Optimal Path Planning For Field Operations

Hofstee, J.W.[1], Spätjens, L.E.E.M.[2] and IJken, H.[1],
[1]Wageningen University, Farm Technology Group, Bornsesteeg 59, 6708 PD Wageningen, Netherlands, janwillem.hofstee@wur.nl
[2]Agrovision, Postbus 755, 7400 AT Deventer, Netherlands

Abstract

Path planning for field operations becomes more and more important. More work is done by workers not knowing the field from experience. A second reason is that in the future more and more operations will done by autonomous vehicles and they require a path. Path planning for rectangular fields is rather simple but for more complex shaped fields tools are needed to support the planning process. GPS developments also enable that more difficult solutions can be realised in practice.

With Matlab a tool is developed that reads the boundary coordinates of a field, determines the real vertices, divides the field into convex subfields if necessary, and calculates the costs for different operating directions to find the direction with the lowest costs incurred. Working time is converted to costs to enable the choice to not operate a part of the field for some reason, for example too small in relation to the effort.

The tool is tested on some real fields. The results for simple fields are expected. The most optimal direction is the direction parallel to the longest side of the field. For more complex fields that are divided in two or more subfields the solutions are optimal for the individual subfields but the solution for the whole set of subfields is not necessarily optimal because for this interactions between subfields have to be taken into account too. Also, situations where tramlines are not perpendicular to headlands, resulting in small parts of the field either operated twice or not operated at all, have to be taken into account.

The developed tool is a good first start but has to be elaborated more to be able to handle more complex field situations and to deliver for these fields also realistic optimal solutions.

Keywords: obstacles, concave fields, spraying

Introduction

Many farmers in the Netherlands rent each year new fields to grow potatoes or flower bulbs. With these fields they have no experience from the past and have to do a path planning before starting the work. Most fields are not rectangular but have non-parallel sides, are L-shaped, or have obstacles within the field and it is not always easy to make plan. Contractors face the same problem when they arrive at the field of the customer and have to do path planning immediately.

In the future we have to deal with the same problem with autonomous vehicles for field operations. They need to have a plan; there is no driver to guide the vehicle over the field. So there is a need for a tool for path planning of agricultural operations.

Many factors play a role in path planning for agricultural operations. Stoll (2003) considered operation strategy, neighbouring area, field geometry, field specific data, machine specific data, and terrain relief. He tested all neighbours to decide whether it could be used for turning; the operation direction was set parallel to the longest side of the field and the headland turnings were set accordingly this direction and the neighbour test. He did not take terrain relief into account in his study because of its complexity. Major factors in the work of Taïx *et al.* (2006) were the slope, the working direction, and the size of objects in the field. The slope is important for sliding and traction (Taïx *et al.*, 2006) but is also important in relation to erosion (Stoll, 2003). The working direction was also chosen by Taïx *et al.* (2006) to be parallel to the longest side of the field. The size of objects was related to the width of the tool. For large objects a turning area around them was created and for small objects an avoidance trajectory was created.

Oksanen and Visala (2007) developed for path planning both a top down and a bottom up strategy. In the top down strategy complex fields are split into smaller less complex fields with a trapezoidal shape and merged again when specific requirements are met. The last step is determining the best driving direction; for this step heuristics are used. In the bottom up strategy the problem is solved recursively by following the shapes of the field edges and not considering them to be straight until the whole field is covered. All possible routes along the side of the field are tested and the most efficient one is selected.

Taïx *et al.* (2006) defined different areas (working, turning, input and output) and a steering edge. The latter determines the direction and the path planning is based on that all of the working and turning area have to be covered, starting in the input area and ending in the output area. Both a search for the best Hamilton path and geometrical reasoning were used to find the optimal path, using in both cases a minimum cost criterion.

Jin and Tang (2006) developed an algorithm that searches for the optimal decomposition and coverage direction. Both the field and the obstacles are described by polygons. The algorithm decomposes the field in multiple regions and each region has to be covered by a boustrophedon path. By recursively applying the algorithm the most optimal coverage method is searched for. Finally the sub-regions are coupled in an optimal way in a way similar to the Travelling Salesman Problem, with the entrance and the exit of the field as restrictions.

Sørensen (2004) optimized the driving pattern based on a priori information about the field, vehicle, and implements. Optimal routes were determined for the headlands, the main field, and the sequence of the operational tasks. The a priori information is transformed to graphical information which is mapped to a set of paths in terms of a graph work. The search problem is limited to this network of possible solutions. Optimisation techniques are used to find the most optimal path.

