

Centre for Geo-Information

Thesis Report GIRS-2010-12

OPTIMIZING ROUTES ON AGRICULTURAL FIELDS MINIMIZING MANEUVERING AND SERVICING TIME

***BASED ON GEOGRAPHIC DATA OF FIELDS, WORKING PATTERN AND
MACHINE PROPERTIES***

Mark Spekken

May 2010



WAGENINGEN UNIVERSITY
WAGENINGEN UR

OPTIMIZING ROUTES ON AGRICULTURAL FIELDS MINIMIZING MANEUVERING AND SERVICING TIME

***BASED ON GEOGRAPHIC DATA OF FIELDS, WORKING PATTERN
AND MACHINE PROPERTIES***

Mark Spekken

Registration number 83 08 24 789 080

Supervisors:

Dr. Ir. S. de Bruin

A thesis submitted in partial fulfilment of the degree of Master of Science
at Wageningen University and Research Centre,
The Netherlands.

May 2010
Wageningen, The Netherlands

Thesis code number: GRS-80436
Thesis Report: GIRS-2010-12
Wageningen University and Research Centre
Laboratory of Geo-Information Science and Remote Sensing

Acknowledgments

Many were those who guided and supported me during the developing of this work, among them there were some who took an essential part in it: my supervisor Sytze de Bruin and my MGI friends. I would like to thank them for all their help.

There are a few things in the world that are just too noble to be human. In our daily fight for survival, comfort and fulfilling our duties; one thing that surpasses all of these is our calling. Calling is something unique for each person, it cannot be chosen nor denied. It makes us dependent on each other making the one who is proud and powerful to bow down to the simple one whose gift he cannot have.

This is a voice inside us claiming for results, solutions and improvements in disregard to any reward. It takes us away from the time passing and makes us immune to it.

For one observer it is not understandable the focus and effort spent by one who following his calling, nor can the follower himself explain how exactly is he being capable of doing it.

Calling is not something spontaneous or random. If this thesis will yield any benefit for this world, the fruits should be regarded to the origin of the gift that made this work possible.

To the One who always showed me that He was right, and I was wrong.

Abstract

Cost for operating farm machinery have been rising in recent years demanding a more efficient use because farm machinery are not always doing in field the work they were developed to do. Also the advance in on-board sensors and geo-positioning systems in agricultural machines demands information in advance of how they will move on the field free of human intervention. These issues push the development of route planning for machinery.

To optimize a route in advance, it is required to define which cost issues are going to be optimized. Many authors working with path planning and route planning worked with different cost issues (number of maneuvers, field coverage, overlap of field operations, performance of maneuvers, servicing of machinery on field), their methodologies were mainly based in simulating in advance the behavior of a machine in field and the savings studied by authors were, in general, focused on one single cost-issue.

This work focused on minimizing non-working time spent by machines merging two cost issues that are time related: maneuvering and servicing. To obtain it, methods of previous authors were studied and applied (or adapted), together with proposed new methods in order to create routes on fields. Optimization of maneuvering time posed a Travelling Salesmen Problem (TSP) and was solved through a heuristic approach; servicing was optimized through influencing the maneuvers and the route.

The routes are based on a single direction of swaths in the main inner field for which the maneuvering and servicing times were retrieved; it tries 180 directions of work (at steps of 1 degree), and uses given field geometry and machine properties. This methodology was implemented in an algorithm built in Visual Basic in macros interacting with a Microsoft Excel spreadsheet. It was tested on fields with different shapes and sizes using eight machine and operation properties for the optimization.

Six case studies were processed using the algorithm. Three case studies with small fields, where no servicing was taken into consideration, supported the suitability of the methods, reducing the maneuvering time to less than half of the time when comparing the optimal maneuvering along tracks calculated with the standard maneuvering to the adjacent track. Also the different directions of work tried showed the time impact of choosing a specific direction on non-working time, given a set of user criteria.

Three case studies with larger fields that considered servicing as an issue found no relation between servicing and maneuvering time for different directions of work tried. It was found that choosing a direction of work taking maneuvers as priority for optimization may lead to high consumption of time for servicing because the machine needs to stop to be served when its capacity has not been efficiently used. This was observed in a harvesting case study where ranges of time for servicing surpass the range of time for maneuvers.

The routes calculated seem suitable but no exhaustive research (i.e. testing all existing options) was done to validate the outputs. The heuristic approach used is strongly influenced by the entering and leaving spots of the machine in the field and leaves a research opening of how working this issue (finding a better entrance point) may improve the optimal route.

Secondary outputs were also retrieved from the algorithm, like the area demanded for headlands, but, because it's not a time related issue, it was not taken into consideration in the optimization.

Coverage optimization is a line of study that is case study dependent because of the many parameters that influence the optimal route and merging optimization issues is strongly required in obtaining a global optimization of field work.

Keywords: efficiency of machinery, coverage planning, precision farming, servicing in field operations, robotics.

Table of contents

1. Introduction:

1.1 Background	1
1.2 Field complexity in farm operations	2
1.3 Agricultural operation planning	2
1.4 Optimal route along tracks	3
1.5 Merging path and turn planning	4
1.6 Servicing of machinery	4
1.7 Problem definition	6
1.8 Main objective and research questions	6

2. Methodology

2.1 Overview of optimization problem	8
2.2 Conceptual model	11
2.2.1 Input data	12
2.2.2 Creating tracks for a given angle	12
2.2.3 Obtaining optimized route along tracks	14
U-maneuver	14
Ω -maneuver	15
Optimizing choice of tracks	16
2.2.4 Servicing	18
2.2.5 Looping over angles	19
2.3 Implementation	21
2.3.1 The environment for data analysis, interpretation of the data by the algorithm and tools used along the processes	21
Interpretation of field and intersection tool	21
Polygon offsetting tool	22
Polygon perimeter distance tool	23
2.3.2 Creating tracks for a given angle	24
Creating tracks	24
Creating headlands	24
2.3.3 Obtaining optimized route along tracks	26
Creating a U-maneuver between nodes	26
Creating a Ω -maneuver between nodes	27
Optimizing the choice of tracks	28
Pseudo-Code	32
2.3.4 Servicing	33

3. Example applications

3.1 Suitability of the chosen methods	34
3.2 How does route change with fields of more complex shape	36
3.2.1 Exploring optimization of maneuverings for different directions of work	37

3.3 Impact of servicing in route planning	39
3.3.1 Optimized results found for maneuvering and servicing time	41
3.4 The issue of the entrance and leaving spot of the field for machinery	46
3.5 Headland demanded for maneuvering	47
4. Discussion	
4.1 Methods and route planning	49
4.2 Impact of servicing in route planning	50
4.3 Other issues	50
4.3.1 The entrance and leaving spot of the field	50
4.3.2 Headland demanded for maneuvering	50
5. Conclusion	
5.1 Answers to research questions	51
5.2 Further study and recommendations	53
References	55
Appendix	
Table of definitions	57

1. Introduction

1.1 Background

Machinery and equipment are major cost items in farm businesses. Larger machines, new technology, higher prices for parts and new machinery, and higher energy prices have caused machinery and power costs to rise in recent years; and this cost goes into the field operations. Decisions about technology to be used require accurate estimates of the costs of owning and operating farm machinery (Edwards, 2005).

In the role of field costs and operating farm machinery, some issues have been considered:

- Overlap of field operations, leading to higher consumption of inputs (like fertilizer or agrochemicals) mainly in field margins. This aspect has economic and environmental impacts because of the overuse of inputs in specific spots (de Bruin et al., 2009);
- Turning, which is a time consuming operation in which the machine does not perform the activity for what it was acquired. Optimization of turning has been widely studied with respect to the number of turns on fields (Visala and Oksanen, 2007; Jin and Tang, 2006; Taix, 2006) and also regarding the performance of turning and choice of tracks to minimize turning time (Vougioukas and Bochtis, 2008; Bochtis and Oksanen, 2009) ;
- Loading and offloading, which are also operations that either require the machine to stop its operation either to re-load or offload away from its current position, or require auxiliary machinery to allow this operation to happen on the position where the machine is located when servicing is required. Refilling or emptying is a crucial part of field operations. (Oksanen, 2007);

For example, with more overlapping area, a large number of turns, inefficient turns and increased times to load or offload a machine, the costs are higher.

Path planning, in an agricultural perspective, is a term used for defining in advance how a machine is going to move inside a field, for example aiming that this machine stays working as long as possible in the activity which it was developed for, reducing the non-working time (like maneuvering, loading and offloading) or reducing overlap of this machine on the area, avoiding overuse of agricultural inputs. There has been a strong effort spent in path planning in the past years because of the development and improvement of guidance and self-steering systems on machines (Keicher and Seufert, 2000).

The advance in geo-positioning systems, applied in guidance and self-steering of farm machinery, creates a demand for coverage path-planning, where machinery can operate free of human intervention (robots). Research activities concerning automatic guidance of agricultural vehicles — or implements — have led to various solutions. Sensors, including mechanical ones, global navigation satellite systems (GNSS), machine vision, laser triangulation, ultrasonic and geomagnetic, generate position, attitude and direction-of-

movement information which are essential inputs for control algorithms. Actuators, like hydraulic valves, are used to transform guidance information into changes of position and direction (Keicher and Seufert, 2000). In general, a dedicated pre-planning of the routes and tasks of the operation has been shown to improve overall efficiency (Palmer et al., 2003).

1.2 Field complexity in farm operations

Complex shapes of fields and the presence of obstacles make decision-making towards increasing the efficiency of field operations difficult.

In Finland, Klemola et al., 2002 (cited by Oksamen et al. 2007) concluded that "The shape of a field has the greater effect on small fields. As the field size increases, the shape's effect decreases". In addition: "The effect the field size and shape have on the time spent working in the fields is almost entirely related to turning times".

Peltola et al., 2006 (cited by Oksamen et al. 2007) studying properties of land, used perimeter and area of the land to create an index for field complexity, but concluded that this gives only a and raw impression of the effect of the shape.

Oksamen and Visala, 2007 also studied the issue of complex geometry of fields in the Uusimaa county (Finland) using shape indexes (convexity, compactness, rectangularity, moments, triangularity and ellipticity), but concluded that majority of fields (75%) cannot fit properly in the classes defined or can be classified as complex shape.

1.3 Agricultural operation planning

The development of methods for path planning is strongly pushed by the common availability of positioning systems that are already being implemented on field machinery. Different path planning algorithms have been proposed, each focusing on different issues of efficiency and cost.

Bochtis et al., 2006; Hansen et al., 2007 worked with driving patterns avoiding complex fields, assuming them as rectangular in harvesting operations.

Different issues that play a role in the definition of path planning, Stoll (2003) considered as factor for path planning: operation strategy, neighboring area, field geometry, field specific data, machine specific data and terrain relief.

Turning on the headlands can take a considerable amount of time. Stoll (2003) calculated the turning time with the help of the effective working width, the minimal turning radius, the driving speed and the acceleration of the vehicle in the turning. An additional stop time is added when there is a change of driving direction during the turn.

In the aim of reducing maneuvering work in fields, Jin and Tang (2006) proposed an algorithm that defines that a machine covering the field working always in parallel swaths as being the best choice for farm coverage, the algorithm works aiming to find globally optimal decomposition of fields applying splitting lines on specific edges of the field, afterwards finds the best direction of work for each of the sub-fields created, being this direction based on one of the field sides. The same approach is used by Hofstee and Ijken (2009) in finding the

concave vertices of a field and simulating all field-border directions from them creating sub-fields. Inside the created sub-field created, all it's borders is simulated in it to find the optimal working direction. Other approach for the same aim proposed by Oksanen and Visala (2007), called split-and-merge, uses trapezoidal decomposition of fields and rules for merging those, finding later on the best direction path inside each subfield using an heuristic approach to simulate different directions in the created sub-field.

Taix et al. (2006) proposed an algorithm that creates turning areas inside the field and outside obstacles depending on the direction of work guaranteeing field coverage while minimizing overlaping. He also suggests the working direction to be parallel to the longest side of the field.

Considering area losses in headland and avoidance of overlap in field operations, de Bruin et al. (2009), computed path patterns assessing economic impact of uncropped field margins. The economic factors taken into consideration where: loss of uncropped area, turning costs and subsidy received for field margins.

1.4 Optimal route along tracks

Route planning is a further step in field coverage, which concerns also with the movement of the machine outside the parallel swaths (or tracks).

Once tracks are defined in a field, remains the issue how to connect them so that the optimal trajectory is followed by the machine. The choice of the tracks have to consider the machine properties to perform the turn, and also the right sequence of tracks to be driven so that all the global time needed for turning is minimized, for example.

When path planning research started to consider the machine specifications for turning and also the turning pattern, coverage path planning approaches for field operations were proposed, and direction paths were combined in routes. Vougioukas and Bochtis (2008) considered two kinds of turns for a agricultural machine in the headlands: Ω -turn (longer one, Figure 1a) and U-turn (shorter one, Figure 1b) and developed an algorithm that, after a operator finishes a track selects the optimal next one for turning, this reduces global maneuvering time. By using optimum sequences he could reach savings up to 50% depending on the kind of operation.

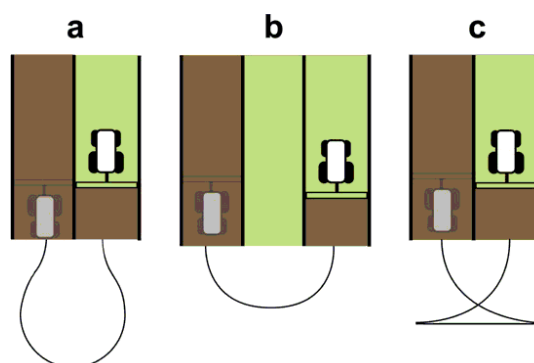


Figure 1. Examples of maneuvering options for turning and selecting the next track
(Vougioukas and Bochtis, 2008)

1.5 Merging path and turn planning

Bochtis and Oksanen (2009) also applied the concept to minimize outside-field work, using an approach that chooses the best next track in complex fields by splitting them previously and choosing the best entrance path in the created subfields.

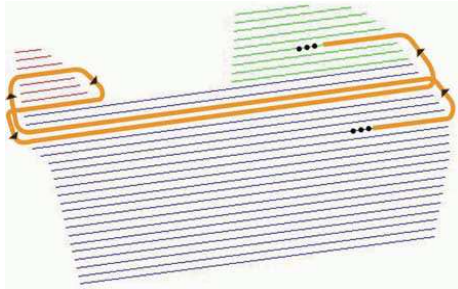


Figure 2. Choice of tracks for machinery route defined by splitting the field and choosing the faster global maneuvering option. Bochtis and Oksanen (2009).

In a set of parallel tracks in a field (for e.g.) every time a operator finishes working a track, stays the problem of which coming track should he maneuver into. The problem is that the number of possibilities (or maneuvering options between the tracks) is very high, posing a Travelling Salesman Problem (TSP).

TSP is a problem faced by a traveler that have to visit a given number of locations for which the distances between them are known, aiming that the route sequence of visiting all the locations be the shortest as possible. When working fields, the same problem is faced by an machine operator that has a given number of tracks to be followed and have to choose which next track should be followed so that his final route is the shortest or less time consuming as possible.

The way in which this problem was tackled by Bochtis et al. (2009) and Vougioukas et al. (2008) was by computing a cost for each turn option, based on the distance taken for each turn. The cost is calculated by the given turning properties, and the kind of turn that is going to be performed (like in Figure 1). Each end of a track is a node, and the relation with this node to others is defined by a cost, the linking of this nodes creates a net of options which is solved trough heuristics by a savings algorithm.

1.6 Servicing of machinery

As mentioned, some machinery working on fields require loading of agricultural inputs, like seeds, fertilizer or agrochemicals (see Figure 3b) or off-loading, such as the harvest (see Figure 3a). This operation is only possible with either a stop of the machine and it's relocation to a recharge/discharge location, or with the help of auxiliary machinery that goes to the specific spot where the field operation is executed. The latter is typically faster, but it requires an additional operator as well as auxiliary machinery. Both operations are known as servicing.



Figure 3. Example of servicing. In (a) an auxiliary grain transporter is used to offload a combine harvester on field and on (b) a sowing machine stopped near the border of the field waiting to be filled with seed.

Servicing has a significant impact on machine efficiency, as can be seen in Table 1.

Table 1. Efficiency and velocity rates for farm machinery. Coates (2002).

Machine	Requirement for loading/offloading	Field efficiency		Field Speed	
		Range %	Typical %	Range km/h	Typical km/h
Molboard plow	No	70-90	85	5-10	7
Heavy-duty disk	No	70-90	85	5.5-10	7
Chisel plow	No	70-90	85	6.5-10.5	8
Field cultivator	No	70-90	85	8-13	11
Row crop planter	Yes	50-75	65	3-6.5	9
Self-propelled harvester	Yes	65-80	70	3-6.5	5
Potato harvester	Yes	55-70	60	2.5-6.5	4
Boom-type sprayer	Yes	50-80	65	5-11.5	10.5
Fertilizer spreader	Yes	60-80	70	8-16	11

In Table 1, the first column refer to the machine or equipment that is going to work, the second column refer to the necessity of servicing of this machine, columns 3 and 4 refer to efficiency of machinery in field (or how the percentage of the time that a machine spends in field doing the work it was developed to do in relation to the total time spent by the machine on field), and the last 2 columns refer to speed of the machine in field. Observe that two machines with similar field speed like the field cultivator and the fertilizer spreader have very different efficiencies on field, the first have a typical efficiency of 85% while the latter has 70%, this difference is explained by the time consumed for loading the spreader.

Oksanen and Visala (2007), in a second algorithm for path planning, called predictive and recursive method, considered the servicing of machinery. The algorithm uses the vertices of the field building the route by linking this vertices inside the field (on-line approach). A servicing spot is defined and the machine follows a route being built on-line, if the coming

segment to be followed will lead the machine to it's critical point (empty of full), a new route is calculated that includes a visit to the servicing point, one of it's results can be seen in Figure 4.

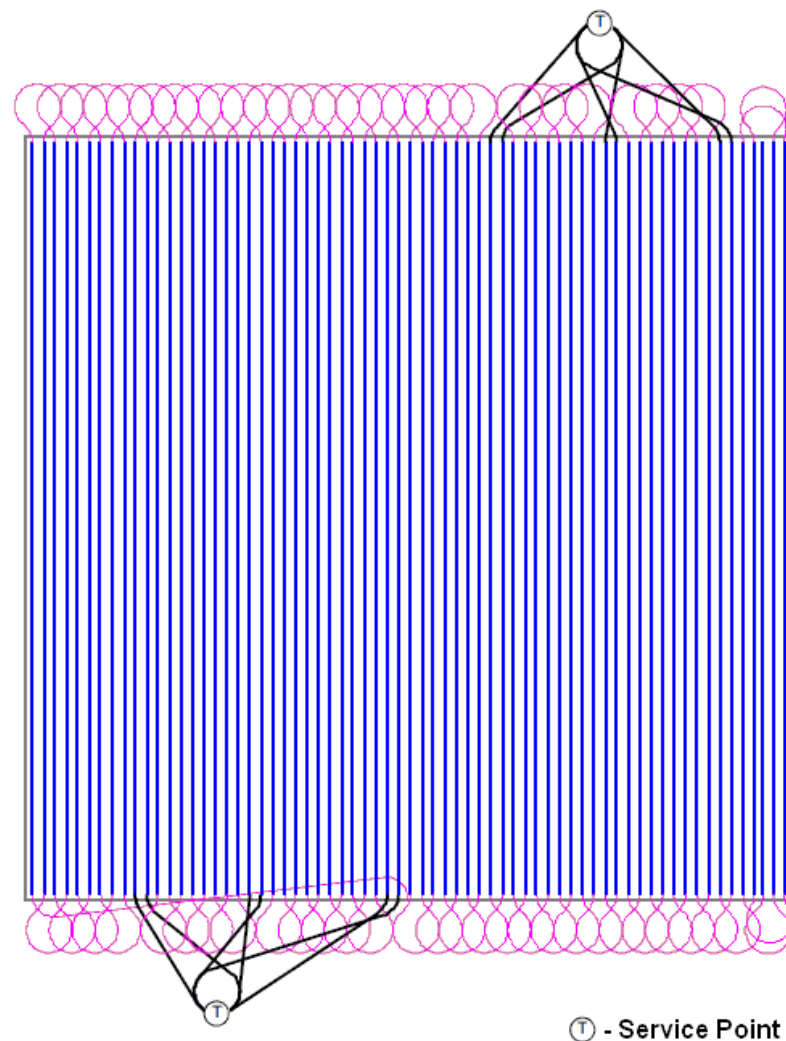


Figure 4. Rectangular field with two service points. The blue lines represent the path inside the field, the red ones the maneuvering in the edges of the land, the black thick lines represent the path into the service point (Oksamen et. al 2007)

The author concluded that the route can be changed when servicing is taken into consideration.

1.7 Problem definition

Studies implementation of path planning and coverage planning methods are available. For small fields, the number and performance of turns play a significance role, but in larger fields their influence on total efficiency is assumed to be less important, because the percentage of time required for turning is relatively small in comparison the time used for effective work on the field. On the contrary, the amount of time used for servicing increases proportionally to a

fields size. Neglecting servicing in route planning may lead to inefficient stops of machinery at very unsuitable locations in the field to be reloaded /offloaded or may require it to stop too often thus sub utilizing its capacity .

It's still required an algorithm that handles geometry of paths, with the routing along the paths with an accurate maneuvering, and also consider servicing trying to maximize the capacity of the machine by getting this one the as most empty/full as possible to a loading/offloading spot.

1.8 Main objective and research questions

The main objective is to reduce non-working time spend by machinery in agricultural fields by:

- increasing the efficiency of maneuvering, using methodology developed in previous work.
- increase efficiency of servicing of machinery by including servicing in the optimization of routes over the field.

The following research questions will be answered to achieve the above objectives.

1. Which are the machine and field properties that are important for planning field operations?
2. Which methods exist for coverage and path planning for field operations?
3. Given the need to incorporate loading, offloading and servicing in path planning, which method is more suitable for coverage and path planning?
4. How can the method be implemented in a computational algorithm?
5. How does the route change with fields that are different in shape and size?
6. How does the route change when turning and servicing are taken into consideration?

