optimized route resulted in the largest reduction in the total weightmeters made for traversing the route compared to the monitored route. The difference in the weight meters was mostly caused by the route that the primary unit traversed. In that case a percentual reduction of 13.81% in the weight meters was achieved. For the service unit an even larger reduction percentage wise was recorded. A percentual reduction of 26.95% in the weight meters was found compared to the monitored route.

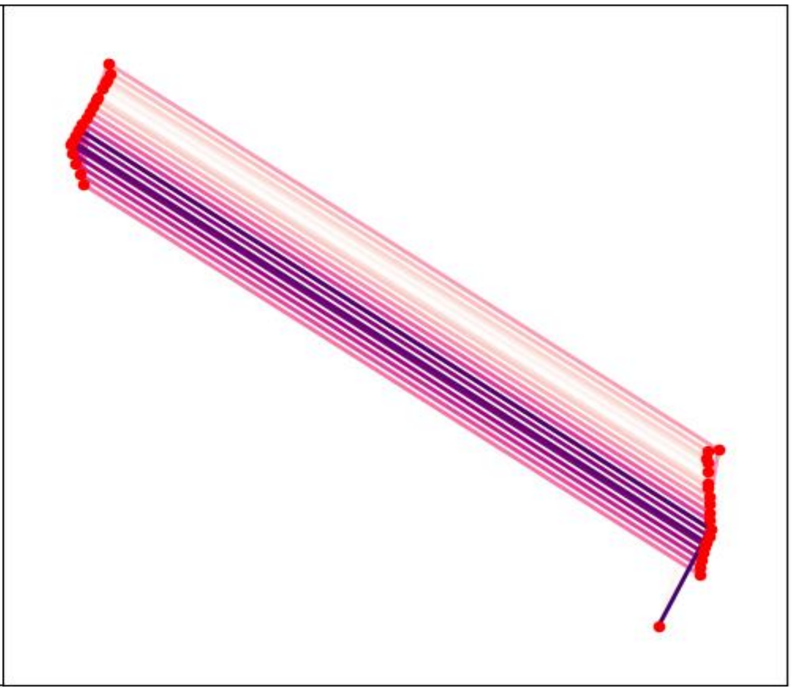
*Table 12: Displays for the Obroek Proefveld initial, optimized and monitored routes for the primary, service and summed the weight meters. The weight meters are expressed in 10^6 (m*kg).*

Obroek Proefveld	Total weight meters route primary unit	Total weight meters route service unit	Total weight meters route
Initial route	422.30	210.87	633.10
Optimized route	421.11	150.46	572.57
Monitored route	488.57	205.96	694.53
Percentage difference monitored versus optimized routes	-13.81%	-26.95%	-10.45%

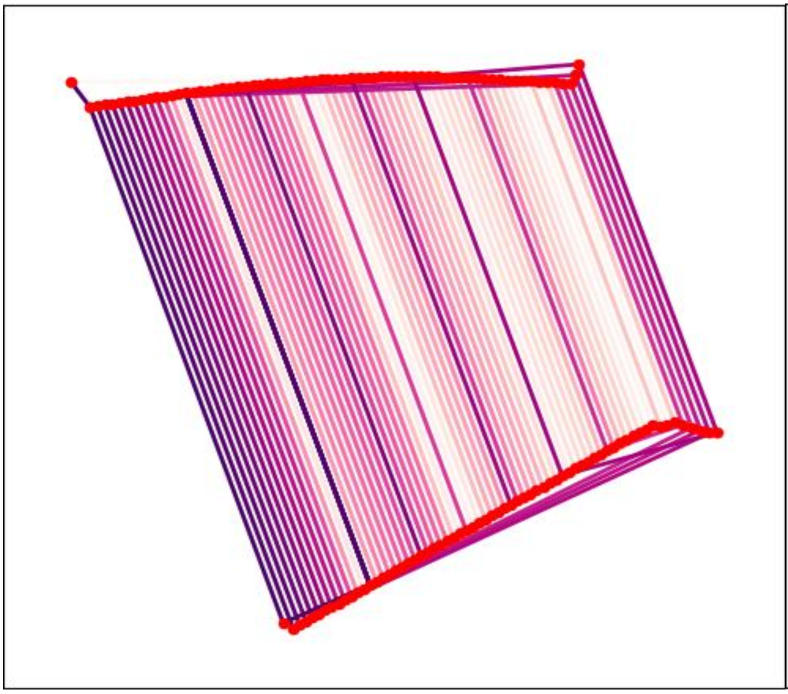
Figure 27 shows graph abstractions of the optimized (left) and monitored (right) route sequences compared to each other. A lower number in the legend in figure 27 indicates that a part of the field was traversed earlier in the harvesting operation, while a higher number indicates that a part of the field was traversed later on during the harvesting operation. When examining figure 27, the monitored routes are more sequentially ordered than the optimized routes, which tend to be less ordered.