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. Bochtis and Vougiakas (2008) distinguished three different types of turn (loop turn or Ω-turn, the double round corner or $\cap$-turn, and the switch back turn or T-turn) and they minimised the non working distance in the field by applying different types or turning.

Path planning is not only used in the agricultural framework. Other path planning methods can be found in problems as floor cleaning, lawn mowing, painting, or robotic demining. However, many of these solution assume that the robot can move freely and that a spot can be visited more than once. For agricultural purposes this is irrelevant or even impossible.

The objective of the work described in the paper is the development of a tool for path planning of field operations. This tool has to consider the shape of the field, the available machinery, the presence of obstacles and the required operations.

The focus of the work in this paper is on spraying of potatoes. Potatoes require several crop protection actions and the tramlines can be used up to 20 times during the growing season. An optimal path for this operation is expected to be the most profitable. This also means that other operations as planting have to be derived from the spraying operation.

Materials and methods

The tool is developed with Matlab. It reads the coordinates of the border of the field. These coordinates are processed and only the coordinates of real corners (vertices) are kept. Vertices

with an angle between 160 and 200 degrees between both sides are considered to be not a vertex. For each vertex it also determined whether the vertex is concave or convex.
The tool considers the crop that is grown, the working width of the machine and the corresponding turning radius, growing or not-growing on headlands, the choice for overlap or non-overlap, and whether there is a crop free area or not. Velocity is used to calculate the time required for fulfilling the task, which is used to calculate the corresponding costs. The basis of the optimisation is costs; this also allows to leave small areas uncropped and take into account the corresponding (financial) yield losses.
The tool allows to make also a complete round inside the field along the border, which is common practice in spraying a potato crop. The width can be adjusted. In this case the field is imploded at all sides by the specified distance.
Fields are split in smaller fields if there is a need for it. Two reasons to split a field are: (1) the field has one or more concave vertices and (2) the presence of obstacles. The developed tool is based on that only convex fields are farmed. Although in general fields that have a trapezoidal shape are the most efficient to farm, it is not required that the subfields have a trapezoidal shape.

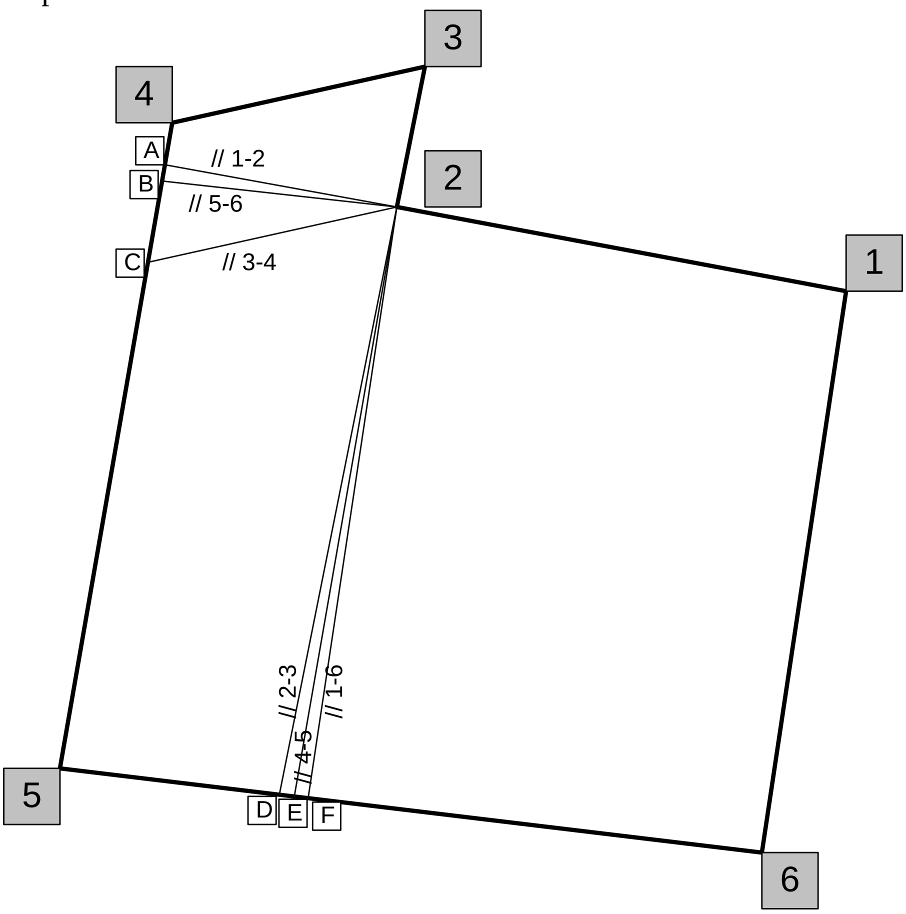

Figure 1 - Typical field and resulting split lines.