In this work adaptation of machinery to specific field geometry, the choice of machinery or changes to field geometry so as to avoid areas of inefficient maneuvering (de Bruin et al., 2009) are not considered. Rather the objective is to optimally cover a field using machinery with pre-defined properties. Different methods are available aiming optimization of field coverage each using sets of tools available. Approaches and tools for transforming given coordinates in topological vector data are available, like GDAL/OGR (OSGeo Foundation, 2009) and Matlab SOM Toolbox (Alhoniemi et al. 2005). Most approaches aim splitting of the field in more regular sub-fields reducing the number of maneuvers (Oksamen et al., 2007 and Jin et al. 2006, Ijken et al., 2009), minimizing the non-working distance in the maneuvers (Vogioukas et al., 2008).

2. Methodology

The methodology is first described with an overview of the issues related to the optimization problem, answering research questions 1 and 2; then the conceptual model gives a better understanding of the processes used, focusing in research question 3; and afterwards the implementation specifies how each process obtain the its results, in regard to research question 4. All steps and processes are related to the conceptual model that is presented in Figure 7.

2.1 Overview of optimization problem

The optimization aims to reduce the non-working time spent by a machine on field, in this thesis time is the objective function. Two non-working field operations are considered: maneuvering and servicing. Both conditions are related to the complexity of the field and also to the route that the machine will describe to cover it.

Description of field complexity and the ways in which it has been tackle by the authors have been previously described. In this thesis, a field plot is considered as a 2D uniform region.

In regard of machine properties, all the described authors used the width of the machine. This machine property is used: to obtain the distance between the tracks (Jin and Tang, 2006; Hofstee and Ijken, 2009; Oksamen and Visala, 2007; Taix, 2006; etc), to determine types of turning (Vougioukas and Bochtis, 2008), or determining the width of the headlands (de Bruin et al. 2009; Jin and Tang, 2006). In this thesis, all three approaches are used with the width property.

The turning radius of a machine is the radius of the arc followed by a machine based in the Ackerman steering (see Figure 5).

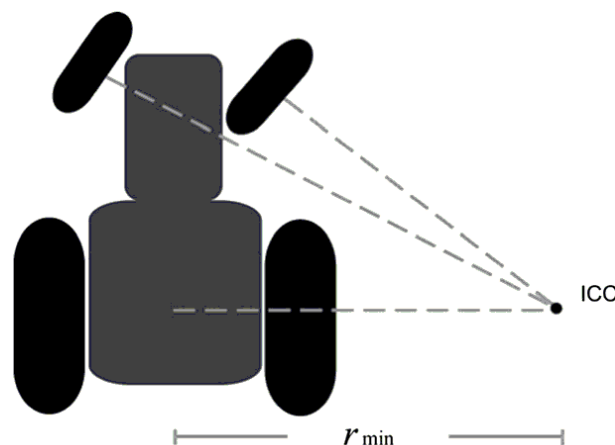


Figure 5. Turning radius using the Ackerman steering. ICC is the Instantaneous Centre of Curvature and r_{min} is the minimum turning radius. Extracted from Vougioukas et al. (2008)

In this thesis, the machine has to cover the whole field following a series of straight parallel tracks separated by the given width. The edges of the tracks, which from this point on are referred as nodes, must be placed at some distance from the border of the field giving room for the machine to perform it's turn, this room given for turning is defined as headland. Jin and Tang (2006) calculate this distance by a relation between the angle of the direction of the machine towards the border, Taix et al. (2006) uses a full width for this distance.

Bochtis et al. (2006) defines the minimum lengths for turning of machines in two patterns: Ω -turns (Figure 6a) and Π -turns (figure 6b), this lengths where calculated using kinematic equations of motion of a non-holonomic vehicle. Through this equations for lengths Vougioukas and Bochtis (2008) obtained a cost for turning and used this cost to define an optimal choice of nodes in turning for reducing non-working distance.

This thesis also considers this approach for connecting the nodes, but the performance of this turns are not calculated by equations, but by computing a path along coordinates through a sequence of movements performed by a machine (this is elaborated in section 2.2.3). This sequence of movements have specific speeds that, together with the calculated lengths between coordinates , allows to obtain the time spend for the whole maneuver.

In this new proposed approach, because of different sequence of movements of a machine, turning is considered only a part of the whole maneuver, and the word "maneuver" is taken as more accurate definition. The movement operation between nodes is, from this point on, referred as Ω -maneuver (instead of Ω -turn) and U-maneuver (instead of Π -turn).

The relationship between the turning radius and the width determines if a Ω -maneuver will be necessary. If the width is higher than twice the turning radius (or the turning diameter), than no Ω -maneuver is necessary.

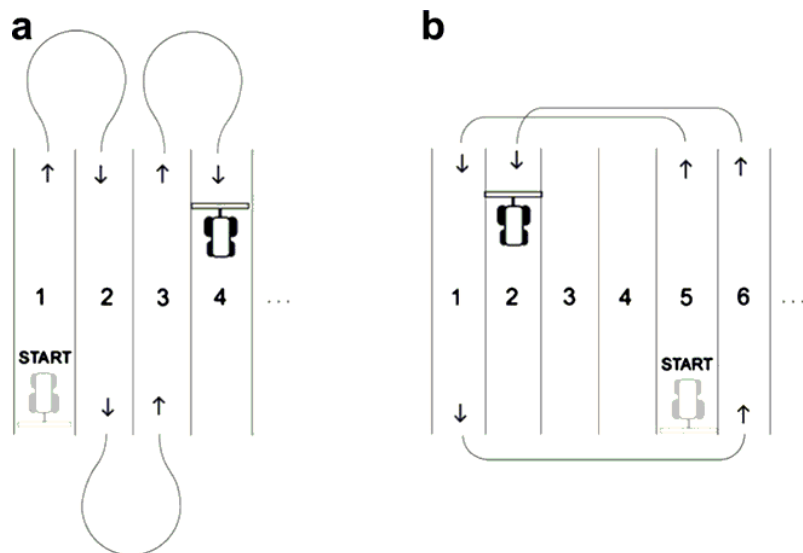


Figure 6. Headland pattern: (a) adjacent and (b) non-adjacent traversal; tracks are arbitrarily ordered from left to right. Extracted from Vougioukas and Bochtis (2008).

As it can be seen in Figure 6, the Ω -maneuvers are longer; optimization of choice of tracks increasing the U-maneuvers as done by Vougioukas et al. 2008 reduced the total maneuvering length, and it's here assumed to reduce the time spent in maneuvering.

The direction of work influence the number of tracks inside a field, lower number of tracks leads to less maneuvering and to reduced non-working time.

The refilling or emptying rate depends on the rate and tank size of machines. (Oksanen et al., 2007). The tank size or capacity of the machine holds a quantity (of product being distributed or space for storing yield) that decreases along with each track worked by the machine for a given rate.

The lengths of the tracks play a role for machinery that requires servicing during its course on the field. When a track is very long a machine may not be able to finish it's remaining capacity and the operator may wish (or be obliged) to perform the servicing at a previous node , i.e. before the machine's full capacity has been used.

The number and the length of the tracks, in agricultural fields, depend on the direction of work of a machine in it. By changing the direction of work, the length of the tracks also change and, for a given capacity and rate, a specific length of tracks may lead the machine to stay longer working and needing less stops for servicing, reducing the non-working time.

In this thesis, for each case study, the algorithm takes: the vertices of the field (field polygon); the width, the turning radius and the capacity (machine properties); and the rate (operation property) as static parameters. Additionally, a set of speeds are provided also as parameter for calculation of the time spend in the maneuvers and the working time (these speeds are also operation properties).

With this parameters, the complete route of the machine is simulated for different directions of work in the given field. Each simulation gives the maneuvering and the servicing time spend by the machine.

Figure 7 shows that in this work minimization of total non working time is considered to be achieved by optimizing two (sets of) properties :

- By the choice of sequence along the tracks to be followed by the machine, giving the total route (see Figure 6).
- By changing the direction with which tracks are laid out over the field, because it will influence the total number of tracks, the turn pattern and the length of the tracks.

2.2 Conceptual Model

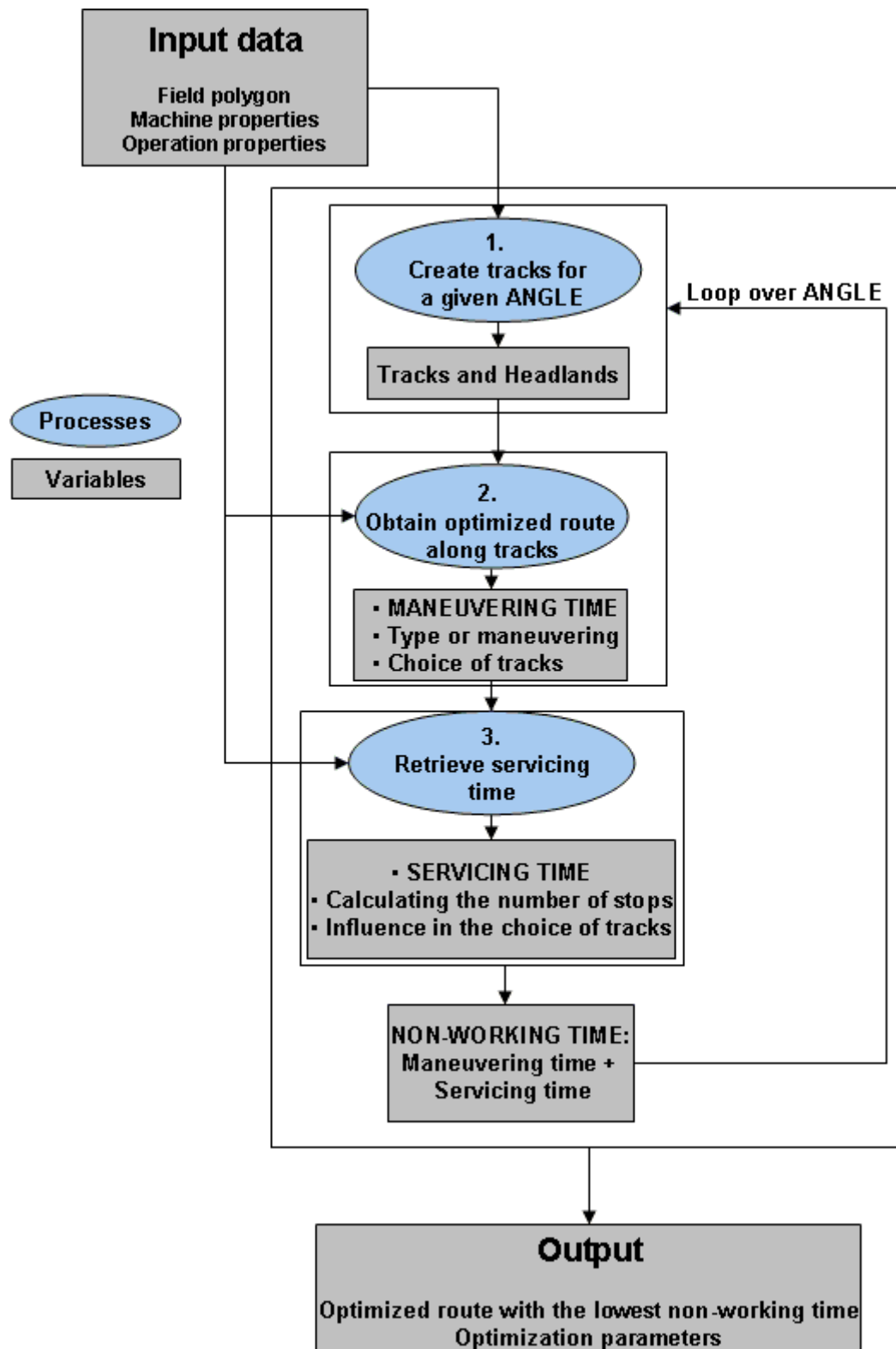


Figure 7. Flow chart of the main processes used in the algorithm for one given case study.

The conceptual explanation for the processes is explained in the following sub-sections.

2.2.1 Input data

As mentioned before, each case study is composed by the given input data parameters: field polygon, and machine and operation properties. The field and obstacle vertices are provided in metric coordinates. Machine properties (mentioned in previous section) of width, turning radius and capacity and operation the property rate are provided. The calculation of a maneuvering (see section 2.2.3 Obtaining optimized route along tracks) requires two speeds: turning speed and straight non-working speed. These speed parameters must also be provided along with the working speed.

The angle determines the direction of work and is the only variable that is simulated in the route optimization for one given case study.

2.2.2 Creating tracks for a given angle

This section corresponds to the process 1 in Figure 7.

Initially a headland is created. Headland is the area between the nodes of tracks and the border of the field required for the maneuvering of the machine. Headlands can be created by a buffer inwards a field or outwards an obstacle that keeps the machine working inside the field thus avoiding collision with the borders and/or the obstacle.

The calculation of the distance of a headland from the border uses the machine properties width and the turning radius of a machine, and it is influenced also by the direction of work of the machine on field.

The width is used to create a space for the machine to move along one track and another near the border of the field, this can be seen later on in Figure 10, where the 'Machine maneuvering limit' is separated from the border of the field by a distance of halved width. For the turning space the calculation considers the angle between the direction of the machine towards the border (like in Figure 8) and the turning radius.

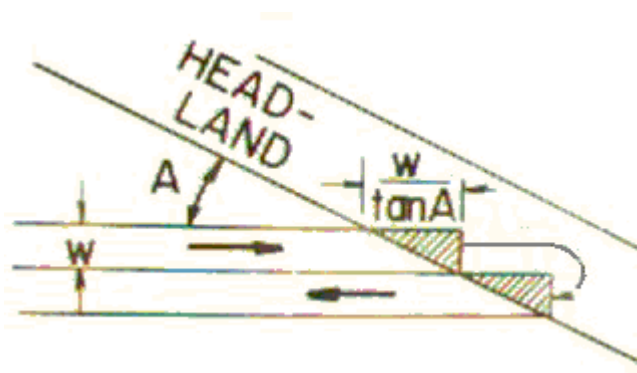


Figure 8. Direction of work influencing the size of a headland required for turning. 'A' is the angle between the direction of work and the border and 'w' is the width. Extracted from Jin and Tang (2006).

In this thesis, the room for turning does not follow the exact approach of Jin and Tang (2006) in Figure 8, but uses the turning radius of the machine for retrieving the turning space required, an example of this turning space can be seen in Figure 10 in the distance between the nodes and the 'Machine maneuvering limit'.

Because of the relation of direction of work and border, the headland may differ for each side of the field. If no relation is found, meaning that if a border is not reached by any track, no headland is created. The relation of the direction of work towards the headlands can be seen in Figure 9.

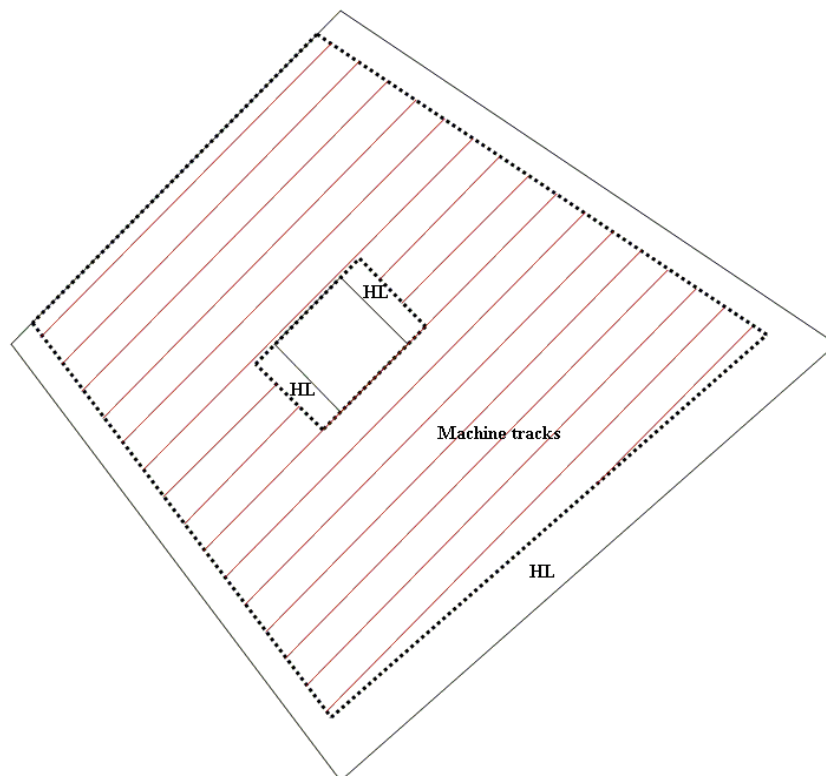


Figure 9. Headlands (HL) created inside a field with an obstacle.

The choice of this approach for definition of headlands leads to the creation of the minimum loss of area necessary for a machine's maneuver. This follows the practical choice of farmers for some operations of machinery in headlands, but does not take into consideration any kind of issues towards crops being grown in the headland area (like overlap of machine coverage). The use of fixed width, like done by Taix (2006), would be unsuitable for some farming operations for which the turning space surpasses the width of the machine (like ploughing for e.g.). Nonetheless the issue of definition of headlands was not the main focus of this work. The area taken for the headland is calculated and stored together with angle that defines the direction of work.

After a headland is retrieved for the main field, in the remaining inner area, a sequence of parallel tracks are created according to the given angle (see Figure 9). These tracks are separated in the distance given by the width (see 'w' in Figures 8). The tracks represent the

working pattern of the machine on field, and it's between the nodes of different tracks that the maneuvering of a machine will start and end. The number of nodes together with the heading of a machine towards the border will influence the number and the type of the maneuvers, which are essential for calculation of non-working time in this project.

The work on the track itself is not studied in this thesis, because is not related to non-working time. The working speed of the machine is only provided for a future calculation of machine efficiency (relation of working time with the total time spent to follow the whole route).

2.2.3 Obtaining optimized route along tracks

This section corresponds to the process 2 in Figure 7, it concerns with the maneuvering time spent by a machine and the ways in which this can be optimized.

For the optimization of the route, the approach of Vougioukas et al. (2008) is used. The cost of going from one specific node to all other nodes is obtained and stored; it mean that, for a set of calculated tracks (and nodes), the cost for going from one node to any other is known. In this thesis, the cost is the time spent by the machine to maneuver from one node to another.

As mentioned in section 2.1, two types of maneuvers are considered: U-maneuver and Ω -maneuver. The sequence followed by a machine to do each of them follows:

I. U-maneuver

The U-maneuver is defined by the following steps:

1. The machine, as soon as it finish it's working track, continues straight in the direction of the track (see segment "a" in figure 10), until it starts the turn. This step is not always necessary; sometimes the machine may start the turn immediately after it finishes a track.
2. The machine turns, in a circular pattern to left or right, until it reaches the machine maneuvering limit. This step is represented by the segment "b" in Figure 10.
3. The machine follows along the machine maneuvering limit until it starts a turn towards a new track (see segment "c" in figure 10). This step is not always required, because the machine may move to a track that is adjacent to the one just finished.
4. The machine turns, also in circular pattern, until it heads in the direction of the next track that is going to be worked. This step is represented by segment "d" in Figure 10.
5. The machine moves straight in the direction of the node where the working track will start (see segment "e" in figure 10). This step is not always needed as the machine may reach the node right after it finishes turn "d".

In the steps 1,3 and 5 the machine is moving (mainly) straight in a specific speed, which may differ from the turning speed in the steps 2 and 4, this speeds are given as parameter as a machine property. Distances for the straight pattern are summed, likewise for the turning pattern. The speeds together with the distances gives the total time for one maneuvering.

One example of a U-maneuver can be seen in Figure 10 where the combination of segments from “a” to “e” are displayed:

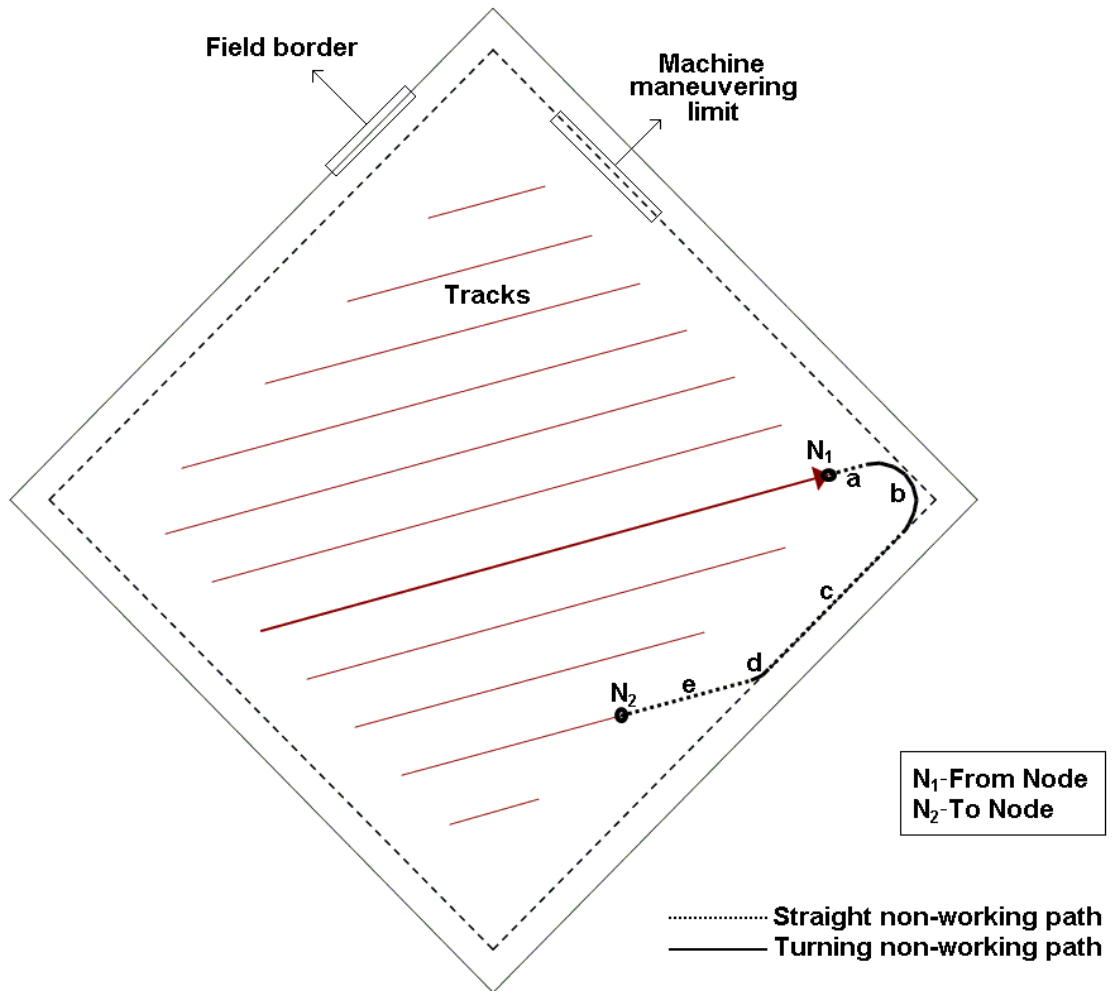


Figure 10. U-maneuver performed by a machine going from node N_1 to node N_2

II. Ω -maneuver:

The Ω -maneuver is defined by the following steps:

1. The machine, as soon as it finish it's working track, continues straight in the direction of the track (see segment “a” in Figure 11), until it starts the turn. This step is not always necessary; sometimes the machine may start the turn immediately after it finishes a track.
2. The machine turns, in an almost circular pattern to left or right, until it reaches the direction that heads to a another node. This step is represented by the segment “b” in Figure 11.
3. The machine moves straight in the direction of the node where the working track will start. This step is not always needed because the machine may reach the node right after it finishes the turn.