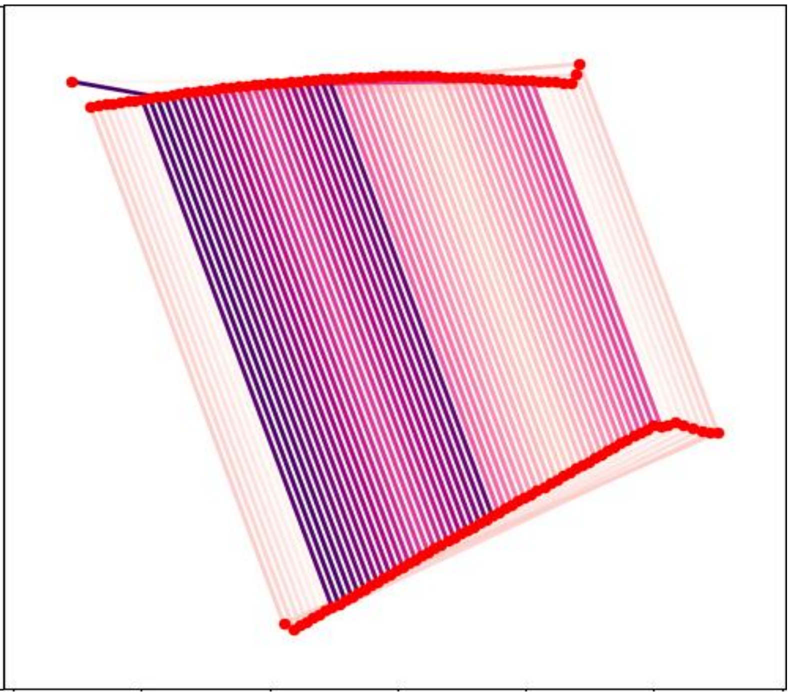
A: Novifarm subfield optimized route. Total weight meters = 2753.40 * 10^4 (m*kg)



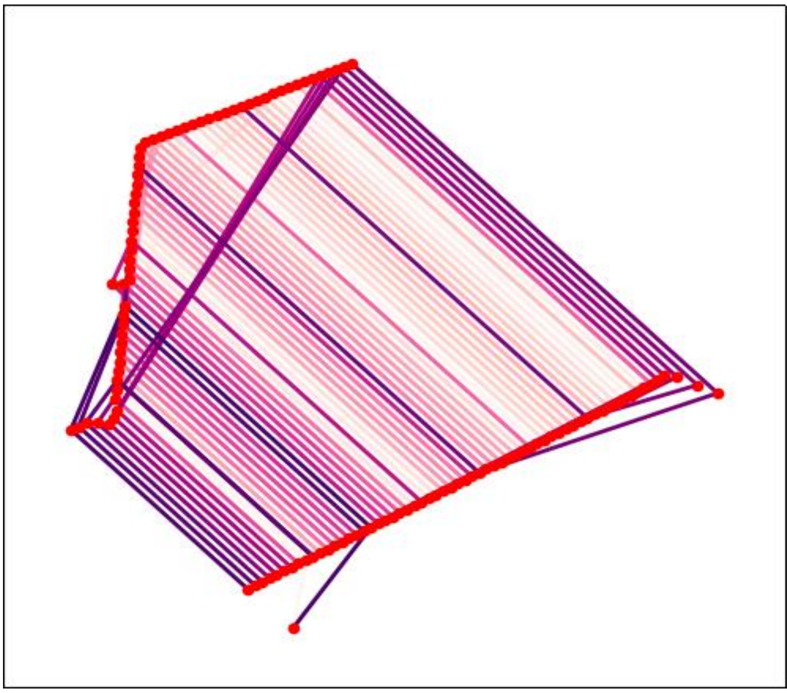
B: Novifarm subfield Monitored route. Total weight meters = 2267.48 * 10^4 (m*kg)