Concave shaped fields are recursively split until only convex fields are left (Figure 1). At the first convex corner (2) split lines are projected parallel to each side of the field, resulting in a certain number of subfields as shown in Figure 1. The projected split lines are ordered, starting with '// 1-2' and ending with '// 1-6'. The first subfield is the field with the corners 2, 3, 4, and A. This subfield is enlarged by merging it with the subfield 2-A-B; this merge process is continued until the resulting subfield will be convex again. This is the case after merging with the subfield 2-D-E; this means that this subfield is not merged and the resulting subfield will be 2-3-4-5-D. The procedure will be repeated for the remaining part of the field

2-D-6-1 (which is already convex). The procedure can be repeated in reverse order, finally resulting in the two convex fields 1-A-5-6 and 2-3-4-A. Different types of obstacles can be distinguished. Obstacles can be small or big, low or high, ‘no go area’ or ‘rather no go area’, and can be in the tramline or besides the tramline. A decision to split the field depends also on the type of the obstacle. A small high obstacle not located in the tramline does not need a split of the field since the boom of the sprayer can be folded to pass the obstacle. In addition to the splitting of the fields based on obstacles there should be an optimisation process to reduce the number of split subfields by positioning the tramlines on the field.
Figure 2 shows a field with an obstacle that requires to split the field into subfields. For this field 14 subfields that can be merged in different ways to create larger convex subfields, for example 1-2-3, 4-5-6-7, 9-10-13-14, 8-11 and 12. Each of the resulting combinations has to be tested for optimality.

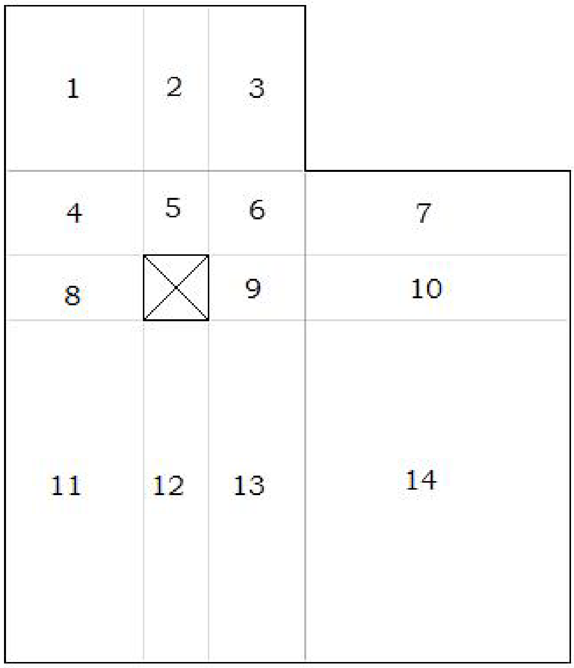

Figure 2 - Field with obstacle and possible subfields.

Different times are assigned to the different turning methods. For potato spraying it is assumed that the headland is large enough to realise a normal turn. The travel distance to turn is approximated by one and a half times the working width of the implement; dividing the distance by the working speed yields the time. The total number of turns is equal to the total number of tramlines minus one. The total length of the tramlines and the turns yield the total operation length.
Tramline directions are in many situations not perpendicular to the headlands. This results in that parts of the field in case of spraying, are sprayed twice or not sprayed at all, depending on the choice made whether to overlap or not.

The optimal solution is the solution with the lowest total costs. Operations for each subfield are at this moment only planned parallel to each side of the subfield itself; random directions or directions derived from neighbouring subfields are not considered. Each of the subfields is operated in the for that field optimal way. For each direction the costs for the operation are calculated. The costs are based on working speed, total length of the tramlines and the turns, and fixed hourly costs for the operation; the costs are set to € 65 per hour. Working speed and width can be set and depend on the operation; working width determines the distance between

the tramlines and hence also the number of tramlines and turns. The costs base makes it possible to add costs for overlap or no overlap of operations, additional travel time, or the decision to not farm small inconvenient subfields or small strips when the remaining width after the operations is small compared to the width of the machine. Finally, all subfields have to be visited.
The developed tool is tested for several real fields. Results for three fields (A, B and C) are presented in the next section.