The Ω -maneuver, in this work, disregards the border of the field because the headland is calculated based on U-maneuvers, the Ω -maneuver may trespass the border of the field because this turning requires a bigger headland. However a solution for this was not implemented in the current work.

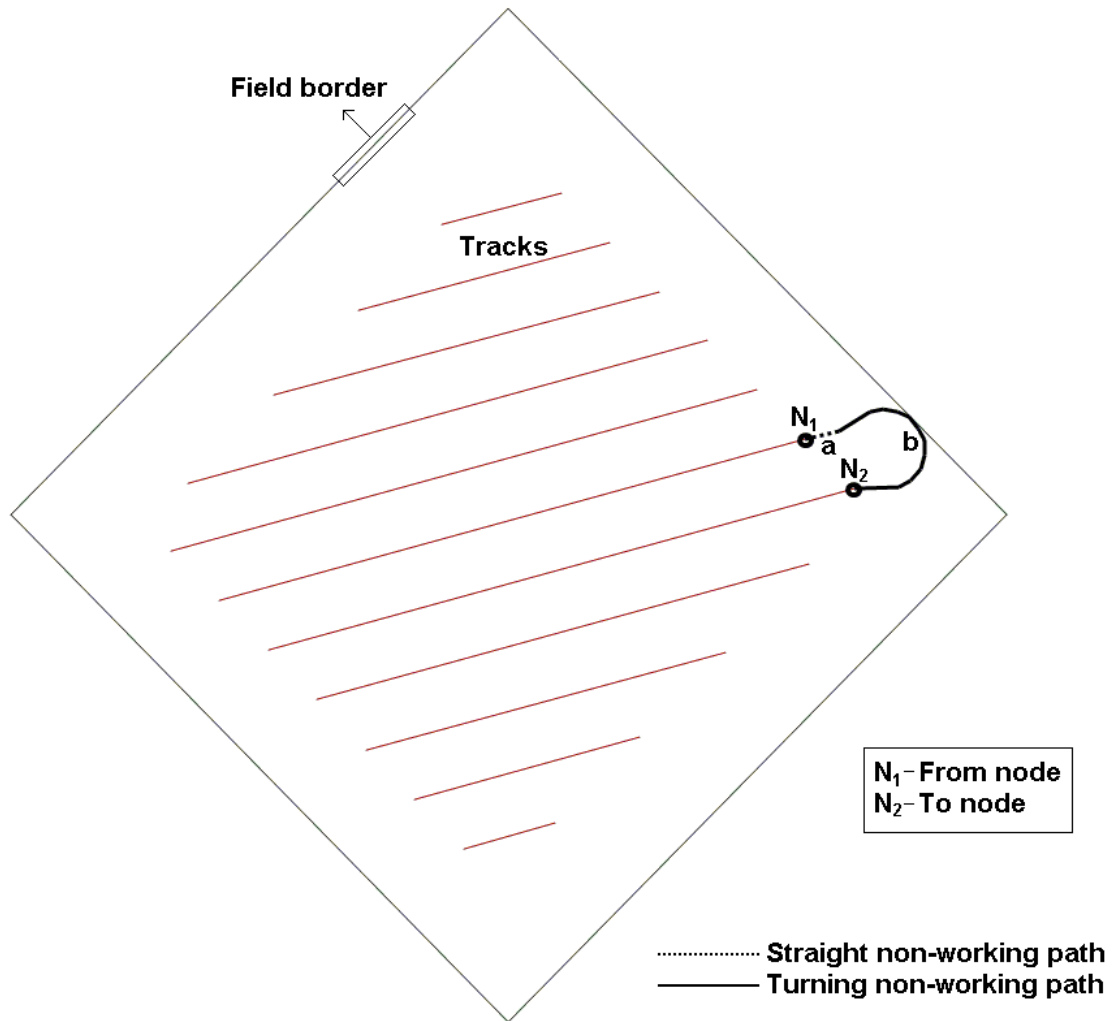


Figure 11. Ω -maneuvering performed by a machine going from node N_1 to node N_2 .

After the cost of maneuvering from one node to any other node is known. The optimization of the choice of tracks still has to be solved. The complete number of options to follow all the tracks in a field is a permutation on the number of tracks.

Optimizing the choice of tracks

This problem was solved through a heuristic approach, using a savings algorithm that retrieves an optimized route. The amount of time required for an exhaustive research, or a study of the complete set of options for all permutations, is very high for the majority of fields (because of the number of nodes). Although heuristic solutions cannot be proven to give the most optimal solution, they are typically able to generate relatively good solutions with very high savings in processing time in comparison to the exhaustive research.

A modified approach of Clarke-Wright, also used by Vogioukas and Bochtis (2008), was applied as a savings algorithm.

The Clarke-Wright savings heuristic (Clarke-Wright or simply CW for short) is derived from a more general vehicle routing algorithm due to Clarke and Wright [1964]. In terms of the TSP, we start with a pseudo-tour in which an arbitrarily chosen city is the hub and the salesman returns to the hub after each visit to another city (Johnson et al., 1995).

Golden et al. (1980), comparing heuristic approaches for TSP, obtained for a 5 sets of 100 nodes to be visited, a range of 1,62% to 6,37% of above the best known solution to visit all of them for the Clarke-Wright solution. The author mentions that the results for a lower number of nodes (25, 42 and 70) worked well despite its simplicity, and concluded that CW tour construction should be utilized when a reasonably effective solution is desired.

In this thesis, no other heuristic approach was tried to solve the TSP, nor was enough time to do an exhaustive research to validate the any end result.

In CW savings algorithm, from a given starting point to locations to be visited, the cost of covering is initially calculated in two routes:

1. Going from the starting point to an specific first location and back, and afterwards going from this starting point to a second location and back;
2. Going from the starting point to the first location, from this first location to the second location, and from the second location back to the starting point;

The difference found between the cost to cover both routes gives the saving obtained by the short-cut.

An illustration of the concept can be seen in Figure 9:

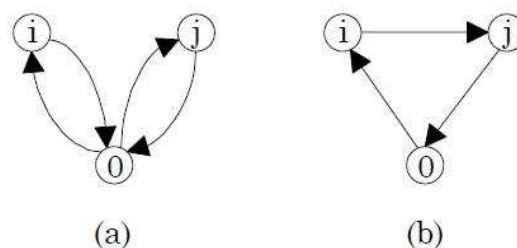


Figure 12. Two routes are calculated: a long route (a) that visits two nodes and returns to the origin after each visit, and a shorter one (b), that goes from the first node to the second before returning to the origin. (Extracted from Lysgaard, 1997).

The algorithm uses a modified approach, because while in the classic Clarke-Wright the start and end nodes are the same (in Figure 12 both are '0'), the algorithm uses different start and ending locations to calculate the savings. In comparison to Figure 12b, the modified approach would be: start \rightarrow i \rightarrow j \rightarrow end, so the machine can start (or enter) in one location of the field and end (or leave) in another location.

This process is repeated to all pairs of nodes, and the value of savings is stored for each of them. The savings are ordered from the largest to the smallest and the choice of nodes follows the sequential approach of Clarke-Wright (Lysgaard, 1997), in which only one sequence is built using always the higher savings found.

While the route is being built the cost for the optimized maneuvers are summed until the route uses all the tracks, afterwards the cost is summed into the maneuvering time (see Figure 7, "MANEUVERING TIME") stored together with the respective angle that defined the direction of work.

2.2.4 Servicing

This section corresponds to the process 3 in Figure 7.

When a machine follows a route, it is depleting its capacity at a given rate; for each track followed an area is covered and the respective amount of product is decreased from the machine's capacity. In this work, before a next track is entered a calculation is done to check if the remaining capacity is sufficient for completing that track. If the quantity required to work the next track, is more than the remaining capacity of the machine, then servicing is required and the machine must stop at the end of the track.

In this work, an optimizer for servicing was built that overrules the optimization of maneuvers to use more efficiently the remaining capacity of a machine's tank. The work of this optimizer can be seen in the difference in the choice of tracks in the Figure 13.

The optimizer is based on the work done by Clarke and Wriqth (1964) where a truck is attending the demand of different locations during its route; every time the truck is emptied, it must return to the depot to be loaded again and continue an optimized route. Their savings algorithm does not only optimizes the route to be the shorter, but also to use the capacity of the delivering truck to return as most empty as possible to the depot; it verifies if it's worth to visit a location with a demand that will get the truck as most empty as possible, even if this location is not in the best one to be visited in the sequence of shortest route.

In this thesis, this optimization was based on the capacity of the machine on field, and the demand was based on the length of the tracks.

In the Figure 13a, the algorithm is optimizing the route along the tracks while depleting the capacity of its tank; when the algorithm observes that the coming track (in this case track number 6) is too long for it's remaining capacity, the algorithm defines that the machine must be served before continue to its route. However in Figure 13b, when the optimization for servicing is considered and, when is predicted that the next track is higher than the remaining capacity the algorithm searches for a next closer track that is short enough to allow the machine to use it's remaining capacity; observe that the next track is skipped in comparison to Figure 10a, and that the servicing point and the sequence of tracks are changed.

When a machine is served, its capacity is fully restored to continue following the route.

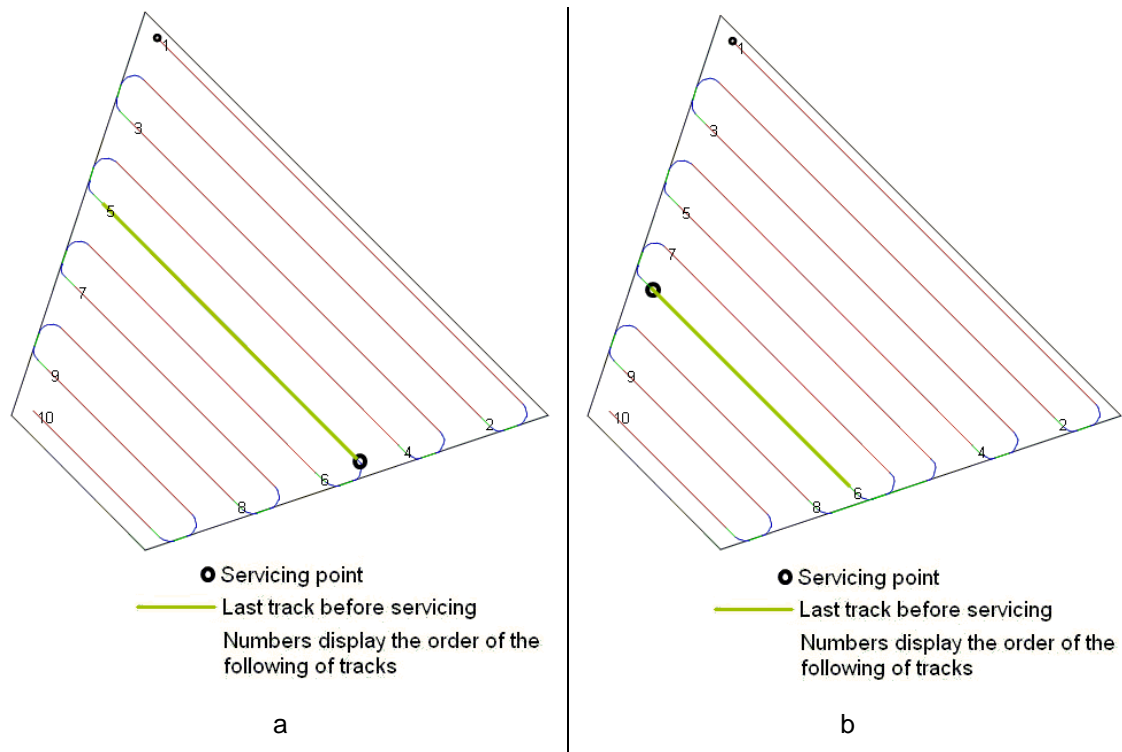


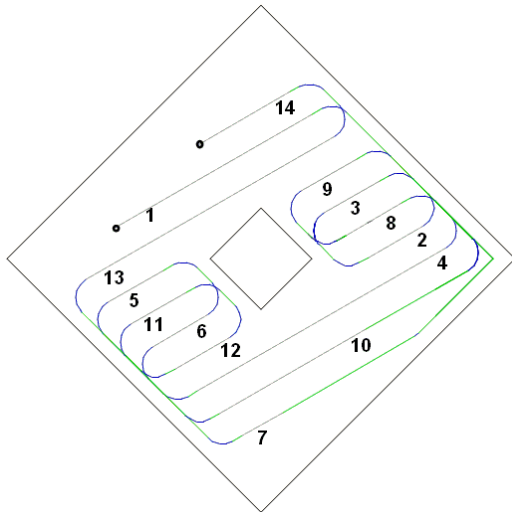
Figure 13. Example of optimization of servicing.

In this work, servicing is allowed to occur at any border of the field. There is no consideration of static servicing, meaning that the machine does not move outside its route to be served.

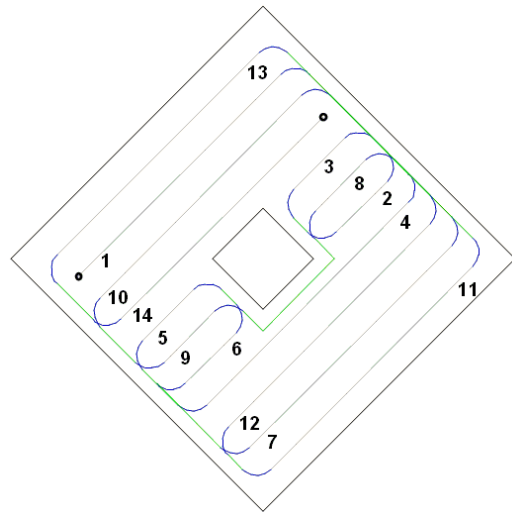
The number of times the machine is served when a complete route is followed is kept. This value is multiplied by the time taken for a machine to be served once, giving the total servicing time (see Figure 7, "SERVICING TIME").

2.2.5 Looping over angles

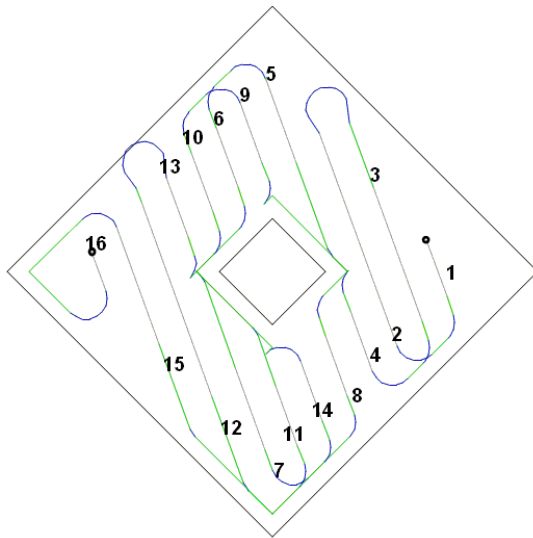
The total turning time and the total servicing time are stored with the specific angle (direction) simulated. The headland area is stored as a sub-result of the algorithm. The algorithm loops into a new angle in 1 degree steps until 180 degrees are tried (see Figure 7 "loop over ANGLE"). In Each loop the value of the non working time as well as other variable values are stored. When the loop is finished, the lowest non-working time is chosen and the simulation is displayed. One example of retrieved optimization parameters while the looping occurs can be seen in Figure 14.



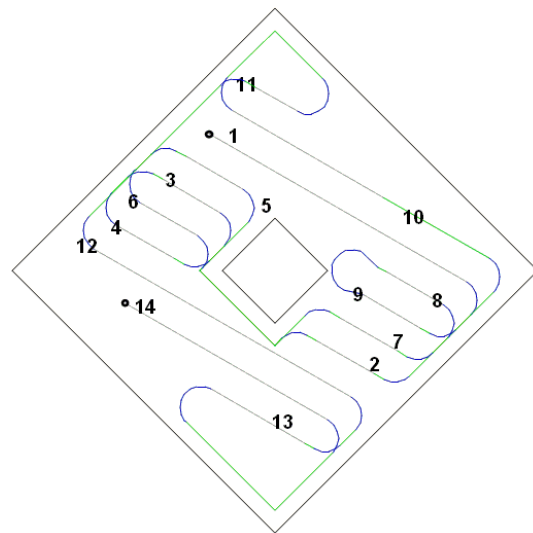
30 degrees angle
7,83 minutes maneuvering



45 degrees angle
8,61 minutes maneuvering



110 degrees angle
9,34 minutes maneuvering



150 degrees angle
7,92 minutes maneuvering

Figure 14. Example of routes built for a given case study while the angle is being looped and retrieving of one optimization parameters (maneuvering time).

Figure 14 displays 4 routes from the 180 created by the algorithm for a given case study. Each route was created using the sequence of processes defined in Figure 7, meaning the an optimized choice of tracks was done for each of the routes created along with the change of direction.

2.3 Implementation

This section is related to research question 4. In here, first there is a description of where and how the data was analyzed and interpreted by the algorithm and also of tools that are used by many processes after, and later it describes the specification of how the processes of previous section are worked by the algorithm.

2.3.1 The environment for data analysis, interpretation of the data by the algorithm and tools used along the processes.

Environment for data analysis

A program was developed in Microsoft Excel© spreadsheet using Visual Basic macros. Excel is a powerful program with a friendly user interface tool for data analysis, and the more advanced macro programming can easily interact with the spreadsheet. The routines and tools were entirely self-programmed, allowing a proper documentation, independence of third party programmed libraries, and possible correction of self-programmed routines.

All the input variables required by the program are given in a spreadsheet and, from there, read by the algorithm.

Interpretation of field data and intersection tool

The field and the obstacles are defined by a table of fixed metric coordinates, this coordinates are interpreted as points located in a Cartesian plane. Relationships between a point and the point next to it have to be obtained in order that this link can be understood by the program as a line. Below is given an example of how the points are related to each other and the properties that can be found from this relationship.

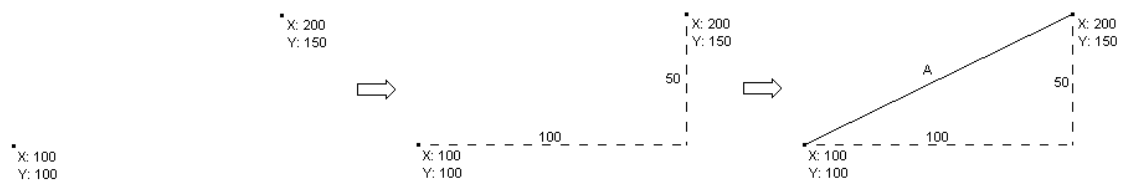


Figure 15. Example of a relation created between two points, creating a line.

From the example given in Figure 15, more information can be extracted from the line created between the points: like the length and the first order algebra function.

The length of the line, can be calculated using Pythagoras, which in this case will be approximately 111,8 meters, which is also the distance between those two points.

A first order algebra function: $y = ax + b$. The “a” value can be calculated by the division of the vertical distance (50 meters) by the horizontal distance (100 meters), which will result in “a=0,5”. The function is then defined as: “ $y = 0,5x + b$ ”.

If the origin of the line (x and y coordinates) are fed into the function so that the value “b” of the algebra function can be found:

$$y = 0,5x + b \rightarrow 100 = 0,5 \cdot (100) + b \rightarrow b = 50$$

So this line can also be seen as a function “ $y = 0,5x + 50$ ” limited by the two given coordinates.

In Figure 16, assuming that the previous given line “A” (of Figure 15) is the border of a field, and this line is going to be crossed by the path of a machine that is defined by line “B”. It is required the path to be limited by the intersection between lines “A” and “B”.

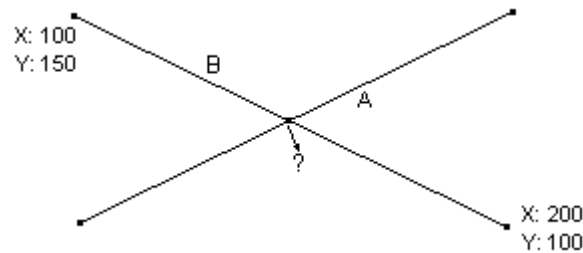


Figure 16. Example of a line “B” crossing the previous given line “A” of Figure 15.

Using the same previous calculation, the line “B” can be represented by a first order algebra function: $y = -0,5x + 200$.