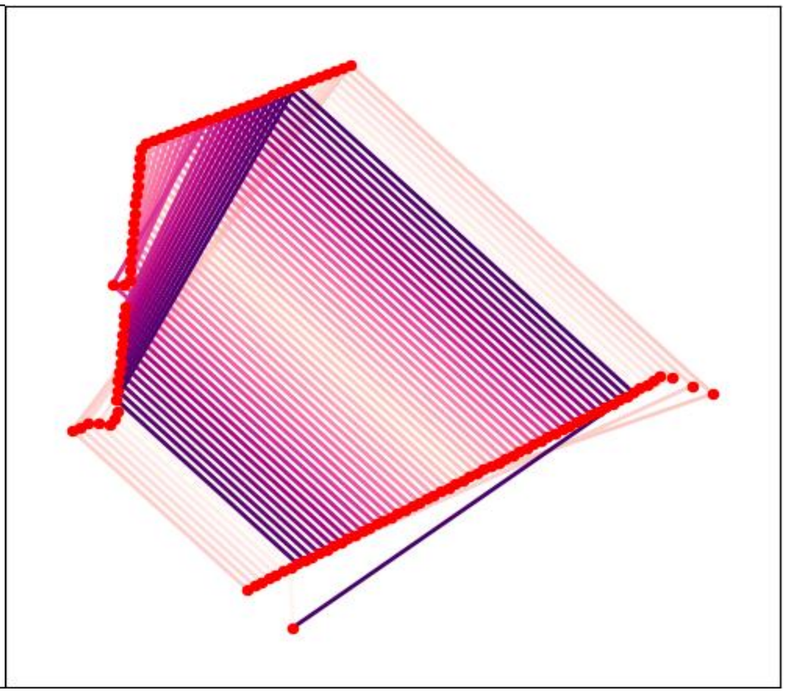
C: Hans Houbraken Spiegroot optimized route. Total weight meters =1830.09 * 10^4 (m*kg)



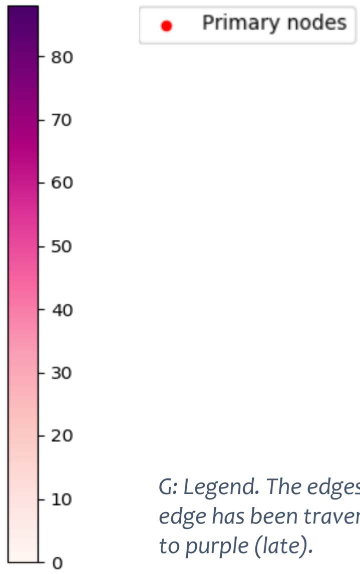
D: Hans Houbraken Spiegroot monitored route. Total weight meters =1935.45 * 10^4 (m*kg)



E: Obroek Proefveld optimized route. Total weight meters = 572.57 * 10^4 (m*kg)



F: Obroek Proefveld monitored route. Total weight meters = 694.53 * 10^4 (m*kg)



G: Legend. The edges are coloured based on when the edge has been traversed, ranging from white (early on) to purple (late).

Figure 27: Maps of the path sequences. A gradient value (white to purple) showing which path sequences were followed during the harvesting operation of the primary unit on the fields. On images A, C and E are shown the optimized routes, on images B, D and F are shown the monitored routes and on G is shown the legend for images A till F.

4 Discussion

In this section the results are discussed. The discussion is discussed in the order of the research questions.