Results

Figure 3 and Figure 4 show a field for which the optimal pattern is calculated for working widths of 18 m and 24 m. For each field the headland option is chosen which means that one round inside the field is made, followed by tramlines parallel to the sides of the field until the whole field is covered. The tramline made around inside the field is not shown in the figures. The resulting costs for the different options are presented in Table 1. The data show that for both working widths the costs and the time for the working direction parallel to the sides '1-2' and '3-4' are almost the same but the values for parallel to side '1-2' is just smaller.

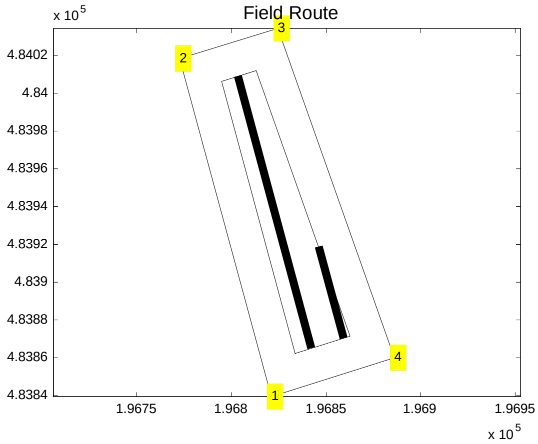

Figure 3 - Field A operated in an optimal way a with a working width of 18 meters. Thick lines represent the tramlines.

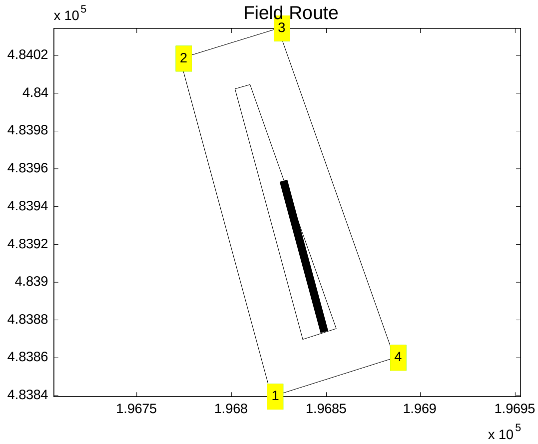

Figure 4 - Field A operated in an optimal way with a working width of 24meters. Thick line represents the tramlines.

Table 1 – Operation costs for all directions of Field A for working widths of 18 m and 24 m. Bold figures are the 'optimal' solution.

	18 metres				24 metres			
Parallel to side	**1-2**	2-3	3-4	4-1	**1-2**	2-3	3-4	4-1
Costs (€)	**15.33**	26.16	15.33	26.18	**12.77**	21.78	12.77	21.76
Time (hour)	**0.24**	0.40	0.24	0.40	**0.20**	0.34	0.20	0.33

Figure 5 and Figure 6 show the tramlines for Field B for working widths of 18 m and 39 m; the resulting tramlines for a working width of 24 m are almost the same as for 18 m and are not shown. The corresponding costs and times are shown in Table 2, Table 3, and Table 4. An estimation of the costs for the situation of one big field is given in the column 'One'.
Figure 6 shows that there is a change in optimal working direction when the working width increases. The sides refer to the numbers inside the field; the actual field with the tramlines is the subfield that is left when one round around the whole is realised.

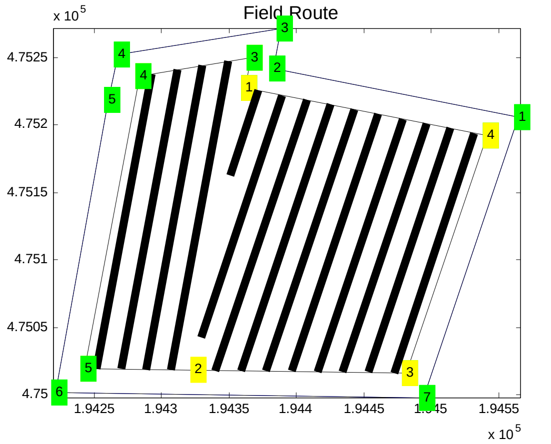

Figure 5 – Field B split in two subfields and operated in an optimal way with a working width of 18 m. Thick lines represent the tramlines.