If both functions are equaled:

$$0,5x + 50 = -0,5x + 200 \rightarrow x = 150$$

And this value “x” (150) found is fed into any of the functions:

$$y = 0,5x + 50 \rightarrow y = 0,5 \cdot (150) + 50 \rightarrow y = 125$$

The point (or coordinate) [150,125] is the intersection location point between them, so as the limit of the path for a machine.

Obtaining intersections is the main tool of this algorithm. It allows limits to be found for tracks, turns and also in other tools.

The relation and properties between the sequence of given vertices of a field (one vertice to the next vertice) are obtained and stored, and is because of this stored values that the field is recognized by all other tool functions of this algorithm.

Polygon offsetting tool

This tool is used for: defining headlands, defining the Machine maneuvering limits inside the field and the offset for the turning radius necessary to locate the central turning point for the U-maneuvers. This tool is also described by Oksamen et al. (2007) in the predictive recursive approach, wherein all the borders of the field are offsetted inwards or outwards by a given offset value.

This tool is also used to retrieve the orientation of the vertices of a field (clockwise or counter-clockwise). A value is used for offsetting all border to the left side, the difference in the area between the original field and the offsetted field leads to the answer of in which direction it

was fed into the algorithm. After this, the coordinates are re-ordered so that the field sequence of coordinates are in counter-clockwise direction and the obstacles within it in a clockwise direction. This is done so that when an offset border is demanded to be created on the left side of all borders, it will be inwards the field (because the orientation of the vertices are counter-clockwise), and outwards the obstacles (because the orientation of the vertices are clockwise). One example how the orientation influences the direction of the offset can be in Figure 12.

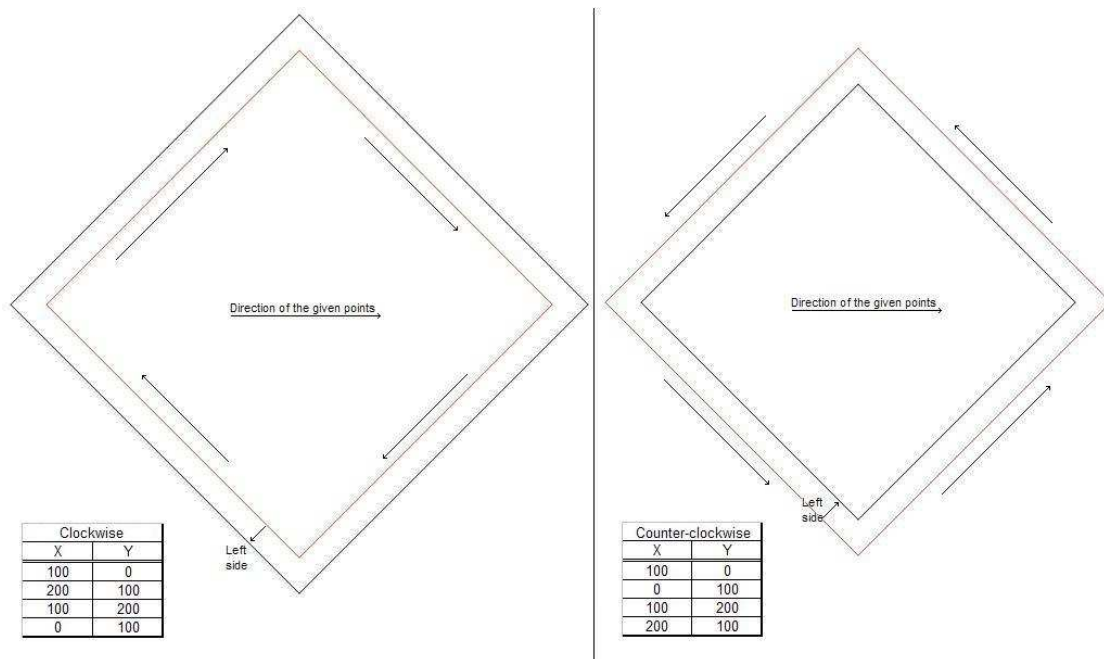


Figure 12. Consequence of an offsetting of borders of a polygon when the vertices are ordered in different sequence.

The values of a new offset field are stored inside a new position in the matrix, with all the attributes for the new borders.

The offsetting is widely used together with intersection tool to find if lines or points are inside the field or outside the field-polygon; for e.g.: one offset is created outside the field, when it intersects with a line, returns that this line (or part of it) is located outside the field.

Polygon perimeter distance tool

This tool is used when there are two points intersecting with a polygon (a field/obstacle or an offset of a field/obstacle), for which the distance between them, by following the polygon perimeter, is demanded.

It uses the location of two given points (X and Y coordinates) and the identification of the sides of the polygon in which these points are located. It starts with a point and goes through the vertices of the polygon, summing the distance between the vertices and finishing in the second point. The procedure tries in both directions: clockwise and counter-clockwise, returning the shortest of the directions tried between the two points.

This tool is used to find the straight distance between the end and the start of a turn (see distance 'c', Figure 10, section 2.2.3), which is essential to obtain, later on, the optimization

for maneuvering. An example of application of the polygon perimeter distance tool can be seen in Figure 13:

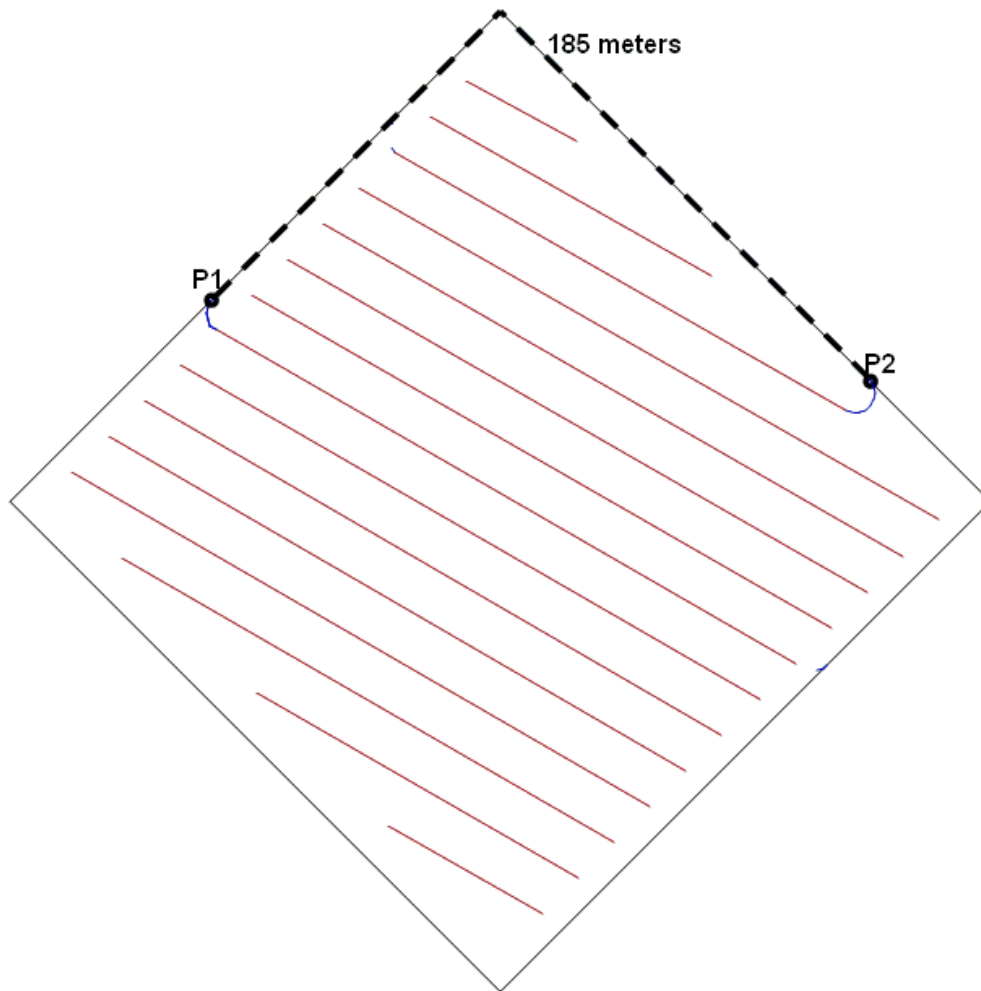


Figure 13. Example of distance retrieved on the border of a polygon for two given points (P1 and P2)

2.3.2 Creating tracks for a given angle

This section is related to process 1 of the conceptual model (Figure 7).

Creating tracks

Parallel tracks are created for a given angle, which is converted from degrees to a function coefficient and by creating sequences of functions that intersect with polygon sides, tracks are defined.

In the current implementation, tracks are assumed to start at the most western corner of the field. The direction of the track is the defined by the angle being simulated (see Figure 7, "ANGLE").

Creating headlands

To create one Headland, the offset tool is used (see section 2.3.1, polygon offsetting).

As explained before in section 2.2.2, the headland width for one border depends:

1. If the tracks are going to intersect with this border (if they are or not parallel to this border).
If tracks are parallel to a border, no headland for turning is needed near it.
2. If tracks intersect with the border, the relation of the angle of the track towards the border will determine the space required for turning (see Figure 8 in section 2.2.2).

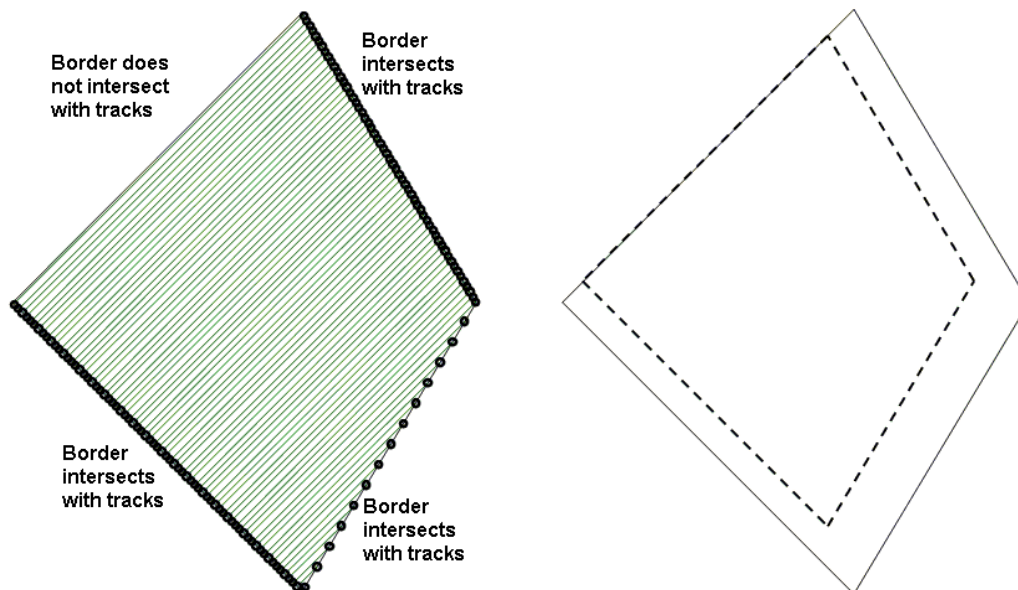
To find which borders of a field are going to be intersected by tracks, first a narrow coverage of temporary parallel tracks (1m apart), in the given angle (see ANGLE in Figure 7), are created in the whole field intersecting all the possible borders and, if a border is intersected by any of those tracks, the offset for the headland is calculated by:

$$(\sin(\text{Track_angle} - \text{Border_angle}) + 1) * \text{Turning_Radius} + \frac{\text{Width}}{2}$$

Where, Track Angle and Border Angle are given in radians.

Observe that three factors are being taken into consideration: the angle of the track towards the border, the turning radius of the machine, and the width. So all this three factors affect the size of the headland.

An example of the steps to create the headlands can be seen in Figure 14.



A set of very narrow tracks, in a given direction, is created inside the field. The black dots show where the tracks intersect with the border.

For borders being at least once intersected by tracks, an offset of the border is calculated, resulting in the headlands.

Figure 14. Example created by the headland tool. Observe that if a border is reached by no track on the given direction, no headland is created near that border.

2.3.3 Obtaining optimized route along tracks

This section is related to process 2 of the conceptual model (Figure 7).

Creating a U-maneuver between the nodes:

An offset of the field sides is made inwards creating the machine maneuvering limit with the room of half width. This offset is done to keep the whole machine inside the field during the maneuver.

Figure 15 shows an example of the steps followed to create a U-maneuver.

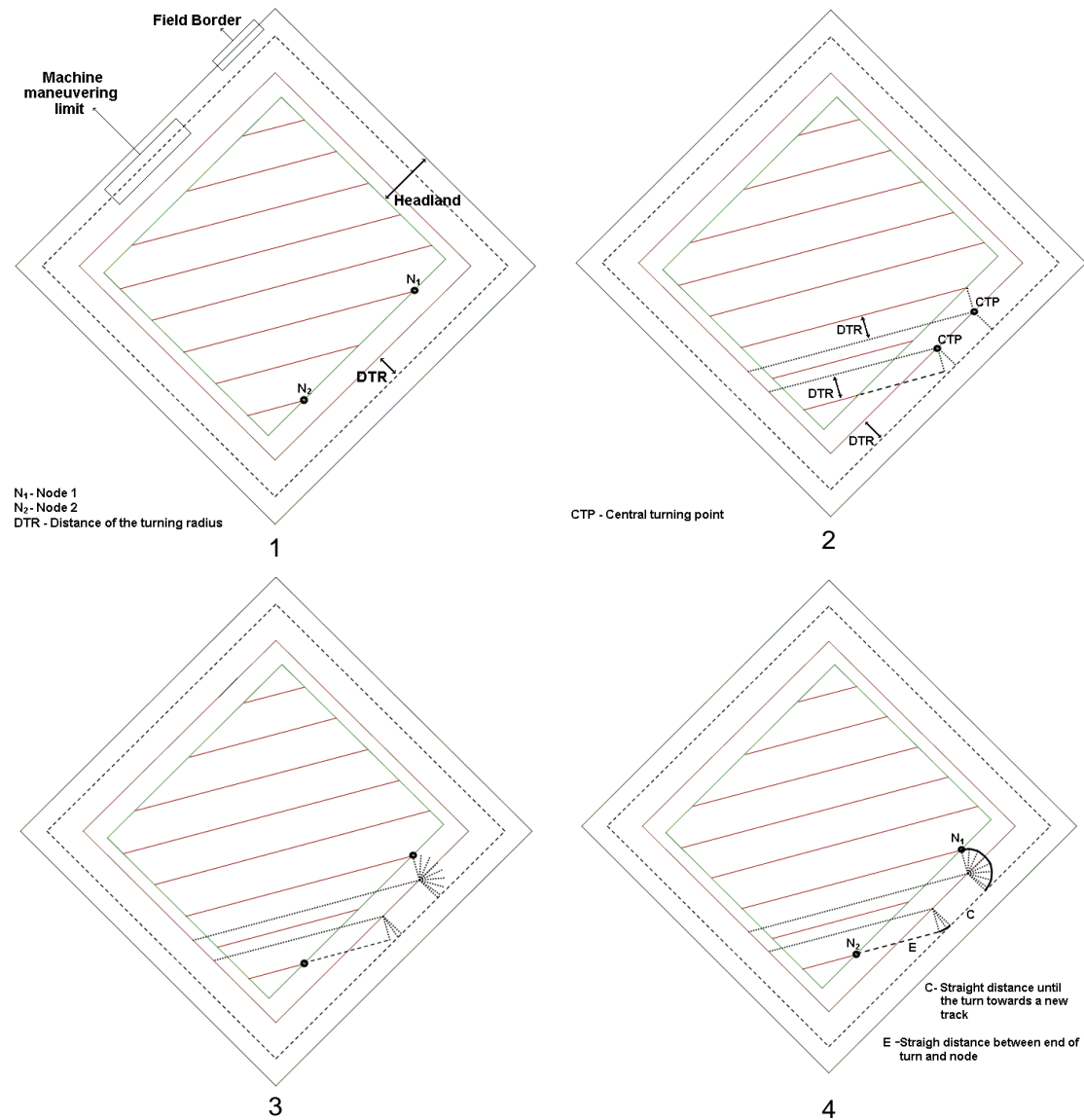


Figure 15. Steps used by the algorithm to create the turn patterns for the U-maneuvering.

As can be seen in Figure 15, step 4, the end of the turn is not always exactly at the node. In this maneuver, the steps 2, 3, 4 and 5 from Figure 10 (section 2.2.3) can be seen.

The distance between the turn that leaves a track until the turn that heads to another one (distance 'C' in step 4, Figure 15) is calculated by following the machine maneuvering limit. This distance is calculated by using the polygon perimeter routing tool, in which the two given

points (the end of the first turn and start of the second turn that intersect with the machine maneuvering limits) are used.

Creating a Ω - maneuver between nodes

Figure 16 shows an example of the steps followed to create a Ω -maneuver.

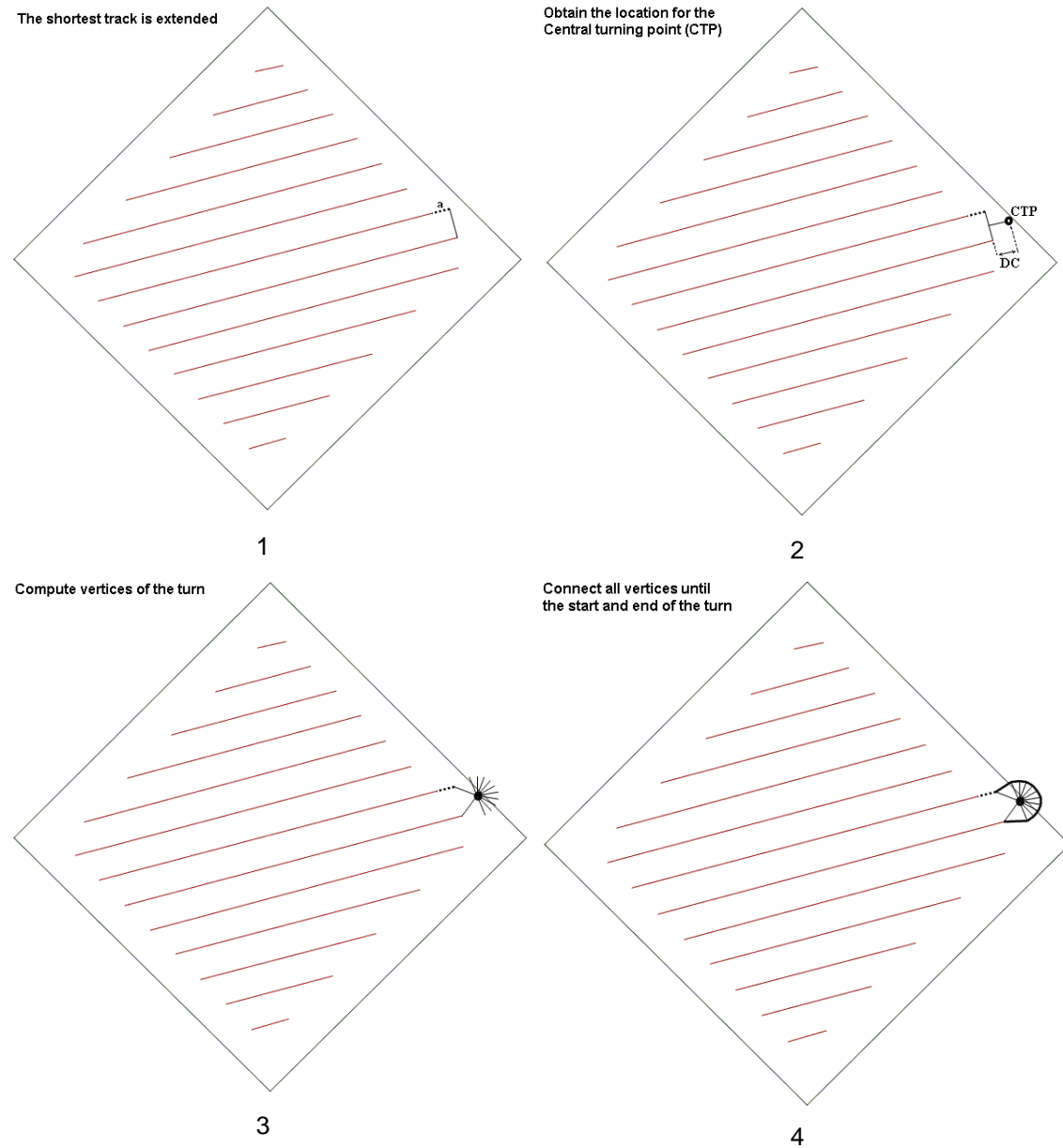


Figure 16. Steps used by the program to create an Ω -maneuver.

In Figure 16, in step 3, created by computing vertices of point along an arc which are 20 degrees separated. To avoid narrowing the angle for entering and the leaving the turn, the first and the last vertices are suppressed, given the Ω shape to the turn.

To calculate the Distance to Center:

$$DC = \sqrt{\text{Turning radius}^2 - \left(\frac{\text{Width}}{2}\right)^2}$$

Optimizing the choice of tracks

A sequence of calculations is done obtaining the cost from going from one node to all other nodes. When two nodes are located at a smaller distance than twice the turning radius, an Ω -maneuver between them is constructed, otherwise a U-maneuver is used to retrieve the distance. For each maneuver, a complete set of distances is retrieved.

As mentioned in section 2.2.3, the savings algorithm uses a given location from which savings are calculated between this location and all the nodes. Using the modified approach of Vougioukas et al. (2008), the savings were calculated between a start and end locations located on the vertices of the field.

An example of the process is given in Figure 17. This example is used to explain the CW savings algorithm.