4.1 Optimal route service unit

Table 6 shows that to minimize the amount of weight meters the primary and service units have a preference for avoiding making turns, if these turns have only a small distance between the start and destination paths. Because this results in a higher amount of weight meters compared to a turn where there is a larger distance between the start and destination paths (figures 22 and 23). At the same time primary and service units will avoid turns where the distance is too large between the start and destination paths (figure 23 and 24), because in that case the straight segment of Dubins path becomes too long. Resulting in unnecessary traversed weight meters. Therefore, an optimal route will consist of turns for which the total turning distance is minimized, because of the smaller cost for the execution of a turning manoeuvre. This is in line with what Bochtis et al. (2008) mention in their paper that reducing the minimizing the non-working distance (e.g. turning manoeuvres) leads to reduced induced soil compaction in the headland area. However, turning manoeuvres are only one of the factors on which an optimal route is judged and will therefore not always be minimized.

Based on table 2 and table 6, it is expected that primary and service units would prefer to traverse a dry spray path, due to the fact that this action results in the least weight meters compared to traversing a wet spray path and a normal path which is either dry or wet. Therefore, depending on the turning manoeuvre, primary and service units would select the path, resulting in the least weight meters.

The weighting scheme (table 2) applied on table 6 showed that the costs of certain operation is largely influenced by the total weight and distance. Minimizing the weight in areas with a higher susceptibility to soil compaction and minimizing the total distance would result in less weight meters. These results are in line with the results by Saffih-Hdadi et al. (2009). However, the weighting scheme (table 2) is not representative for the actual difference in water content in soils. This is also because in reality other factors (e.g. clay content) are also important for determining the induced soil compaction (Hamza et al., 2005). Therefore, the in this research used weighting scheme is only a simplification of the situation in reality.

Due to the dependence of the service unit on the primary unit. An optimal service unit route is a result of a primary unit route which has been altered to suit the service unit. Altering the primary unit route to suit the service unit minimizes the total amount of weight meters for the service unit. However, this should not necessarily result in the minimal weight meters for the primary unit. Therefore, in harvesting operations the goal should be to minimize the total weight meters of both the primary and service units. For example, a consequence could be that the weight meters for the primary unit increase while a larger reduction in the weight meters is generated for the service unit, and or vice versa, overall resulting in less weight meters. This can be observed in table 11 in section 3.3.

Bochtis, Sørensen, et al. (2010) conducted a research with a similar approach regarding restrictions as the set of restrictions used in this research. However, the main differences were that they only implemented boundary restrictions for the service unit. Boundary restrictions indicate that the service units are only able to drive at one side of the primary unit when adjacent to a boundary. Otherwise they are able to drive on both sides of the primary unit. This in comparison with the in this research stricter set of restrictions, resulted in that the service unit is less dependent on the route of the primary unit in the research by Bochtis, Sørensen, et al. (2010). This will have a large effect on what is classified as an optimal route, because of the larger amount of possibilities to select during the optimization process.

Optimization of the service unit route in real life is very complicated because time and variable speed are to be considered. In a paper by Higgins et al. (2005), the importance of the optimization of the utilization of primary units while reducing costs is stressed in a time dependent setting. Higgins et al. (2005) developed a capacity planning model for transportation in a sugar cane harvesting operation. Results showed that changing starting hours resulted in a more efficient transport service. Therefore, in practice an optimal service unit route consists of both the minimization of the total amount of weight meters and the optimization of the utilization of units operating in an operation which is time dependent. Compromises between these factors have to be made in practice.

4.2 *Representation harvest operation as a graph*

An agricultural harvesting operation is represented in a graph abstraction by making use of an arc based approach. An arc based structure is suitable for verifying that all the to be harvested edges are indeed completely harvested. The arc based approach is more suitable for these kinds of problems than the VRP approach, which wants to make sure all nodes are traversed. Bochtis and Sørensen (2010) decided to use a Vehicle Routing Problem with Time Windows (VRPTW), which is a node based solution for converting an agricultural operation to a graph abstraction. In that case the edges are represented by a node (customer) which has to be visited before a harvesting operation can be finished. This thesis required however, an arc based structure because of the continuous harvesting process. A VRP would be less suitable for this approach.