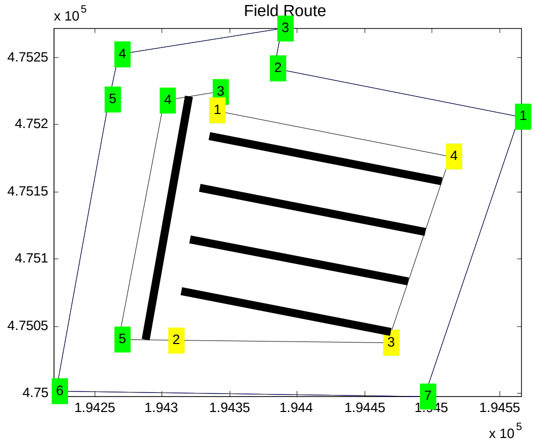

Figure 6 – Field B split in two subfields and operated in an optimal way with a working width of 39 m. Thick lines represent the tramlines.

Table 2 - Operation costs for all directions of Field B for the left and the right subfield with a working width of 18 m. Bold figures are the 'optimal' solution.

	Left subfield				Right subfield				One
Parallel to side	2-5	**5-4**	4-3	3-2	1-2	2-3	**3-4**	4-1	3-1/1-2
Costs (€)	30.08	**13.15**	28.30	15.03	30.12	33.65	**30.10**	33.68	45.15
Time (hour)	0.46	**0.20**	0.44	0.23	0.46	0.52	**0.46**	0.52	0.69

Table 3 – Operation costs for all directions of Field B for the left and the right subfield with a working width of 24 m. Bold figures are the 'optimal' solution.

	Left subfield				Right subfield				One
Parallel to side	2-5	5-4	4-3	**3-2**	1-2	2-3	**3-4**	4-1	3-2/1-2
Costs (€)	20.29	9.64	20.22	**9.62**	22.96	22.91	**21.04**	22.90	32.58
Time (hour)	0.31	0.15	0.31	**0.15**	0.35	0.35	**0.32**	0.35	0.50

Table 4 – Operation costs for all directions of Field B for the left and the right subfield with a working width of 39 m. Bold figures are the 'optimal' solution.

	Left subfield				Right subfield				One
Parallel to side	2-5	5-4	4-3	**3-2**	1-2	2-3	3-4	**4-1**	3-2/1-2
Costs (€)	10.28	3.01	10.16	**3.00**	27.62	25.97	27.60	**25.86**	30.62
Time (hour)	0.16	0.05	0.16	**0.05**	0.42	0.40	0.42	**0.40**	0.47

Figure 7 shows the results for Field C. The corresponding data are in Table 5. The most interesting is the right subfield. The most logical direction at first sight would have been parallel to side 7-6 but the most optimal direction is parallel to side 5-2.

Table 5 – Operation costs for all directions of Field C for the left and the right subfield with a working width of 12 m. Bold figures are the 'optimal' solution.

	Left subfield				Right subfield					One
Parallel to side	1-2	2-3	3-4	**4-1**	2-1	1-7	7-6	6-5	**5-2**	1-2/5-2
Costs (€)	6.13	11.57	11.57	**4. 34**	38.10	34.53	32.68	32.72	**29.08**	35.21
Time (hour)	0.09	0.18	0.18	**0.07**	0.59	0.53	0.50	0.50	**0.48**	0.57

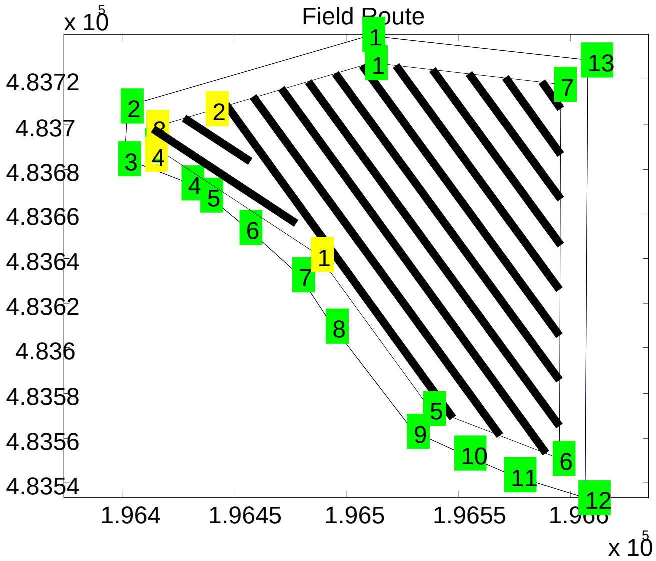

Figure 7 - Field C split in two subfields and operated in an optimal way with a working width of 12 m. Thick lines represent the tramlines.