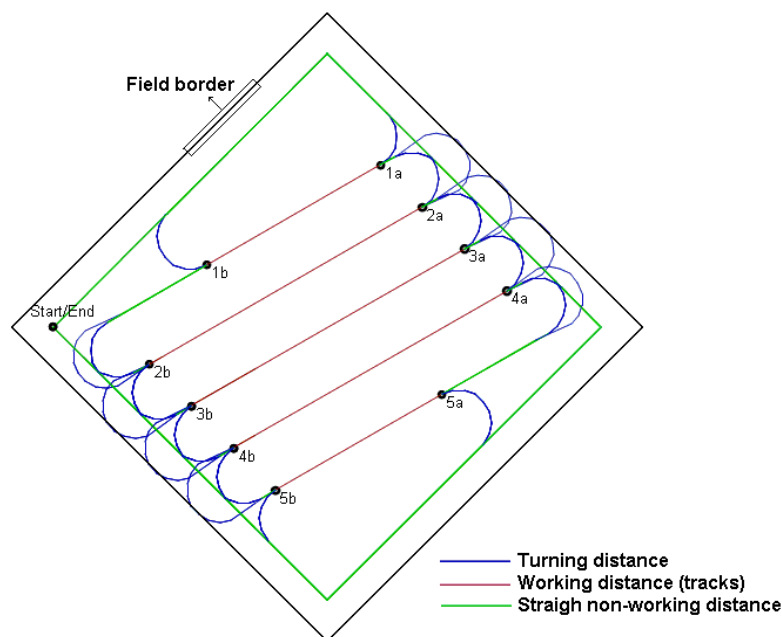


Figure 17. Example of a simple field with five tracks where all the nodes (black dots) are connected to each other. Each node has an identification of a number that represents to which track it belongs and a letter ("a" or "b") that identifies in which edge of the track this node is located.

In the example, to obtain the maneuvering cost, where used the speeds of 25 km/h for straight non-working time and 5 km/h for tuning.

Table 2 displays, in the first 2 columns, the origin and the destiny of the maneuver, columns 3, 4 and 5 display the distance and the type of distance followed by a machine during its maneuver, column 6 shows the kind of maneuver required (' Ω ' for a Ω -maneuver and 'U' for U-maneuver), and column 7 has the time spent for the maneuver calculated from the obtained distances and the given speeds.

Table 2. Table of linked nodes generated by maneuvers between all nodes for the example of Figure 16.

From	To	Straight Non-Working Distance	Turning Non-Working Distance	Worked Distance	Type of turn	Cost (seconds)
Start/End	1a	172.3	21.9	0.0	U	40.6
Start/End	1b	24.3	21.9	0.0	U	19.3
Start/End	2a	194.1	21.9	0.0	U	43.7
Start/End	2b	21.2	15.6	0.0	U	14.3
Start/End	3a	215.8	21.9	0.0	U	46.8
Start/End	3b	42.9	15.6	0.0	U	17.4
Start/End	4a	237.6	21.9	0.0	U	50.0
Start/End	4b	64.7	15.6	0.0	U	20.6
Start/End	5a	221.1	34.4	0.0	U	56.6
Start/End	5b	86.4	15.6	0.0	U	23.7
1a	2a	5.6	61.6	73.1	Ω	45.2
1b	2b	36.4	61.6	73.1	Ω	49.6
1b	2a	135.3	43.8	73.1	U	51.0
1a	2b	200.0	31.3	73.1	U	51.3
1a	3a	25.1	21.9	73.1	U	19.4
1b	3b	67.1	37.5	73.1	U	36.7
1b	3a	157.1	43.8	73.1	U	54.1
1a	3b	221.7	31.3	73.1	U	54.4
1a	4a	46.8	21.9	73.1	U	22.5
1b	4b	88.8	37.5	73.1	U	39.8
1b	4a	178.8	43.8	73.1	U	57.3
1a	4b	243.5	31.3	73.1	U	57.6
1a	5a	113.6	21.9	73.1	U	32.1
1b	5b	110.5	37.5	73.1	U	42.9
1b	5a	238.8	56.3	73.1	U	74.9
1a	5b	263.6	21.9	73.1	U	53.7
2a	3a	5.6	61.6	115.1	Ω	45.2
2b	3b	5.6	61.6	115.1	Ω	45.2
2b	3a	243.5	43.8	115.1	U	66.6
2a	3b	243.5	31.3	115.1	U	57.6
2a	4a	25.1	21.9	115.1	U	19.4
2b	4b	25.1	37.5	115.1	U	30.6
2b	4a	263.6	37.5	115.1	U	65.0
2a	4b	263.6	21.9	115.1	U	53.7
2a	5a	91.8	21.9	115.1	U	29.0
2b	5b	46.8	37.5	115.1	U	33.7
2b	5a	175.1	56.3	115.1	U	65.7
2a	5b	241.9	21.9	115.1	U	50.6
3a	4a	5.6	61.6	115.1	Ω	45.2
3b	4b	5.6	61.6	115.1	Ω	45.2
3b	4a	241.9	37.5	115.1	U	61.8
3a	4b	241.9	21.9	115.1	U	50.6
3a	5a	70.1	21.9	115.1	U	25.8
3b	5b	25.1	37.5	115.1	U	30.6
3b	5a	153.4	56.3	115.1	U	62.6
3a	5b	220.2	21.9	115.1	U	47.5
4a	5a	39.4	61.6	115.1	Ω	50.0
4b	5b	5.6	61.6	115.1	Ω	45.2
4b	5a	131.6	56.3	115.1	U	59.5
4a	5b	198.4	21.9	115.1	U	44.3

A table of costs is generated, which lists the time costs for each unique combination of a from node and a to node, see table 3 for an example.

Table 3. Table of costs (in seconds) for going from node to node from Table 2.

Node	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b
Start	40.6	19.3	43.7	14.3	46.8	17.4	50.0	20.6	56.6	23.7
1a			45.2	51.3	19.4	54.4	22.5	57.6	32.1	53.7
1b			51.0	49.6	54.1	36.7	57.3	39.8	74.9	42.9
2a					45.2	57.6	19.4	53.7	29.0	50.6
2b					66.6	45.2	65.0	30.6	65.7	33.7
3a							45.2	50.6	25.8	47.5
3b							61.8	45.2	62.6	30.6
4a									50.0	44.3
4b									59.5	45.2
End	40.57	19.25	43.7	14.31	46.83	17.44	49.96	20.57	56.6	23.7

In Table 3, the start and end locations for a machine to reach and leave the field are the same, and therefore, the costs for both to all nodes are the same. The nodes are never linked with another node in the same track.

From the cost table, a new table is generated using the Clarke-Wright approach (see Figure 12, section 2.2.3, optimizing the choice for tracks) retrieving savings calculated as follows:

1. $\text{Cost}(\text{Longest Path}) = \text{Cost}((\text{Start to Node1} + \text{Node1 to End})) + \text{Cost}((\text{Start to Node2} + \text{Node2 to End}))$
2. $\text{Cost}(\text{Shortest Path}) = \text{Cost}((\text{Start to Node1} + \text{Node1 to Node2} + \text{Node2 to End}))$
3. $\text{Savings} = \text{Cost}(\text{Longest Path}) - \text{Cost}(\text{Shortest Path})$

A savings table is generated, see table 4 for a worked out example.

Table 4. Savings obtained using the Clarke-Wright approach on Table 3.

	2a	2b	3a	3b	4a	4b	5a	5b
1a	-11.6	-17.8	17.3	-17.8	17.3	-17.8	10.9	-10.8
1b	-17.4	-16.0	-17.4	0.0	-17.4	0.0	-32.0	0.0
2a			-13.4	-25.8	15.5	-18.8	9.0	-12.6
2b			-34.8	-13.4	-30.1	4.3	-27.7	4.3
3a					-7.2	-12.6	15.3	-6.3
3b					-23.8	-7.2	-21.5	10.5
4a							-5.8	-0.1
4b							-15.2	-0.9

The savings are stored in the table of linked nodes and this is sorted in descending order in the example of Table 5.

Table 5. Values of savings added to the table of linked nodes, and sorted in descending order according to the savings..

From	To	Straight Non-Working Distance	Turning Non-Working Distance	Worked Distance	Type of turn	Cost (seconds)	Savings (seconds)
1a	4a	46.8	21.9	73.1	U	22.5	17.3
1a	3a	25.1	21.9	73.1	U	19.4	17.3
2a	4a	25.1	21.9	115.1	U	19.4	15.5
3a	5a	70.1	21.9	115.1	U	25.8	15.3
1a	5a	113.6	21.9	73.1	U	32.1	10.9
3b	5b	25.1	37.5	115.1	U	30.6	10.5
2a	5a	91.8	21.9	115.1	U	29.0	9.0
2b	4b	25.1	37.5	115.1	U	30.6	4.3
2b	5b	46.8	37.5	115.1	U	33.7	4.3
1b	3b	67.1	37.5	73.1	U	36.7	0.0
1b	4b	88.8	37.5	73.1	U	39.8	0.0
1b	5b	110.5	37.5	73.1	U	42.9	0.0
4a	5b	198.4	21.9	115.1	U	44.3	-0.1
4b	5b	5.6	61.6	115.1	Ω	45.2	-0.9
4a	5a	39.4	61.6	115.1	Ω	50.0	-5.8
3a	5b	220.2	21.9	115.1	U	47.5	-6.3
3a	4a	5.6	61.6	115.1	Ω	45.2	-7.2
3b	4b	5.6	61.6	115.1	Ω	45.2	-7.2
1a	5b	263.6	21.9	73.1	U	53.7	-10.8
1a	2a	5.6	61.6	73.1	Ω	45.2	-11.6
3a	4b	241.9	21.9	115.1	U	50.6	-12.6
2a	5b	241.9	21.9	115.1	U	50.6	-12.6
2a	3a	5.6	61.6	115.1	Ω	45.2	-13.4
2b	3b	5.6	61.6	115.1	Ω	45.2	-13.4
4b	5a	131.6	56.3	115.1	U	59.5	-15.2
1b	2b	36.4	61.6	73.1	Ω	49.6	-16.0
1b	4a	178.8	43.8	73.1	U	57.3	-17.4
1b	2a	135.3	43.8	73.1	U	51.0	-17.4
1b	3a	157.1	43.8	73.1	U	54.1	-17.4
1a	4b	243.5	31.3	73.1	U	57.6	-17.8
1a	2b	200.0	31.3	73.1	U	51.3	-17.8
1a	3b	221.7	31.3	73.1	U	54.4	-17.8
2a	4b	263.6	21.9	115.1	U	53.7	-18.8
3b	5a	153.4	56.3	115.1	U	62.6	-21.5
3b	4a	241.9	37.5	115.1	U	61.8	-23.8
2a	3b	243.5	31.3	115.1	U	57.6	-25.8
2b	5a	175.1	56.3	115.1	U	65.7	-27.7
2b	4a	263.6	37.5	115.1	U	65.0	-30.1
1b	5a	238.8	56.3	73.1	U	74.9	-32.0
2b	3a	243.5	43.8	115.1	U	66.6	-34.8
2b	3a	243.5	43.8	115.1	U	66.6	-34.8

The values of biggest savings are used first and every track once used is marked not to be chosen again.

The result of choice for tracks in following the sequential approach can be seen in Figure 18.

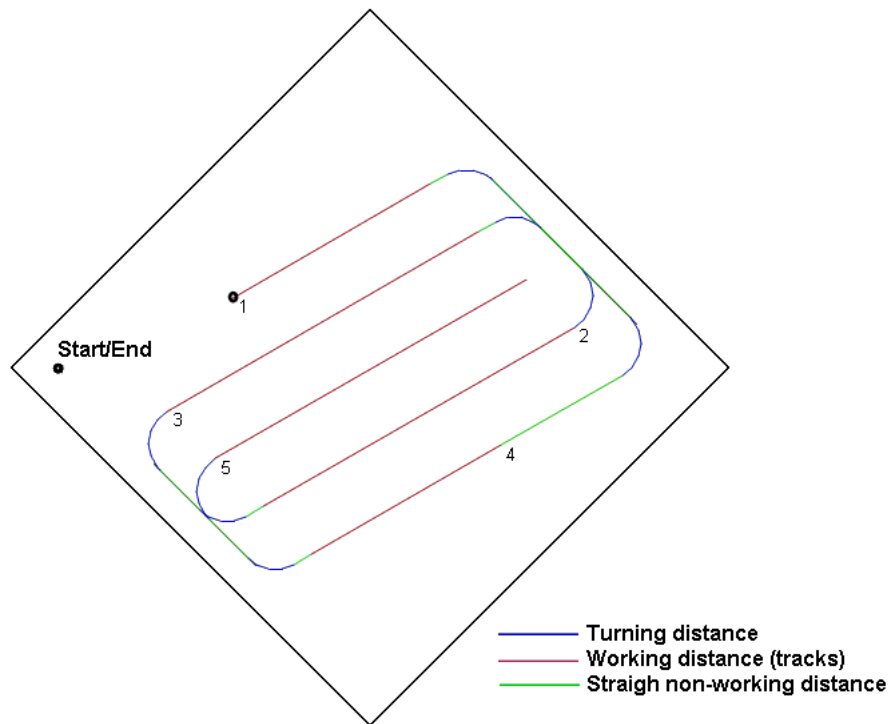


Figure 18. The outcome of the choice made by the savings algorithm. The numbers display the order and are located in the beginning of the track which the machine will follow.

Pseudo-Code

Box 1. Psedo-code that summarizes the approach of savings from the optimization

```

Load_Field
Load_Machine_Properties
Obtain_and_Correct_Field_Settings
Create_Headlands
Create_Tracks_In_Field
For i = 1 to AllNodes
    For j = i+ 1 to AllNodes
        If Distance_Between_Tracks < Turning_Radius * 2 then
            Connect_node_using_omega_turn
        Else
            Connect_nodes_using_U_turn
        Endif
        Node1 = i
        Node2 = j
        Store_in_Cost_Table
    End For
Next
For i = 1 to AllNodes
    For j = i + 1 to AllNodes
        Long_Cost = Cost(i to Start) * 2 + Cost(j to End) * 2
        Short_Cost = Cost(i to Start) + Cost(i to j) + Cost(j to End)
        Savings = Long_Cost - Short_Cost
        Store_in_Costs_Table
    End For
End For
Order_Costs_Table_By_Savings
For i = 1 to AllCosts
    If Track_Not_Used then
        Make_Maneuver_Between_Nodes(Costs(i,Node1), Costs(i,Node2))
        Mark_Track_as_Used
    Endif
End For

```

2.3.4 Servicing

This section is related to process 3 of the conceptual model (Figure 7).

The sequence of track to be followed are defined by the optimization of turning. In the table of linked nodes (e.g. Table 5), the length of each track is stored (see the column worked distance).

A variable stores the amount of product remaining in the machine. This variable reset with the value of the full capacity in the start and for every time it stops for servicing.

For each track followed the remaining capacity of the machine is decreased by the demand of the track. If the demand of the coming track surpasses the remaining capacity of the machine the algorithm, if requested, runs through all the table of costs trying to find the nearer track for which the demand will be lower than the remaining capacity and, if this one is found, it skips the longer track picks a maneuvering to the shorter one.

This is done only if the optimized servicing is requested in the algorithm, otherwise the algorithm will just keep the sequential choice of the shortest track but marking the required spots of servicing without optimization.

The use of the servicing optimizer was inconsistent for some of the tests done, therefore the optimizer was not considered in the example applications used to obtain results.

3. Example applications

Fields were extracted from the Google Earth™ software in a KML format with the coordinates of the vertices in UTM (Universal Transverse Mercator) format.

For interpretation of the route results, the angle found for best direction of work refers to the angle in degrees mentioned in the conceptual model (ANGLE, Figure 7), in which 90 degrees points to the exact north.

Three Dutch fields were selected nearby Wageningen University campus, these fields differ in complexity, are small in size and the farm machinery and operations chosen for them does not require servicing.



Figure 19. Location and identification of three fields located between the cities of Wageningen and Bennekom, Netherlands

In the three case studies, the machine settings were: a tractor pulling a heavy duty disk, with a width of 3 meters, a turning radius of 4 meters, a working speed of 5 km/h, a straight non-working speed of 8 km/h and a turning speed of 2 km/h was simulated in 180 different directions (angles). Field 1 has an area of 1,87ha; Field 2 2,92ha and Field 3 2,01ha.

3.1 Suitability of the chosen methods

This results obtained by the algorithm are related to research question 3.

The use of the approach for optimizing the choice along the tracks also found clear savings in maneuvering time; the results clearly shows that the algorithm chooses more U-maneuvers than Ω -maneuvers. Figures 20 and 21 shows the impact of the length maneuverings found for

the best direction of work (27 degrees angle), and Table 6 shows the computed time impact for the three case studies

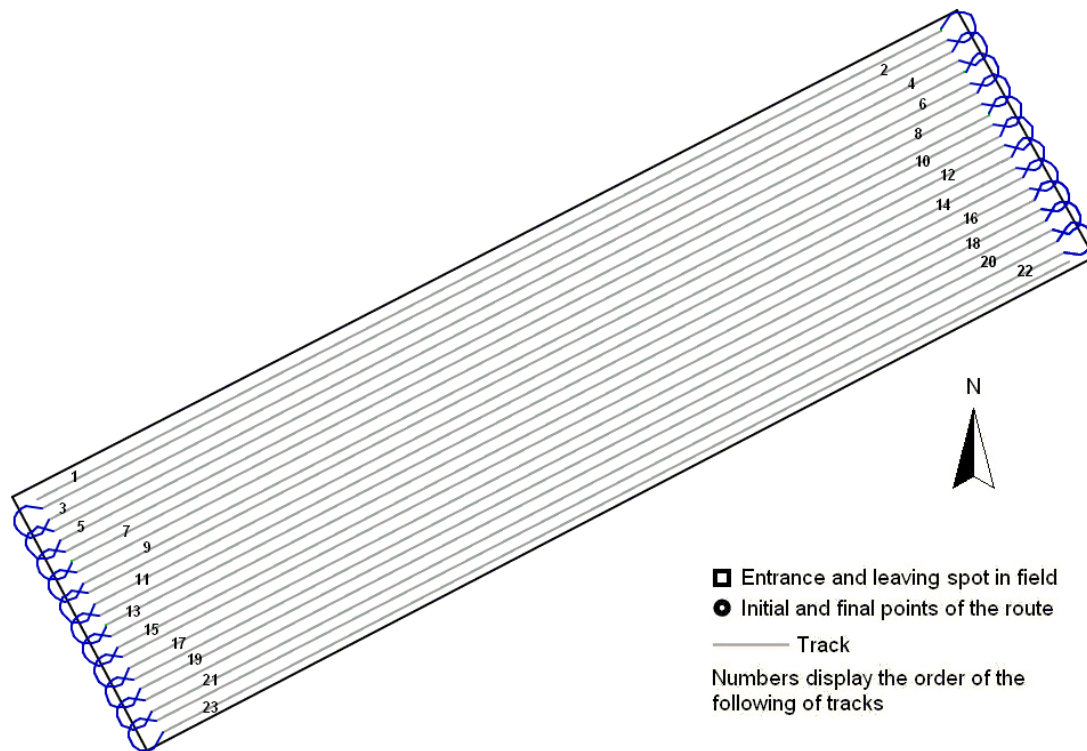


Figure 20. Case study 1 using standard Ω -maneuvers between tracks.

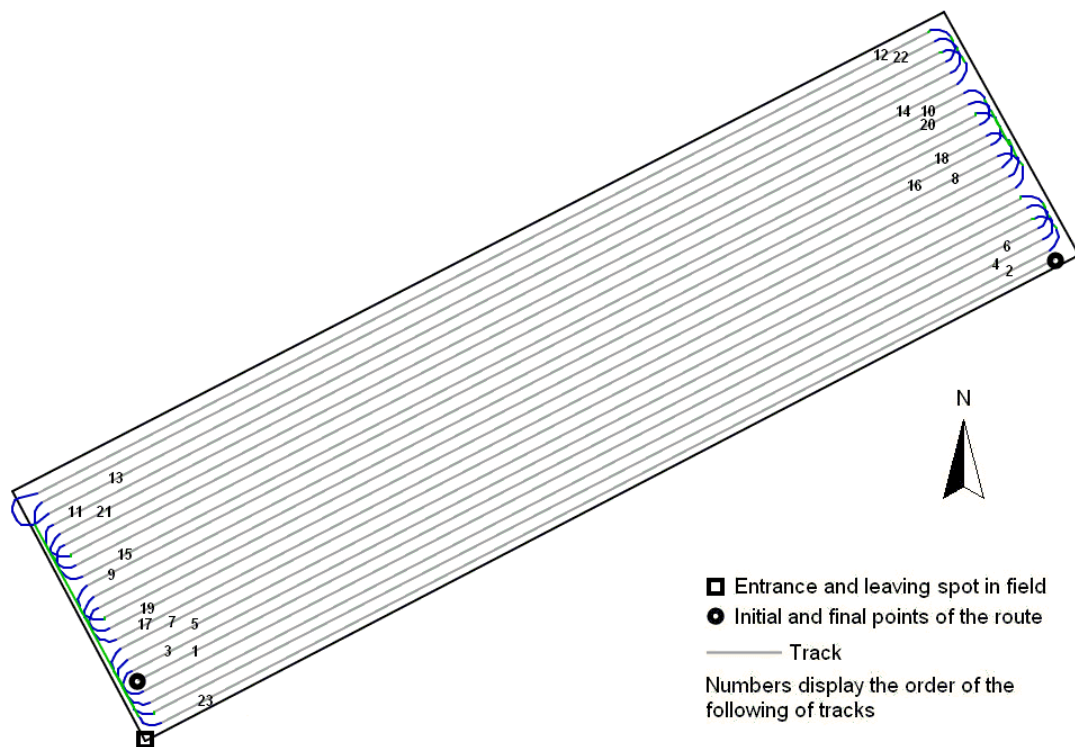


Figure 21. Optimal route found for case study 1, when optimization of time for choice between tracks was applied.

Table 6. Time required for maneuvering using only Ω -maneuvers between tracks or using the optimized choice of tracks for the given parameters of the case study in the optimal direction of work found for all three fields.

	Time spent for maneuvering (minutes)	
	Ω -maneuvers only	Optimized choice of tracks
Field 1	14.56	5.80
Field 2	40.58	19.00
Field 3	23.37	12.10

As mentioned previously, Ω -maneuverings in this thesis do not respect field borders, this issue have to be corrected in further work.