Headland turns were represented by calculating the length of a Dubins path. The Dubins path is a relatively simple approach for making a turning manoeuvre and perhaps not the best method for comparing to the in practice used turning manoeuvres. That is because Dubins path does not allow to make turning manoeuvres, including both forward and backward moves. Therefore, integration of a more sophisticated approach would be more in line with practice. Regarding the turning manoeuvres, the current approach did not take into consideration the boundary of the field. This should not result in problems in most cases, due to the size of the headlands. However, integration of an approach in which limitations like field boundaries are integrated, would lead to a more realistic approach. An example of a research for which field boundaries and a more sophisticated turning manoeuvre were integrated was the research by Bakhtiari et al. (2013). For the optimal integration of fields turns inspiration can be gained from the research by Tu (2013). He researched the integration and optimization of turning manoeuvres in headlands for agricultural vehicles.

Wet spots were implemented as discrete objects. A location in the field was either wet or dry. An arc based approach was therefore suitable for indicating that a spot was either wet or dry. The nodes indicate the starting and ending points of a wet area and the area in between is considered wet. In practice the water content of a wet spot is continuous rather than discrete. This could be achieved, by calculating an average water content factor for a fixed interval (e.g. calculate for every meter in a path the wetness) based on remote sensing data. This water content factor could then be used within the objective function. This was however, outside of the scope of the current research and subsequently not implemented.

4.3 Tabu search heuristic optimizer parameters CARP

For the Tabu search parameters three parameters and their corresponding optimal values were explored. For the maximum number of iterations, the results indicated that the total weight meters dropped until 80 iterations, where after the amount of weight meters became stable. Therefore, a value of 80 iterations was selected for the maximum number of iterations.

The results of the length of the Tabu list, indicated that a Tabu list value of 20 would result in the least weight meters for traversing the route. Therefore, the Tabu list size parameter value was set at 20. For the maximum number of candidates, 80 candidates lead to the least weight meters. Therefore, the maximum number of candidates was set at 80. However, when these three selected are used together in the Tabu search algorithm, figure 26 shows that the Tabu search algorithm converges at around iteration 18. Therefore, the maximum number of iterations could be set to a lower number, which should result in a similar near optimal solution for the Goudswaard field. The parameter values found for this field are likely to differ for each field, depending on the size of the field. This is in line with what Sarmady (2007) also mentions in his paper, that his results are not comprehensive for all problems and are as a result highly specific to a certain problem. Trace plots are an important tool for identifying, if a Tabu search algorithm has led to a converged solution. Because some of the other fields in this research are only slightly larger than Goudswaard. The value of the maximum iterations is set at 80 iterations, to verify that a near-optimal solution is always found, for the fields used in this research.

The Tabu search algorithm applied in this research required more computational time in comparison to Tabu search algorithms used in similar researches (Brandão et al., 2008; Hertz et al., 2000; Mijnheer, 2018). This can be largely attributed to the complexity of the swapping method. Since solutions had to comply with a set of constraints, additional steps were required before a random swap could be made.

4.4 Comparison

In the comparison, optimized and monitored routes for three fields, Novifarm subfield, Hans Houbraken Spiegroot and Obroek Proefveld were assessed (figure 26). Unfortunately, the optimization of the Novifarm subfield did not meet expectations. Multiplying the harvest rate, weight and capacity of the primary unit to compensate for the fact that the route of a single harvester was assumed rather than the two operational ones, resulted in significantly less weight meters for the service unit than was the case for the optimized route. The weight meters for the primary unit in the monitored route were, however, similar to those of the optimized route. A potential explanation is that a service unit would normally need approximately three full loads of the primary unit to reach its maximum capacity. However, since the capacity of the primary unit was increased by a factor two, a service unit could only pick up two loadings before the maximum capacity was reached. Hence, the service unit has to traverse fewer paths, before the maximum capacity is obtained, because only two full-nodes have to be visited instead of three. As a result, the service units generate less weight meters. On the other hand, for the other two fields (Hans Houbraken Spiegroot and Obroek Proefveld) reductions between 5.44% and 10.45% of the total weight meters were realized. Therefore, it can be concluded that the monitored harvesting operations can be further optimized. Improvements can be achieved concerning minimalization of the induced soil compaction.