Discussion

The results presented before show that for regular convex shaped field the optimal solution is the expected solution, usually with the first tramline parallel to the longest side.
For more complex situations, as for example concave fields that are split in two or more convex fields, the solutions appear to be not logical. The main reason for this is that the subfields are managed individually and not in connection with each other. In for example Figure 5 a more logical solution would have been for the both the left and the right subfield a direction parallel to side 3-2 of the left subfield or 1-2 of the right subfield. The total costs then would have been 45.15 euro (compared to 43.25 euro). This is due to that at this moment the tool does not include a penalty for outcomes as shown in for example Figure 5 which result in a lot of turning in the middle of the field.
For Field C the optimal solution (parallel to side 2-5) has 3.60 euro less costs than the more logical solution (parallel to 6-7). The more logical solution has less of situations where the field is either not operated or operated twice. This can be due to that there is at this moment no penalty for not or twice operating an area. When this penalty is included, it can be still true that parallel to side 2-5 is the most optimal solution. If that is the case, it will be clear that the most logical solution is not always the most optimal solution. Such a tool is therefore also helpful to reconsider the way operations are executed and new technologies such as RTK-GPS may enable more optimal solutions that are in practice more difficult to realise without these new technologies.
The costs for one big field are 4 to 6% higher, compared with the ‘optimal’ solution. The costs for one big field are based on that the direction is parallel to the split line of the field. In some specific situations one tramline can be saved but then there will also be some additional costs for the area not covered or covered twice at the transition between the two subfields.
At this moment the starting point is that the tramline direction is parallel to one of the sides of the field. In the case of two neighbouring subfields there will always be an operation where the directions of the tramlines for both subfields are the same (i.e. parallel to the dividing line between both subfields). In case of three or more neighbouring subfields the direction of the second nearest neighbour should be considered because this can yield at the end the most

optimal solution. Required for this is that penalties are introduced for non optimal solutions (i.e. solutions with overlap, not operated areas, or turning inside the field).
Not implemented yet is the start point for the operation in each subfield. Choosing appropriate start points can result in less driving over the field to operate all subfields.

Conclusion

We have developed a tool for determining the optimal path for field operation. However, the tool is not complete yet. It gives optimal solutions for single convex fields. When fields consist of more than one subfield the current optimal solutions are not necessarily the optimal solutions. For this it is necessary to include also a penalty for operating parts of the field twice or not at all (when tramlines are not perpendicular to the headland), and for solutions that require turning inside the field around the dividing line of two neighbouring subfield that are both part of the total field.

Acknowledgement

This paper is based on the MSc thesis work of Hans IJken. This work is executed in close cooperation with Agrovision in Wageningen/Deventer, The Netherlands.

References

1. Bochtis, D.D.and Vougioukas, S.G., 2008. Minimising the non-working distance travelled by machines operating in a headland field pattern. Biosystems Engineering 101(1):1-12
2. Jin, J. and Tang, L., 2006. Optimal path planning for arable farming. ASABE Paper 061158, St. Joseph, Mich.: ASABE
3. Oksanen T. and Visala, A., 2007. Path planning algorithms for agricultural machines. Agricultural Engineering International, The CIGR EJournal, Volume IX
4. Sørensen, C.G, Bak, T. and Jørgensen, .R.N., 2004. Mission planner for agricultural robotics. [Unpublished]
5. Stoll, A., 2003. Automatic operation planning for GPS-guided machinery. Precision agriculture. Eds Stafford, J. and Werner, A. Wageningen: Wageningen Academic Publishers, 657-644
6. Taïx, M., Souères, P., Frayssinet, H. and Cordesses, L., 2006. Path Planning for Complete Coverage with Agricultural Machines. Field and Service Robotics. Volume 24. Berlin / Heidelberg: Springer, 549-558