3.2 How does route change with fields of more complex shape

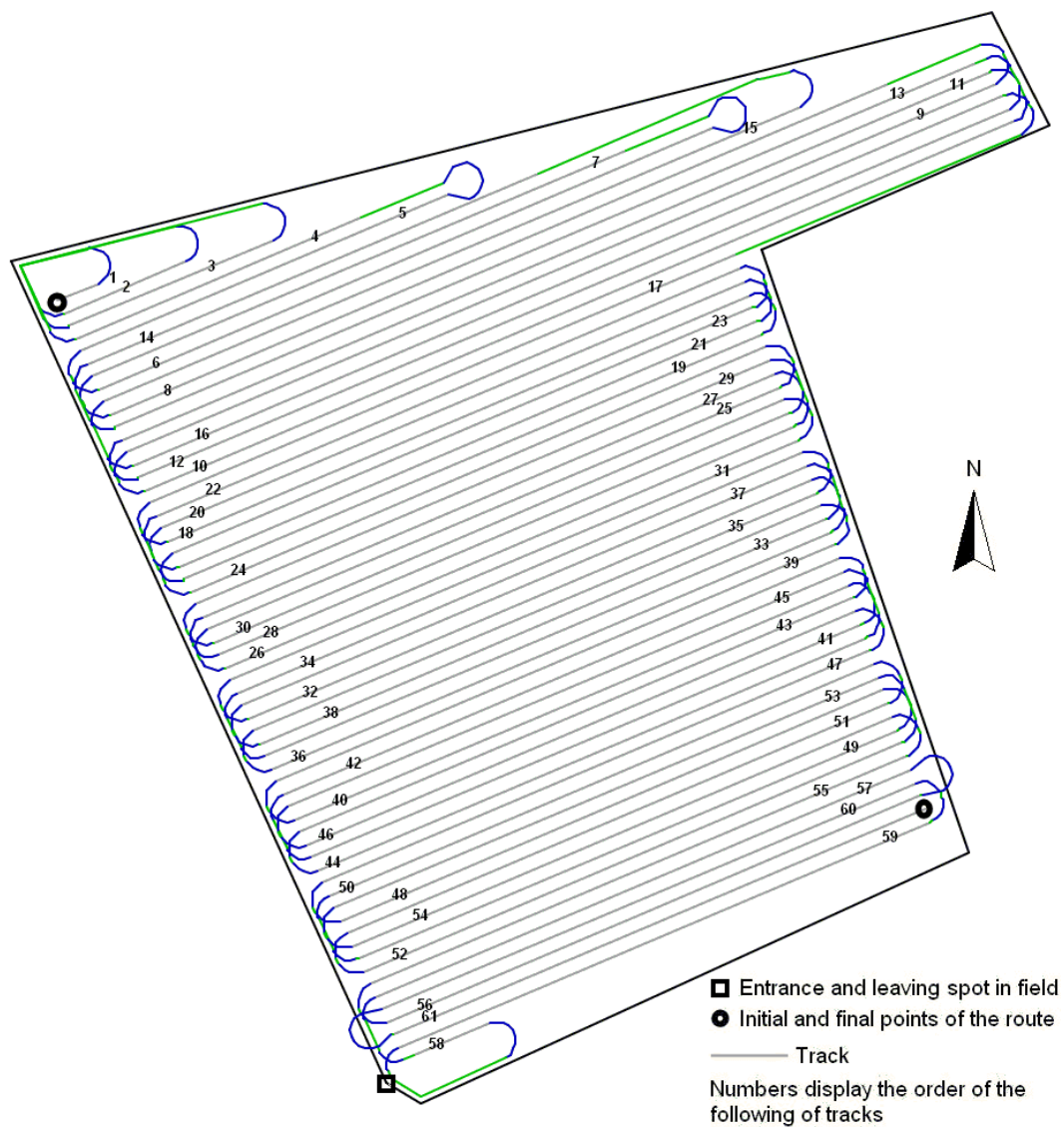


Figure 22. Optimal route found for case study 2.

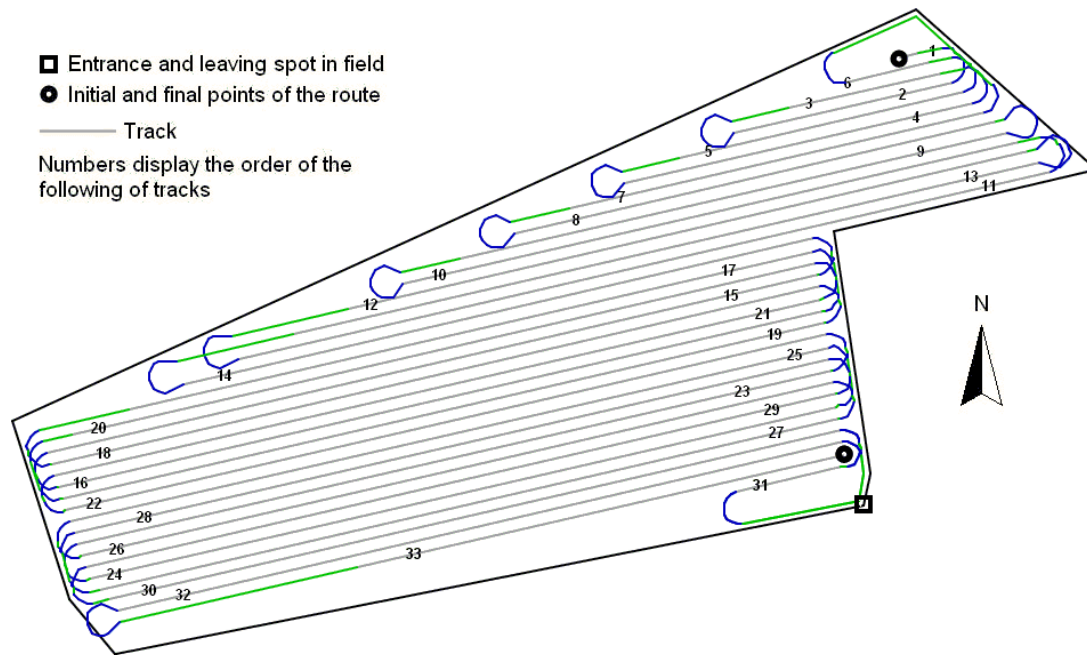


Figure 23. Optimal route found for case study 3.

Here is also shown that the algorithm tries to avoid Ω -maneuvers, but they are chosen sometimes depending on the angle that the machine heads towards the border of the field. When the angle between the direction of machine and the border of the field is too narrow, the nodes of the near parallel tracks are far away and, therefore, higher are the distances and time consumed to skip nodes, so the algorithm chooses nearer nodes even with Ω -maneuvers.

3.2.1 Exploring optimization of maneuverings for different directions of work

The algorithm creates a route for any direction of work chosen for a field, but its influence in maneuvering time is high. Figure 24 displays the results found for maneuvering time in relation to all directions of work tried for the three Dutch-fields case studies. Figure 25 displays the operational efficiency, or the fraction of time that the machine was working the tracks in relation to the total time spent on field (working time plus maneuvering time).

The range of maneuvering time in different directions was: for Field 1, between 5,8 and 31 minutes; for Field 2, between 19,1 and 45,6 minutes; and for Field 3, 12,1 and 33 minutes.

The operational efficiency was calculated only for main area of the field (means excluding the headland area), the range of efficiency in different directions was: for Field 1, between 63,8% and 92,2%; for Field 2 was between 67,1% and 83%; and for Field 3 was between 64,5% and 82,6%.

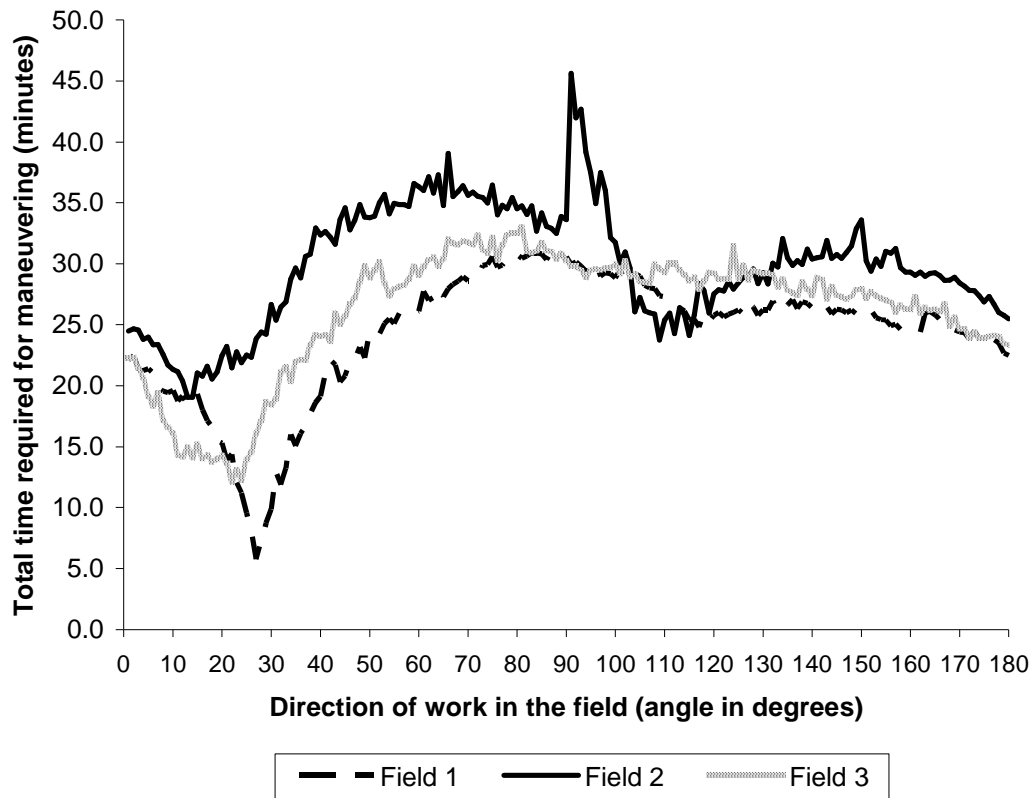


Figure 24. Maneuvering time (or total non-working time in this case), for different directions (angles) simulated in the three Dutch case study fields.

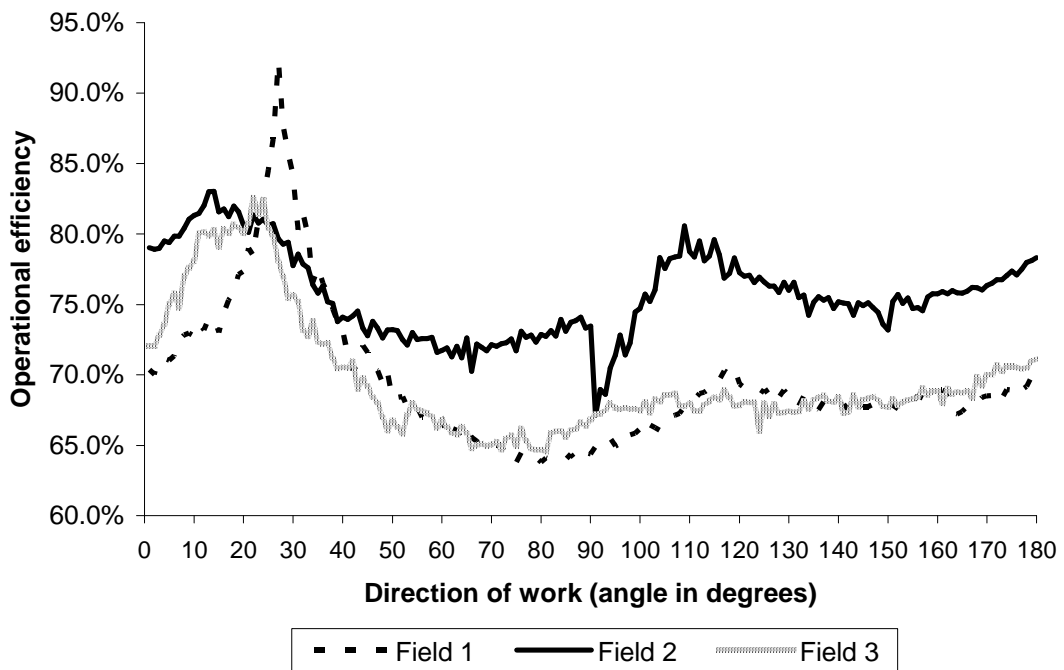


Figure 25. Operational efficiency, or fraction of time in which the machine spends doing what it was developed to do in field, for different directions (angles) simulated

The results found for the case studies in the graphs of Figures 24 and 25 do not aim to show any correlation between fields for the direction of work. Each field is a case with specific properties and, almost always, have a specific optimal direction that may not relate at all with the optimal direction of work for another case.

For the first case study, with rectangular shape, the best angle found agrees with the common sense choice for direction of work (for savings in maneuvers), showing that the algorithm is retrieving comprehensible results.

Figure 25 displays an opposite view of machine savings, higher peaks of efficiency are, in this case, aimed. The operational efficiencies for the optimized route found for the three fields are among the results obtained from Coates, 2002 (Table 1) for machinery that does not require loading and offloading.

3.3 Impact of servicing in route planning

To evaluate the impact of servicing in the algorithm, three case studies were chosen. Three fields with relative large areas (compared to the Dutch case studies) were extracted from locations for which the machine properties that operate them are known.

The location of the case studies, their identification and scale can be seen in Figures 26, 27 and 28; the machine and operation properties that are simulated on them is found in Table 7.

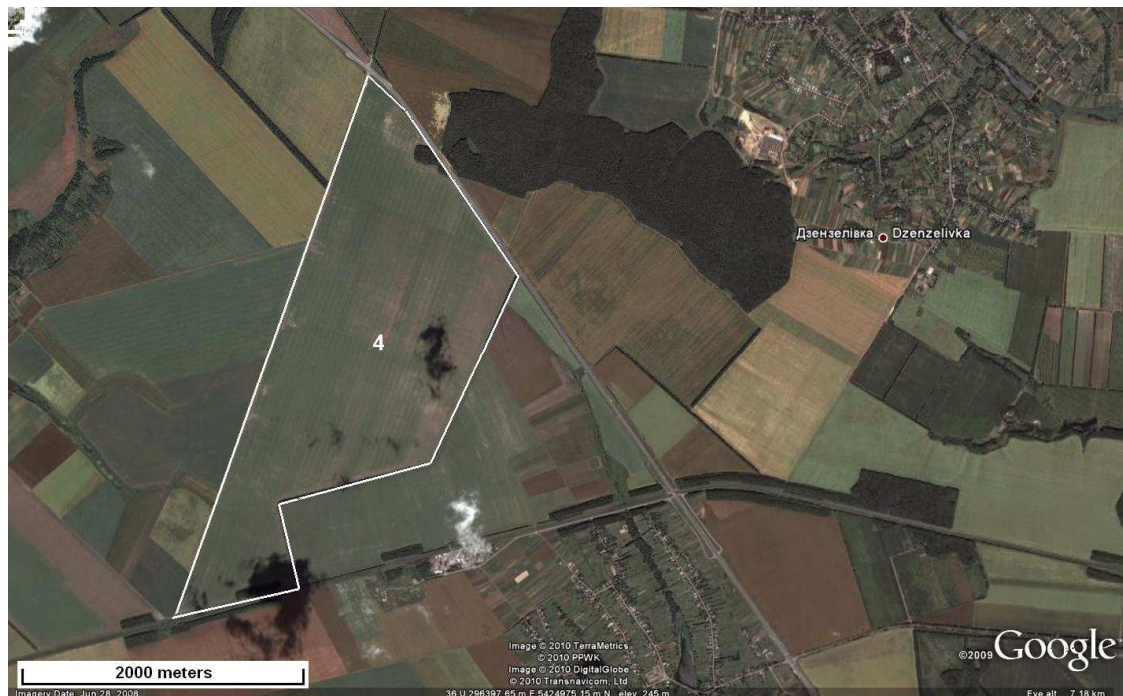


Figure 26. Arable field located in the province of Cherkassy, Ukraine.

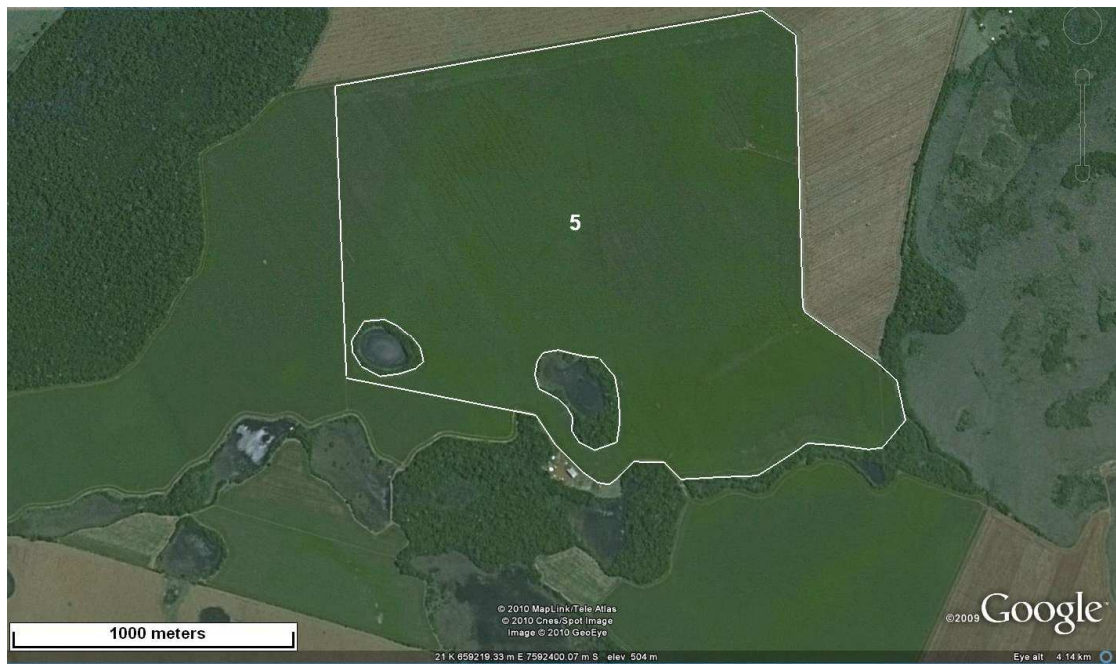


Figure 27. Arable field located in the province of Mato Grosso do Sul, Brasil.



Figure 28. Arable field located in the province of Mato Grosso do Sul, Brasil.

Each field was studied with their specific operations and machinery and treated as a case study identified in accordance with the field.

Table 7. Machine and operation properties used as parameters for the case studies.

Case study	Field area (ha)	Machine properties						Operation properties	
		Width (m)	Turning radius (m)	Straight-non-working speed (km/h)	Turning speed (km/h)	Working speed (km/h)	Capacity (units)	Rate (units/ha)	Servicing time (minutes)
4	397.6	40	5	18	5	12	5000	150	10
5	269.8	27	5	25	5	18	2300	150	10
6	84.5	9	8	10	2	6	7000	3000	5

In Table 7, the machines that are simulated in case studies 4, 5 and 6 are respectively: a pulled boom-sprayer, a self-propelled boom sprayer and a self-propelled harvester.

3.3.1 Optimized results found for maneuvering and servicing time

Results found for each case study can be found below. Figures 29, 31 and 33 shows the optimized route based on the lowest maneuvering + servicing time found. The maneuvering and servicing times required for each direction of work are displayed in the graphs of Figures 30, 32 and 33.

Because of the scale of these fields, maneuvers are too small to be properly seen, but their length and calculation follows the same procedures used in the previous case studies.

Case study 4

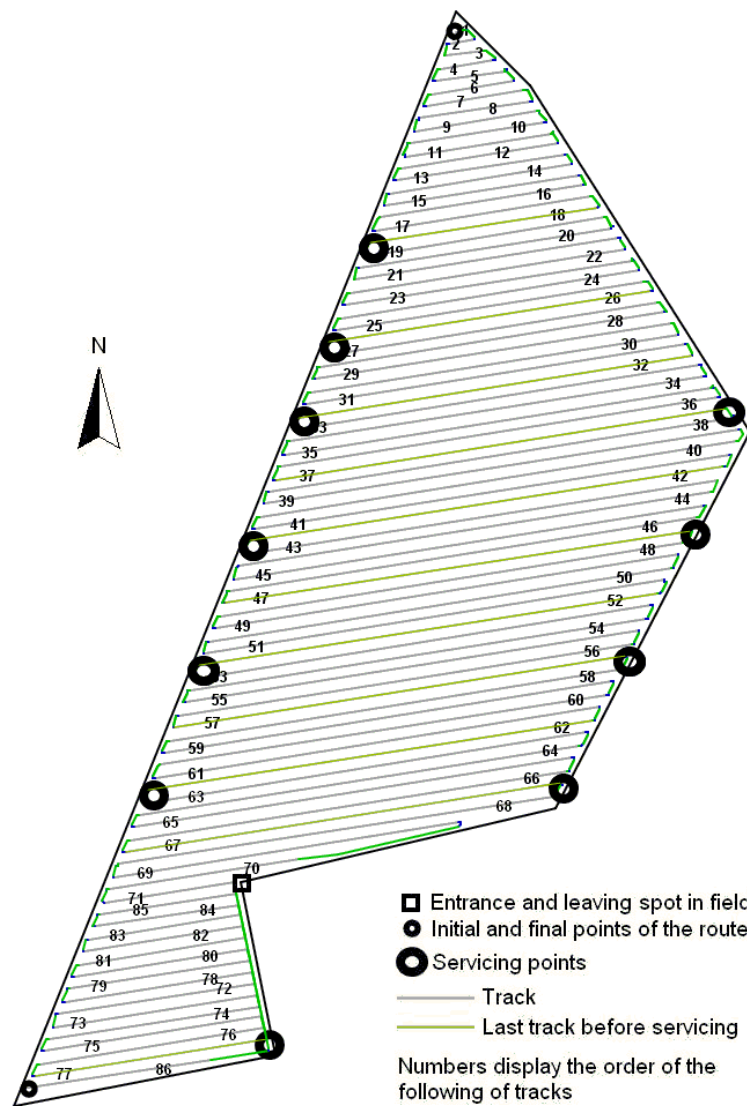


Figure 29. Optimal route found for case study 4.