Interesting to see was that in the three monitored fields different approaches were chosen for traversing the field. This indicates that in practice there is no general accordance to how a harvesting operation should be approached. It was intriguing to see that the sequences that were followed during the harvest the main constraints as set in this research were not always complied. For example, in the field Hans Houbraken Spiegroot the primary unit did not start next to a spray path but chose instead to start next to a normal path. This might have to do with the initial pattern that Jacob van der Borne tends to follow when harvesting his fields. He prefers to traverse in circles around the field for the first six paths. By doing this, he also harvests the headlands. Due to the fact that in this research only the main body of the field was observed, the effectiveness of Jacob van der Borne his harvesting strategy could not be assessed properly in the comparison.

A habit of the operators of the service units observed during the harvesting operation on the Novifarm field was that service unit operators tended to turn around in the middle of the edge they were traversing. The developed algorithm was not capable of working with infield turns, partly because turning in the field was seen as undesirable behaviour and partly because of the difficulty of the implementation.

Although the wet spots created in this research were fictional, they did not have any implications on the results. The wet spots were merely added to show the capabilities of the implemented algorithm. The current fictional wet spots could be replaced by fields consisting of actual wet spots and the algorithm would return similar results. Therefore, the fictional wet spots do not retract from the methods used in this research.

A component of an optimal route that is not taken into account are the unforeseen circumstances influenced by time. In a real time situation like the data with which the script was compared, situations can occur like a breakdown of a primary or a service unit, variation in yields, or other events which cannot be determined a priori. These events can influence the optimal path which has to be taken by the primary and service units used in the operation. The current script is not capable of taking these events into account. Making the script suitable for real time changes is not possible due to several factors. For example, running the current script takes too long in a real time situation to make it useful in situations where real time decisions need to be made. This is a result of what Canny (1988) mentions in his book, that that the computational complexity of path planning for multiple vehicles is exponential for the number of vehicles used. Due to this, the computational requirements would make real-time planning for multiple vehicles non-feasible with current computer power(Bochtis, Sørensen, et al., 2010).

Not considering traffic outside of the field leads to an unrealistic representation of a harvesting operation. This could be solved by the implementation of a built-in delay between the time the service units leaves the field and the moment it is ready to enter the field again. The result would be an estimation of the time spent outside the field by the service unit. Integrating this built-in delay would make it possible to implement fleet optimization, which would be beneficial for farmers to calculate the number of required service units for optimally serving their primary units. In the case of fleet optimization, the velocity, number of vehicles and locations of individual vehicles are also required. For example, collision avoidance of primary and service units has to be integrated, to confirm that no collisions occur. Another example is that for the optimization of the fleet the velocity of service units in the field and harvest speed of the primary unit have to be known. The current turning and graph implementation would have to be extended for the integration of these components.

As was mentioned before, it is nearly impossible to determine the variation in yield across the field a priori (Bochtis & Sørensen, 2010). The harvest rate was therefore, simplified in the script. The uncertainty of these factors makes it very hard to determine in reality what decisions need to be made to generate an optimal solution.

5 Conclusions and recommendations

A method was created to generate near-optimal routes for capacitated agricultural harvesting operations with given predefined paths to minimize the induced soil compaction by the primary and service units. The method is successful in reducing the weight meters while taking into account weight variation in the process, wet spots, variation in soil compaction and restrictions regarding driving patterns.

Research Question 1: What is an optimal route for service units operating alongside a harvester with regards to soil compaction and wet spots within a field?

- An optimal route for a service unit operating alongside a harvester is a route optimized specifically for the service unit, where the weight meters [m*kg] of the service unit are minimized. The total weight meters of a route are lower when turning distances are minimized and areas in the field with a higher susceptibility to soil compaction are avoided while carrying larger weights. This should minimize the total induced soil compaction during a harvesting operation.

Research Question 2: How can an agricultural harvesting operation including headland turns and wet spots be represented by a graph abstraction?

- An agricultural harvesting operation can be presented by an arc based approach. In this arc based approach the headland turns can be described by calculating the distance for the Dubins paths between primary nodes located at the headlands. Wet spots can be presented by implementation of nodes which indicate the start and end locations of a wet area. Limitations in the current approach are related to the number of headlands, chosen turning approach and field boundaries during the turning manoeuvres.

Research question 3: Which are suitable meta parameters for a heuristic optimiser applied to the CARP?

- A Tabu search algorithm was considered the most suitable heuristic optimiser for solving a CARP. Due to the ability of the Tabu search algorithm for finding high quality solutions within a reasonable time period. For the Tabu search algorithm three parameters were found as most influential for generating a good solution. The parameters found were the maximum number of iterations, Tabu list size and maximum number of candidates. In order to generate a near optimal solution, for these three parameters optimal parameter values had to be found. The following parameter values were found: a maximum number of iterations of 80, a Tabu list size of 20 and a maximum number of candidates of 80. These values may however differ for larger or smaller problems.

Research question 4: How do test-cases of an implemented system compare to conventional harvesting routes of capacitated agricultural operations?

- For three fields the optimized and monitored routes were compared. For two of the three fields reductions in the weight meters were obtained. The result of the other field was difficult to compare due differences in the circumstances (two versus one harvester). A reduction for two of the three fields indicates together with the variation in harvesting approaches that field routes can be further optimized in practice, when the induced soil compaction is seen as the main judgement criteria.

To improve upon the current research, further research should be conducted on how certain field movements (e.g. turning manoeuvres by a primary and service) are impacted by a variation in soil circumstances (e.g. dry and wet areas). In the current research no differentiation is made between variation in susceptibility for soil compaction for different field movements. Additional information on the influence of soil compaction during field operations should make it possible to identify in more detail of what characterises an optimal route. This can be used to assign various weight factor values for conducting a certain operation. As a start studies related to this topic can be investigated. An example is the research by Duttmann et al. (2014) in which it was tried to predict the induced soil compaction based on GPS data in a silage maize harvest. Additional information about the prediction of induced soil compaction might also be helpful for improving on the weighting scheme. The current weighting scheme is based on the importance of actions occurring in the field compared to other actions. This gave a general idea about the induced soil compaction in those areas compared to other actions in the field. For the exploration and further development of a weighting scheme for induced soil compaction the researches by Hamza et al. (2005), de Lima et al. (2017), Saffih-Hdadi et al. (2009) and Sivarajan et al. (2018) could be used as a starting point.

Another topic for feature research is closely related to the previous topic. Further research should be conducted to find out how in a graph abstraction continuous variables can be used (e.g. water content, soil porosity or other factors influencing induced soil compaction). In the current research discrete variables were used instead. Continuous variables could be presented by an averaged value for a certain resolution (e.g. 1x1 meter) in a graph which is linked to a certain part of an edge. The importance of integration of continuous information like soil-maps in future research is also stressed by Bochtis, Sørensen, et al. (2010).

In the current research, constraints regarding the movement possibilities for the service unit were one of the main limitations. In practice these constraints are not always strictly adhered to (e.g. driving through non harvested normal paths and within field turns). Another limitation was that the headland harvesting strategy was not considered in the harvesting route. Therefore, future research on the generation of optimal harvesting routes could, consider relaxing constraints in certain situations. Feedback is required from farmers, about why certain actions are performed in practice. With this feedback, routes could be improved and possibly parameters could be set to generate an optimal route according to the preferences of the farmer.

In the current research fleet size optimization is not supported, service units spawn whenever they are required. For the integration of fleet size optimization, velocity number of available units and locations are required. The location has to be known because collisions with other units should be avoided. Time spent outside the field could be replaced by a built-in delay for the time spent between the moment a unit leaves and enters the field again. For the integration of this component the researches by Brandão (2009) and Sørensen et al. (2010) could be used as a starting point.

6 Reference list

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