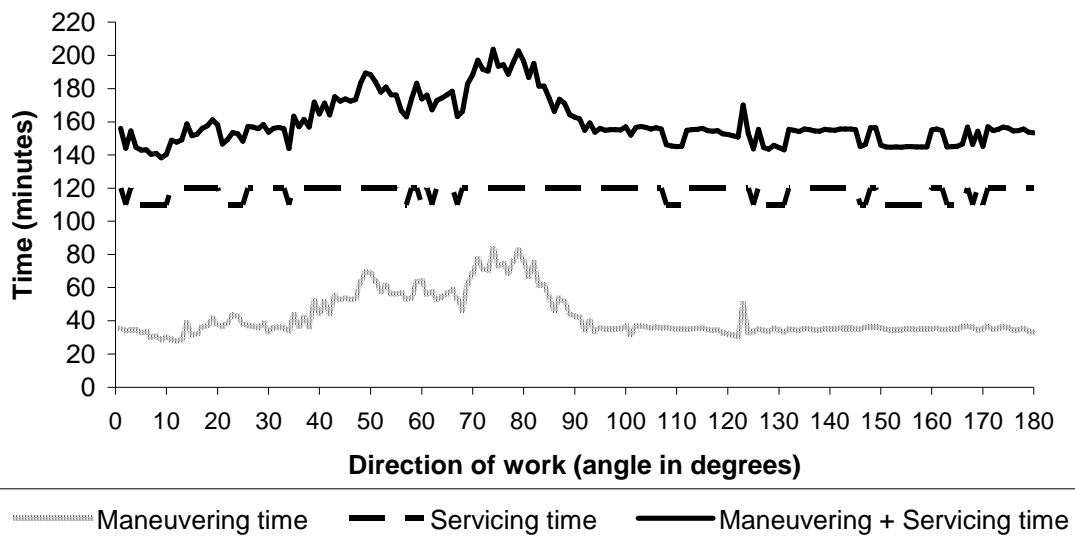


Figure 30. Non-working time spent in case study 4 for different directions of work tried.

Case study 5

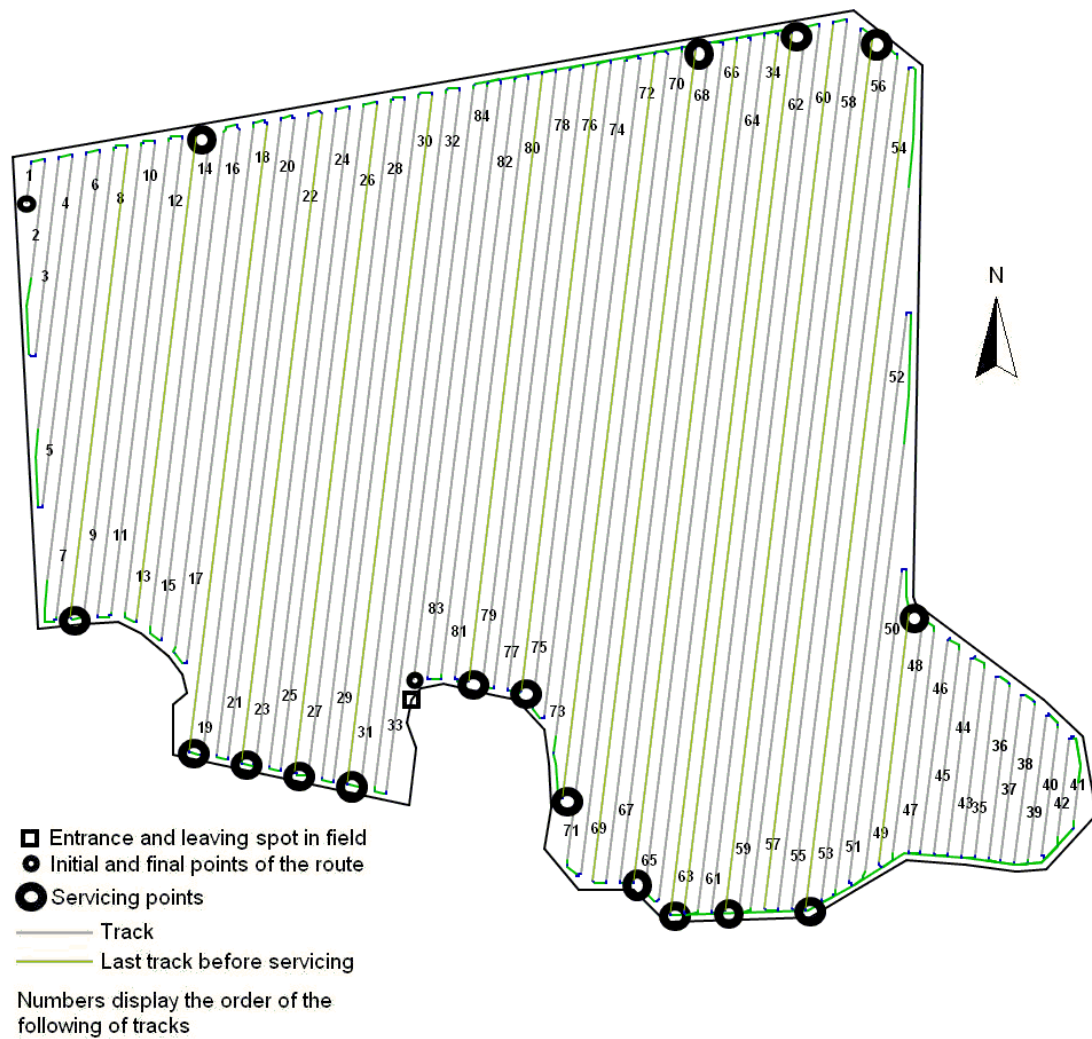


Figure 31. Optimal route found for case study 5.

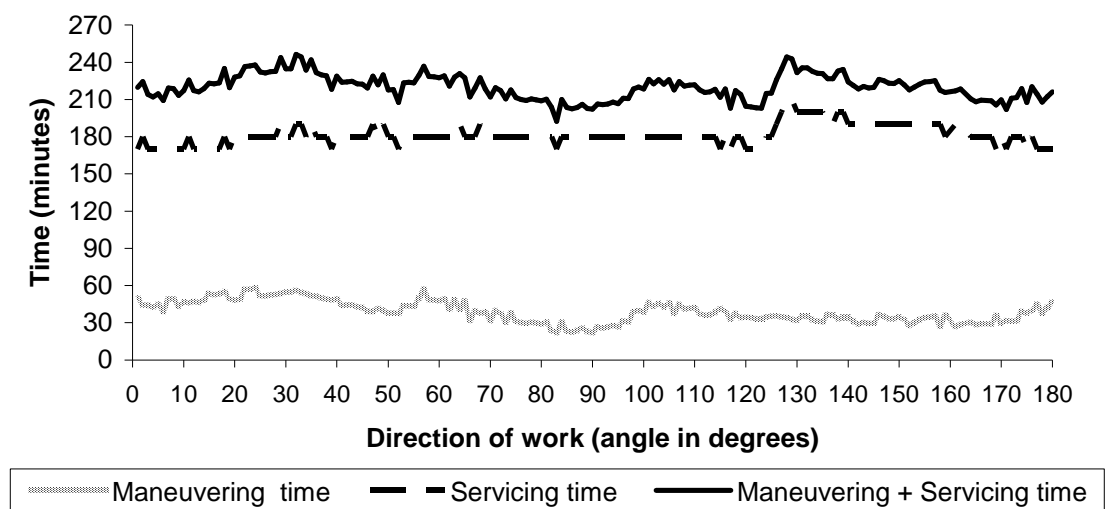


Figure 32. Non-working time spent in case study 5 for different directions of work tried.

Case study 6

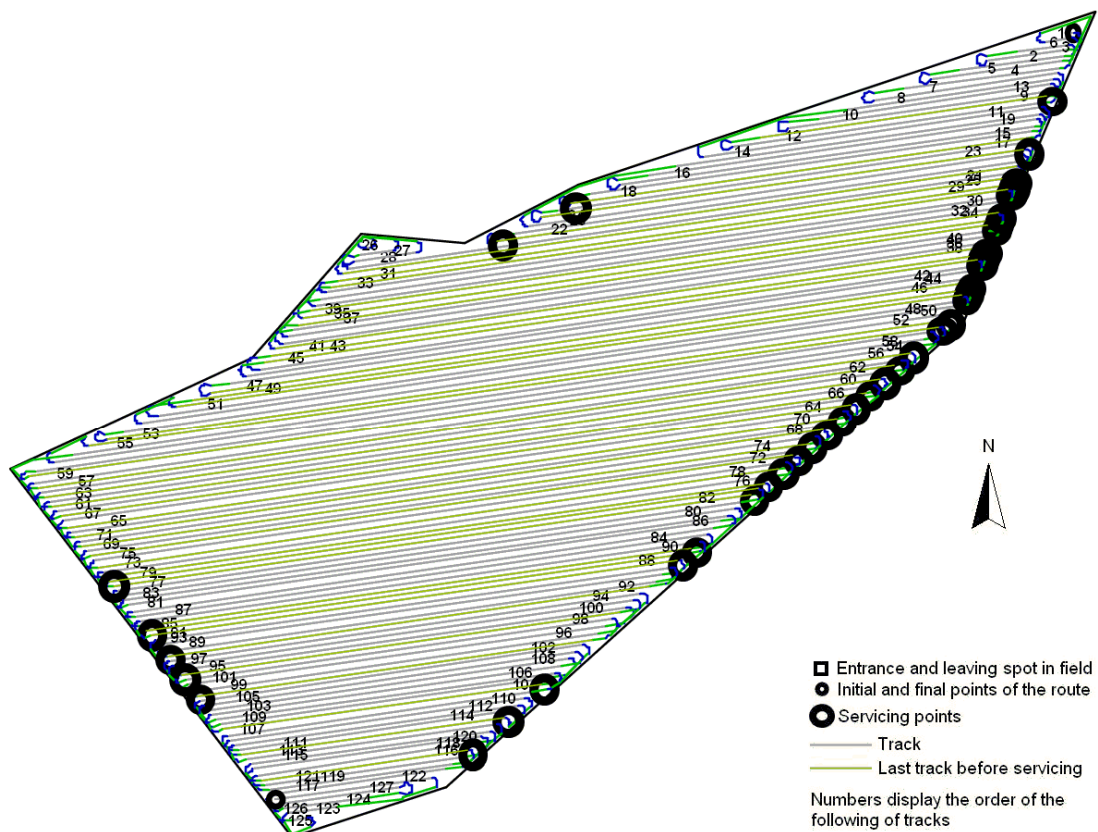


Figure 33. Optimal route found for case study 6.

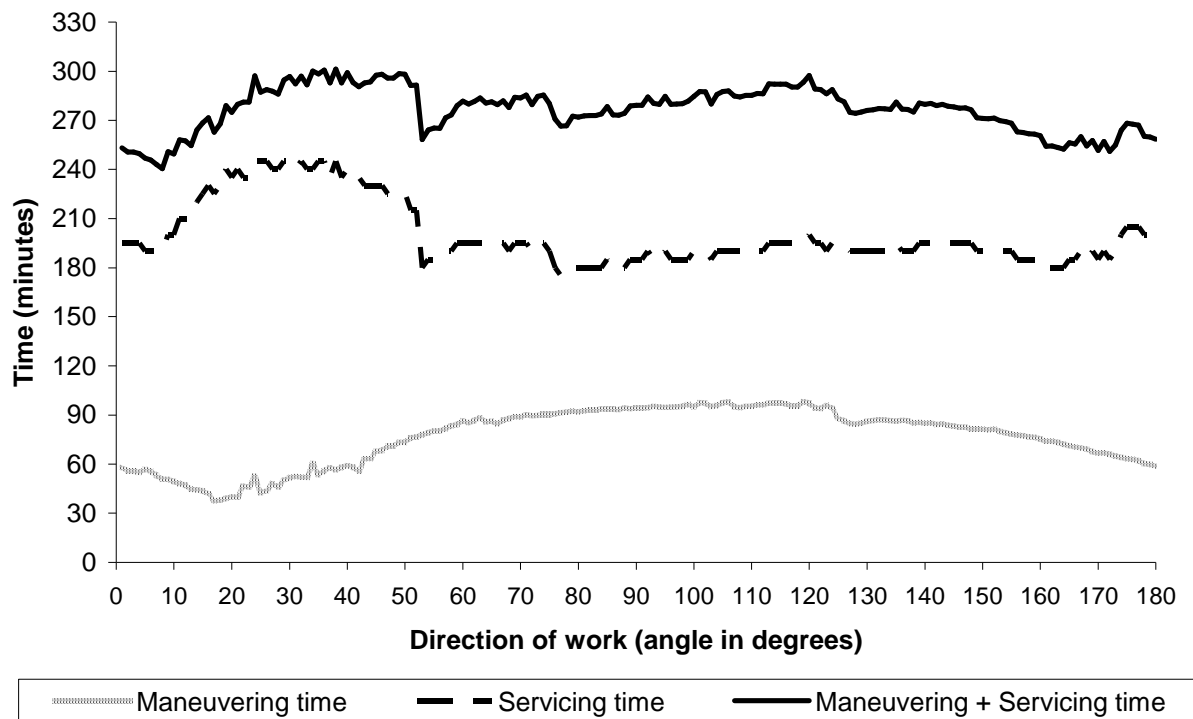


Figure 34. Non-working time spent in case study 6 for different directions of work tried.

Case study 4 showed strong sensitivity to the position for the entrance and leaving point of the machine in the field, influencing the final optimal route found as well as the results for many of the directions of work tested, but this issue will be explored later on and here no further comments on the results are going to be done for Figures 29 and 30.

Case study 5 presents a real field with many vertices and more concavities where the algorithm selected a route that avoids the tracks being interrupted by concavities in the shape of the field, meaning that a machine can follow each track without having to surround the borders of field to continue working in the same path.

The operational efficiencies for the spraying operations (case studies 4 and 5) ranged between 69,4% and 77% for the Ukrainian field and between 56% and 62% for the Brazilian field. The operational efficiencies for the different angles tried can be seen in the graph of Figure 35. This results also stay in the range studied by Coates, 2002 (see Table 1).

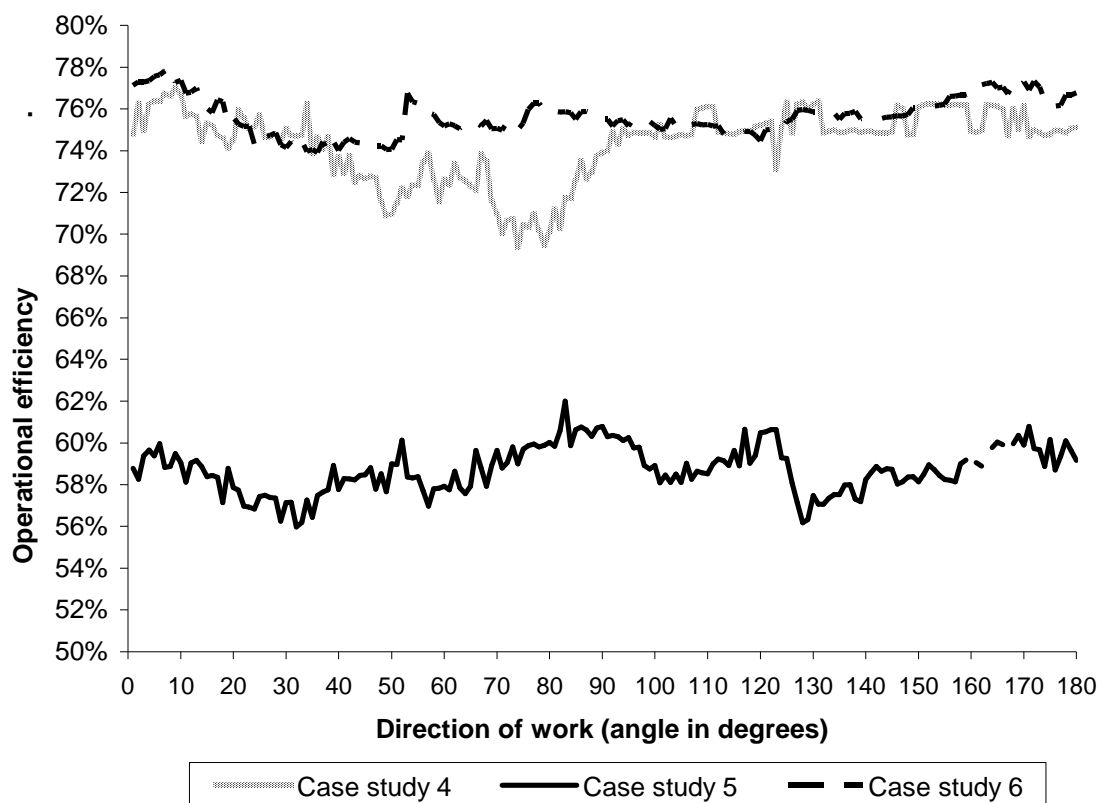


Figure 35. Operational efficiencies calculated by the fraction of working time in the total time spent on field for the 3 case studies that considered servicing.

In Figure 35, the high operational efficiency between case study 4 and 5 is mainly due to the difference in the working speed. The faster that a machine moves working, less time is spent for it increasing the fraction of the non-working time, but it does not mean that the machine is more inefficient for performing its work. The machine of case study 5 is 50% faster in working than the machine in case study 4.

It also explains why the harvester, which spends much more time in maneuvers and servicing have still a higher operational efficiency than the sprayers; the harvester is a lot slower and spends a longer time in its working purpose compared to its non-working time.

In case study 6 a harvesting operation is being simulated, leading to high demand for servicing (36 times). Harvesting operations, because of the higher rates of product (yield) taken (in unit/area), servicing time have higher impact mainly when it is compared to the previous spraying operations. This higher demand is usually supplied by on-field servicing operations with the use of auxiliary machinery (see Figure 3a in the introduction section) that offloads the machine only when it is completely full.

If no headland area into consideration, a machine would have to be offloaded 33 times using the on-field servicing. The algorithm found a route that leads the machine to 3 more stops for servicing than the on-field operations, but that may be preferable if the issue of soil compaction from the auxiliary machinery wants to be avoided, or even if the use of auxiliary machinery is willing to be avoided.

In all of these three case studies (4, 5 and 6), the servicing time surpasses the maneuvering time in any direction of work chosen (see Figures 30, 32 and 34). In Table 8, we can see that the choice of direction of work based on the lowest maneuvering time, when servicing is also an issue, does not always yield the highest savings in total non-working time. By observing the chart in Figure 34, choosing the lowest maneuvering time leads to one of the highest servicing times.

Table 8. Values for non-working time (in minutes) if one of the optimization parameters is prioritized.

Case study	Non-working time when the angle for...		Lowest non-working time found
	... lowest maneuvering time is chosen	... lowest servicing time is chosen	
4	147.64	138.28	138.28
5	192.18	192.18	192.18
6	262.61	266.58	240.47

3.4 The issue of the entrance and leaving spot of the field for machinery

The location where the machine enters and leaves the field is used in the modified Clark-Wright savings approach and it influences the calculation of savings to obtain the best route (see example for optimizing choice of tracks in section 2.3.3 - Obtaining optimized route along tracks).

This influence was significant for case study 4, where the optimal route was strongly changed after the entering and leaving spots where replaced. This effect can be seen in Figure 36.

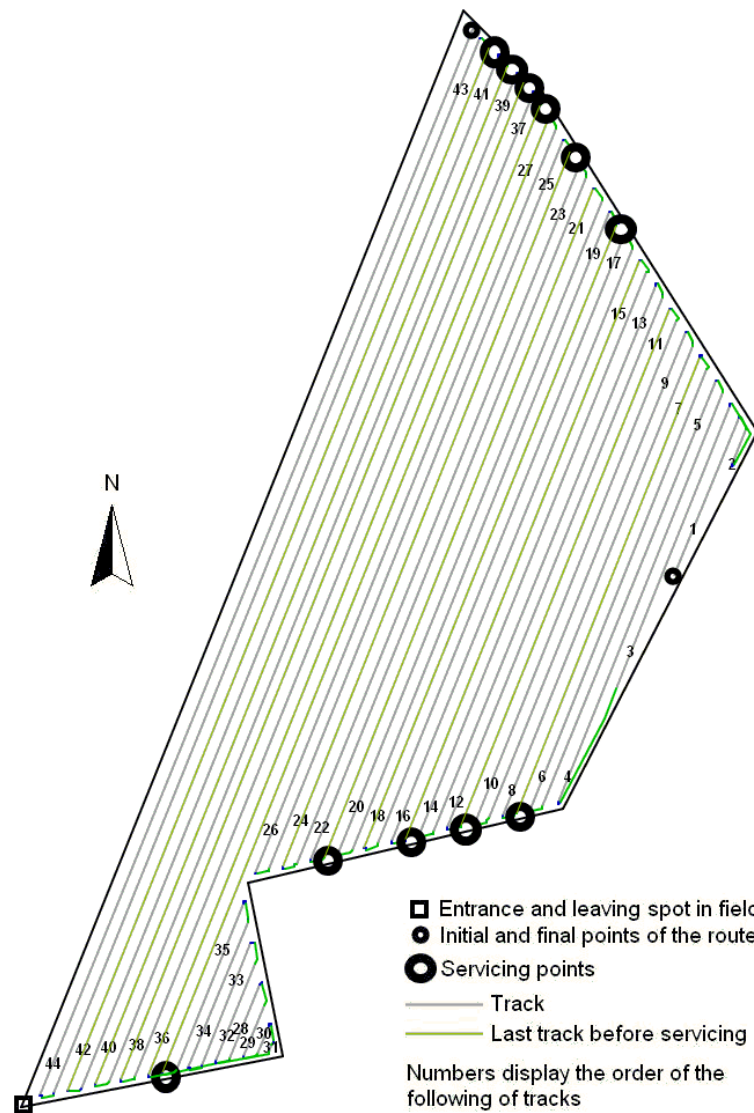


Figure 36. Optimal route found for case study 4 when the entering and leaving spot in field was replaced.

The result found in Figure 36 optimized the direction of work decreasing the maneuvering time to 13,62 minutes, whereas the previous optimal maneuvering time was of 27,6 minutes (Figure 29) while the number of times the machine was served remained the same.

The route is changed for all the fields when the entering and leaving spots are replaced, but only in case study 4 the direction of work is changed to a more optimal one by this change.

There was not time for doing simulations changing the entering and leaving spot for all the case studies. This issue has to be studied in further work.

3.5 Headland demanded for maneuvering

As a secondary result found by the algorithm, the area for maneuvering was retrieved for all directions of work tried. This issue is not related to the objective function of this thesis nor

influences any of the previous results found, but remains also a point for further study when other operation costs are taken into consideration (like overlapping of field operations for e.g.). The fraction of area demanded for maneuvering for the first three case studies (Figure 19) can be seen in Figure 37:

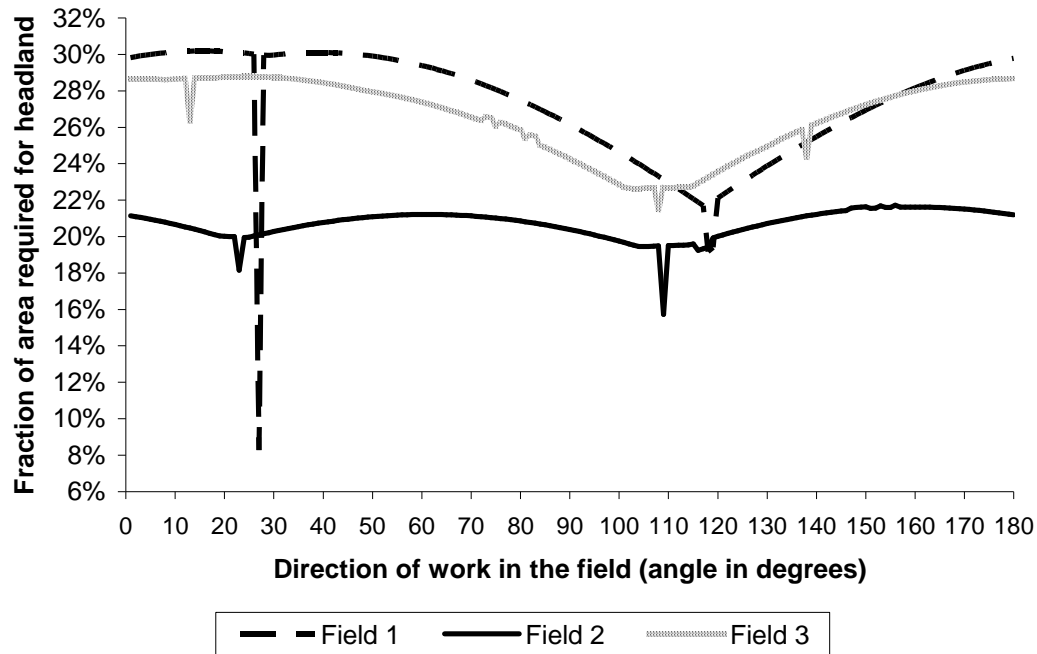


Figure 37. Fraction of area taken as headland for maneuvering in different directions of work for the three case studies with small fields.

Compared to Figure 24, this issue will also be in conflict for the Fields 2 and 3 (more irregular) where lowest maneuvering time does not match with lowest required maneuvering space. For bigger fields (case studies 4, 5 and 6) the fraction of area taken for headland was small (ranging between 6 to 9%) for any direction of work chosen.

4. Discussion

4.1 Methods and route planning

The algorithm is able to create routes inside irregular fields and also to avoid obstacles inside the fields if necessary. The calculation of the required space between the border of the field and the end of a track taking into consideration the width, the turning radius and the heading of the machine towards the border of the field allows to know with some accuracy the correct space needed. This space can be larger than the width of the machine for some field operations and the doubt of the user of how long a machine can continue towards the border of the field until it must start its maneuver is possible to be retrieved in advance.

The uniqueness of each maneuver, which allows stepwise calculation of the track to be followed, retrieves good and comprehensible results, allowing the maneuver to consider the relation between the direction of work and the border of the field. Unfortunately, in the present implementation, this algorithm is only functional for U-maneuvers while for Ω -maneuvers it still needs to be developed (See Figure 20).

This improvement of the computation of turns allowed the savings algorithm to work in field with more irregularities or with working directions that are not perpendicular to the border, which was a limitation in the work of Vougioukas et al. (2008), Figures 22 and 23 show the results of the different types of maneuver towards the border of the field. The result shown in these figures also disagree, in time savings perspective, with Taix et al. (2006) who suggested that the working direction should be parallel to the longest straight side of the field. This suggestion seems to be valid only for regular fields, like case study 1, (see Figure 21).

The sequence of points retrieved for maneuvers allows development of the implementation of guidance of machinery also in the end of the tracks, leading to a complete non-human guided machine in field.

From the distances retrieved from the stepwise points for maneuvering and the given speed parameters the time-cost of maneuvers are calculated keeping a unique cost of each maneuver, allowing the savings algorithm to find an optimal choice of tracks to be followed afterwards.

Table 6 shows the impact in time savings for the case studies when optimization of choice of tracks and maneuvers is applied. But Figures 22 and 23 show that the Ω -maneuvers cannot be totally suppressed in optimization if the angle of the direction of work and the border is taken into consideration, once it influences the distance between the nodes making a U-maneuver not suitable.

Figures 24 and 25 are related to time impact of direction of work in routes. Trying different directions provides decision making information when in the objective function of route planning is different. If a direction of work is chosen for another reason than time savings (a better field coverage for example) the impact on the time can be known.

4.2 Impact of servicing in route planning

Methods chosen for servicing are not yet in full accordance with reality. Servicing locations or area are usually not available around the whole field. In general the machine has to move from a node to a near servicing spot and the time consumed for this movement was not taken into consideration and may, in fact, influence the route chosen and/or the amount of times a machine stops to be served. Large fields can also have roads in the middle that don't have to be avoided by the machine but can be crossed like they were part of the field, but they exist mainly for servicing purposes. These roads should be inserted and interpreted by the algorithm to achieve this purpose.

Nevertheless, the algorithm already provides an idea of the impact of servicing time in relation to the maneuvering time, suggesting that the first should be indeed be taken into consideration for big fields when optimization of time for operations is aimed. This is in contrast with Klemola et al. (2002) who posed that the time spent working in fields is almost entirely determined by turning times.

The graphs of Figures 32, 34 and 36 and Table 8 show that no relation exists between maneuvers and servicing time, and the optimal choice for both should only be found by taking both times into consideration and trying different routes.

Many more case studies should be simulated in the algorithm, which was not done due to lack in time in this work. More cases would allow obtaining more consistent conclusions towards field irregularity and size; the first issue will influence more the maneuvers, while the second will influence more the servicing.

4.3 Other issues

4.3.1 The entrance and leaving spot of the field

Influence of the entering and leaving spot in the route planning exist and can have an important impact as can be seen in the differences between Figures 29 and 36. The extend of this issue was not further studied, but it also opens space for improving route planning by the relocation of entering and leaving spots, which was found for the given case study 4.

Influence of these spots were in agreement with results found by Vougioukas et al., 2008 who also tested the influence of the entering and leaving spots on the optimal route.

4.3.2 Headland demanded for maneuvering

This thesis integrated two time issues in the route planning operations: maneuvering and servicing. Integration of other route planning related costs should also be merged in further route planning studies to obtain a more extensive view on global optimization. In this study the issue of area demanded for maneuvering was also retrieved and the contrast between the graphs of Figure 24 (time for maneuvering) and Figure 37 (area for maneuvering) suggests these issues to be independent from each other. Also issues of direction of work towards overlap in headlands must be merged in further studies.

5. Conclusion

5.1 Answers to research questions

Coverage optimization is a line of study that is case study dependent and, because of the amount of possibilities, computational help is required. In this work an algorithm was built aiming to further previous work.

The algorithm is capable of creating routes in fields of different shapes and sizes, also taking into consideration the presence of obstacles in field.

Two issues were merged in this coverage optimization development: maneuvering and servicing. These issues were tested in six different case studies with fields in different shapes and sizes and also different machinery.

Improvements were implemented in determining the headlands, taking factors of turning properties of machine and directions of work towards borders into consideration; this creates an opening to optimize issues like loss of area for maneuvering with impacts in turning area (like compaction of soil) and overlap for further studies.

Another improvement was done in the reproduction of the maneuvering operations between nodes, with more accuracy of all the steps to perform a complete maneuver and calculating each of them individually.

The objective of this research was to reduce non-working time in route planning in fields considering two non-working issues:

- maneuvering using and improving methods developed in previous work
- servicing, by including its impact in the optimization of routes

The answers to the research questions are given below and demonstrate that the objective was achieved.

1. Which are the machine and field properties that are important for planning field operations?

This research merged methods used and suggested by previous authors to achieve more accurate reproduction of simulation of machine pattern of work in fields. Towards machine properties “width” was used in calculation of headland space, calculation of turning space and to obtain the distance between the parallel tracks; “turning radius” was used for the turning space and for finding the sequence turning of turning points to do the maneuver; “capacity” is essential to calculate how far a machine can keep working. Speeds were required to retrieve the costs for maneuvers in order to optimize them (see section 2.1 for machine properties).

The main field properties used were field geometry and presence of obstacles, all of them being studied in previous literature (see sections 1.2 and 1.3 for field issues in path planning). Size of field is a property less tackled in previous works because of the objective that was aimed; while most works concerned with maneuvering issues (for which in big fields it has lower impact), in this work the study of servicing makes this issue significant (see sections 1.6 for servicing background and 3.3 for results of servicing impact).

2. Which methods exist for coverage and path planning for field operations?

In previous work carried by authors methods were developed reducing complexity of field geometry, complete coverage with simple (single part) objective function, i.e. distance, time, overlap, and incomplete coverage (field boundaries), which requires compound objective function (composed of overlap, non covered areas, subsidy, turns). In general this previous work carried aimed to simulate the actual path (or route) being followed by a machine on a given field (usually a 2D polygon), retrieving optimization parameters and, sometimes, geographic outputs that could be applied on real machinery. These methods used different approaches to tackle issues like space for headlands, maneuvering costs, direction of work, effective field coverage and others (see Introduction in section 1.1, Agricultural operation planning in section 1.3 and Overview of optimization problem in section 2.1).

3. Given the need to incorporate loading, offloading and servicing in path planning, which method is more suitable for coverage and path planning?

Given that the objective function is time, spatial issues of overlapping and optimal field coverage were not considered. Methods were chosen based on savings and more accurate reproduction on machine work on field (see section 2.2 in the conceptual model). The definition of headland used a combination of parameters and methods to know with some accuracy how far a machine can come near the border of a field (sections 2.2.2 and 2.3.2); maneuvers were defined from a proposed approach where the sequence of locations of the route described by a machine is calculated by sequences of coordinates, also retrieving the distances and the kind of pattern being followed (turning and/or straight pattern) (sections 2.2.3 and 2.3.3). These distances, with the provided speed parameters, are able to retrieve the unique time for each maneuver; the optimization of choice of tracks to be followed posed a TSP and it was solved by using a suggested method that uses Clarke-Wright savings algorithm heuristics in skipping tracks to save maneuvering time (see section 2.2.3 for optimizing the choice of tracks). Approaches for saving time in servicing are also proposed in this work by simulating different directions and optimizing the capacity of the machine (see section 2.2.4 for servicing optimization).

4. How can the method be implemented in a computational algorithm?

Geographic modeling packages, tools and routines are available for implementation of methods for route planning. For this research, the methods were applied by understanding the concepts used in previous work and programming it entirely in a computer language known by this author with the use of described tools also self-programmed inside the given algorithm (see section 2.2 Implementation).

5. How does the route change with fields that are different in shape and size?

The algorithm developed is capable of creating machinery routes in fields of different shapes and sizes allowing the input of 8 machine and operation parameters, each one of them can

influence in the route planning in the field, be it in the choice of tracks, or in the direction of work. This algorithm was tested and evaluated in 6 case studies, the first three case studies concerned fields of small area and considered only the issue of maneuvering as non-working time, the last three case studies concerned fields of larger areas in which servicing was considered with different machine and operation settings. An optimized route based on time savings was found for all the fields, also with information about impact in time for a machine to work in other chosen directions. One issue that interfered in the optimization but that was not studied enough in this work is the location of the entering and leaving locations for a machine in the field which interferes in the optimization of the maneuvering method here chosen, but it also opens space to study this issue to improve optimization the field operations. Another issue which was not taken into consideration in this work, since it is not time related, is the area needed for maneuvering of machinery. However, it is computed by the algorithm as a secondary result, so in further research it could be weighed in the objective function together with time savings.

6. How does the route change when turning and servicing are taken into consideration?

When servicing was taken into consideration in three of the case studies tested, it showed to have influence in the operational efficiencies of the machines as well as for the routes. When servicing becomes an issue, the choice of direction of work in a field based on optimization of maneuvering only may lead to higher consumption of time instead of time savings because servicing and maneuvering were shown to be independent attributes in the non-working time of a machine, and optimized routes can only be retrieved by always testing the two issues in each case study.

Among limitations of the algorithm poses the fact that it considers only one straight direction of work in the field, but this limitation already includes a wide range of fields for which no more than one direction of work is required or suitable and; even more limiting is the fact that it doesn't consider the moving of the machine into a servicing spot to have a more accurate calculation of the servicing time or for the calculation of better servicing spots.

5.2 Further study and recommendations

A list of points to be taken into consideration for further study follows:

1. In regard to the existing algorithm:
 - 1.1. Testing this proposed given algorithm and the approaches in more case studies and trying to obtain more consistent conclusions for choice of tracks in fields taken issues of maneuvering and servicing into consideration;

- 1.2. Simulating different entering and leaving spots for machinery around the field observing its influence and trying to obtain methods of optimization based on their location;
 - 1.3. Apply exhaustive research to compare and validate the obtained results of the heuristic method applied;
2. Regarding improvements in the work carried:
 - 2.1. Taking Ω -maneuvers into consideration for defining the headland maneuvering area;
 - 2.2. Including movement of the machine to servicing spots and obtaining a more accurate impact of the servicing in the non-working time as well as finding ways to optimize machine work by reallocating this spots around the field;
3. Regarding to merging other issues in route planning optimization:
 - 3.1. Including a cost in the area of the headland required for turning;
 - 3.2. Consider coverage of field as a cost trying to improve it by shift the position of the tracks and trying other directions taking this issue into consideration;
 - 3.3. Considering the cost of overlap of field operations in headlands;
4. Regarding complexity of fields and obstacles:
 - 4.1. Working with more than one direction of work;
 - 4.2. Working with curved patterns;

References

- Alhoniemi, E., Himberg, J., Parhankangas, J. and Vesanto, J. 2005. Homepage of SOM Toolbox. Available: <http://www.cis.hut.fi/somtoolbox/>. Accessed 25 August 2009.
- Bochtis, D.D. and Oksanen T. Combined coverage and path planning for field operations. Precision Agriculture 2009, Wageningen University.
- Bochtis D; Vougioukas S; Tsatsarelis C (2006). A vehicle routing problem formulation of agricultural field operations planning for self-propelled machines, In: XVI CIGR Word Congress, Bonn, Germany. Abstract in Book of Abstracts, pp 301–302,
- Bochtis D.D., Vougioukas, S., Tsatsarelis C. and Ampatzidis. Y. 2006. Optimal Dynamic Motion Sequence Generation for Multiple Harvesters. Proceedings of the Automation Technology for Off-road Equipment (ATOE) 2006 Conference, Bonn, Germany, pp. 33-40.
- Bochtis, D.D., and Vougioukas S., 2008. Minimising the Non-working Distance Travelled by Machines Operating in a Headland Field Pattern. Biosystems Engineering, 101(1): 1-12.
- Bruin S., Lerink P., Klompe A., van der Wal, T. and Heijting S. Spatial optimisation of cropped swaths and field margins using GIS. Computers and Electronics in Agriculture 68 (2009) 185–190.
- Clarke G; Wright J.,1964. Scheduling of vehicles from a central depot to a number of delivery points. Operations Research, 12(4), 568–581.
- Coates, Wayne E.. College of Agriculture and Life Sciences, University of Arizona. Revised July 2002. Available: <http://ag.arizona.edu/crops/equipment/agmachinerymgt.html>. Accessed: 28 August 2009.
- Edwards, William. 2001. Estimating Farm Machinery Costs. 2005. Machinery Management. Iowa State University. Electronic paper version. Available in: <http://www.extension.iastate.edu/Publications/PM710.pdf>.
- B. Golden, L. Bodin, T. Doyle and W. Stewart, JR. 1980. Approximate Traveling Salesman Algorithms. University of Maryland, College Park, Maryland. Operations Research, Vol. 28, No. 3, Part 2 (May - Jun., 1980), pp. 694-711. Available in <http://www.jstor.org/stable/170036>. Accessed: 22/04/2010.
- Hansen, A.C., Zhang, Q. and Wilcox, T.A. 2007. Modeling and Analysis of Row Crop Harvesting Patterns by Combines. Transactions of the ASABE, Vol. 50(1):5-12.
- Hunt, D. 2001. Farm Power and Management. 10th ed. Ames, Iowa: Iowa State University Press.
- J.W. Hofstee, L.E.E.M. Späjtens and H. IJken. Optimal path planning for field operations. 2009. 7th European Conference in Precision Agriculture. Wageningen, pp. 511-519.
- Jin, J. and Tang, L. Optimal path planning for arable farming. 2006, ASABE Annual International Meeting, Portland, Oregon, American Society of Agricultural Engineers.
- Johnson, D.S. and McGeoch, L.A., 1995. The Traveling Salesman Problem: A Case Study in Local Optimization. Department of Mathematics and Computer Science, Amherst College.
- Keicher, R. and Seufert, H., 2000. Automatic guidance for agricultural vehicles in Europe. Computers and Electronics in Agriculture 25, pp.169–194.

- Klemola, E., Karttunen, J., Kaila, E., Laaksonen, K. and Kirkkari, A.-M. 2002. Lohkon koon ja muodon taloudelliset vaikutukset [The economic effects of field size and shape]. TTS Institutes Publication Series: 386. Helsinki, Finland. In Finnish.
- Longueville, F. Tychon B., Leteinturier B. and Ozer P., 2006. An approach to optimise the establishment of grassy headlands in the Belgian Walloon region: A tool for agri-environmental schemes. Land Use Policy 24 (2007) 443-450.
- Oksanen T. and Visala, A., 2007. Path planning algorithms for agricultural machines. Agricultural Engineering International, The CIGR EJournal, Volume IX.
- OSGeo Foundation, 2009. GDAL/OGR Info Sheet. (Online). Available: <http://www.osgeo.org/gdal ogr>. Accessed: 25 August 2009.
- Palmer, R.J., Wild, D., Runtz, K. (2003). Improving the Efficiency of Field Operations. Biosystems Engineering, 84 (3), 283-288.
- Peltola, R., Mattila, P. and Kasteenpohja, E. 2006. Pellon arvo [Value of agricultural land]. Maanmittauslaitoksen julkaisuja 102. In Finnish.
- Stoll, A., 2003. Automatic operation planning for GPS-guided machinery. Precision agriculture. Eds Stafford, J. and Werner, A. Wageningen: Wageningen Academic Publishers, pp. 657-644.

Appendix

Table of definitions:

Angle	direction followed by the tracks of a machine inside the field. Is a numeric value provided in angle-degrees, in which 90° points to the exact North given in the field points set.	Clark-Wright (or CW)	Designation of an heuristic method to solve TSP logistic problems (see TSP in this table), it was proposed by Clarke and Wright (1964).
Border	is a polygon-side resulted by the link of 2 points representing the side (or border) of a field or an obstacle.	Field	geometric 2-dimentional polygon in a Cartesian plan, defined by points linked in a specific counter-clockwise order.
Capacity	quantity of the target product capable of being carried in the tank of a machine. Which can be grain for a harvester, or mixture for a sprayer-boom.	Headland	width between the nodes of tracks and the border of the field, required for the turn of the machine. Depends on the direction, the border of the field and the turn radius.
Cost	the time consumed by a machine during it's operation on the field, measured in seconds.	Node	is a point (or location) in the field representing one edge of a track. Each track has 2 nodes (two edges of a straight line).
Cost for servicing	Time spent by a machine to load or offload in the servicing point.	Obstacle	geometric 2-dimentional polygon in a Cartesian plan, defined by points linked in a specific clockwise order, and located inside a field.

Rate	quantity of the target product being loaded or offloaded per area. Which can be the yield of a crop being harvested or the mixture being sprayed per unit of area.	Turn	it's an arc of a circle representing the maneuver realized by a machine starting and/or ending in one node. This turn starts in one node of a track and either end in another node, or end reaching the border of the field.
Route	the complete pattern (or multi-line sequences) followed by a machine to cover the whole field. The route uses and unites all the tracks of the field in it.	Turning radius	is the radius of the arc being followed by the machine, provided as parameter for the definition of the turn patterns.
Straight non-working cost	time consumed for non-working time of the machine during it's path between a node and a start of a turn, and between two turns connected to the border of the field.	U-maneuver	movement executed by an agricultural machine operating in a headland pattern (see example in Figure 6b, section 2.1, overview of optimization problem)
Track	center lines of operational swaths, in straight pattern defined by two points located inside the field representing the path followed by the machine during it's work on the field. Several tracks cover the field and they must not cross the obstacles inside	Ω-maneuver	movement executed by an agricultural machine operating in a headland pattern (see example in Figure 6a, section 2.1, overview of optimization problem)
TSP	Travelling Salesman Problem. is a problem in combinatorial optimization. From a set of locations to be visited, the choice of each of the locations changes the overall number of options.	Width	width of the agricultural machine that will work inside the field covering it. The width will determine the space between the tracks.