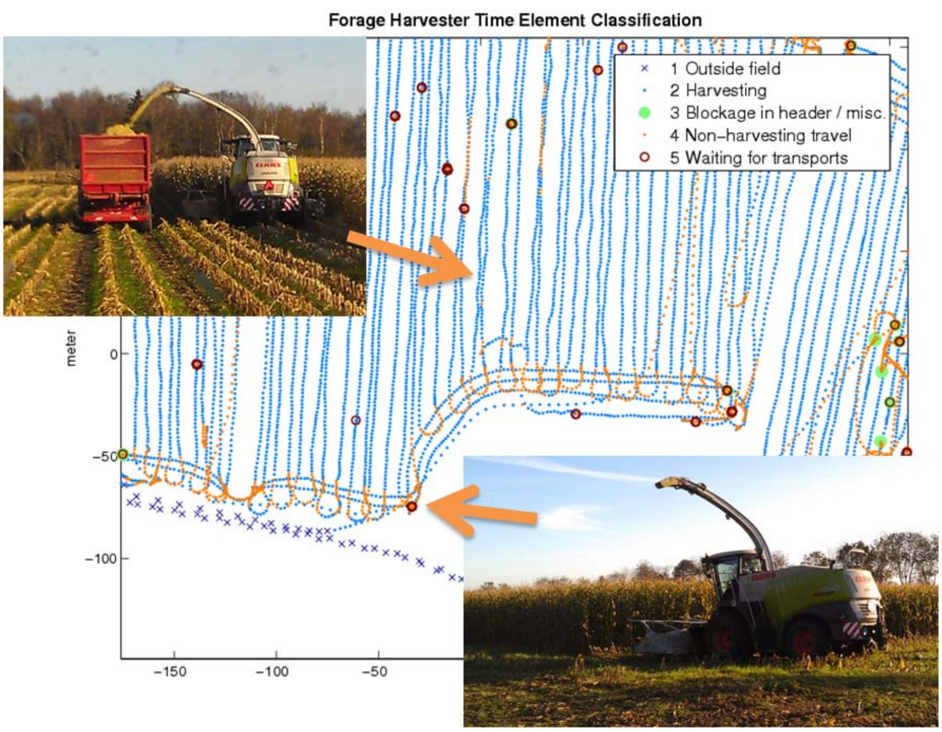
ALGORITHMS FOR OPERATIONAL PLANNING OF AGRICULTURAL FIELD OPERATIONS

Mechanical Engineering
Technical Report ME-TR-3



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1) The GNSS-based monitoring and recording of 5 large scale harvesting operations executed by fleets of agricultural machinery (E.g. Maize harvesting executed by 1 forage harvester and 5 transport carts and grain harvesting executed by 3 combines and 3 transport carts).
2) The development of a method for the automatic extraction of performance statistics from GNSS recordings of multiple-machinery operations. Classification algorithms have been created able to automatically classify the task time elements based on the recordings from GNSS loggers.
3) The development of a path planning method for transport units supporting harvesting operations. The approach incorporated i) the optimization criterions of time or travelled distance; ii) the generation of paths for both in-field and between fields movements of the transport units; and iii) the adoption of restricted movements as imposed by the controlled traffic farming concept.

Keywords: Agricultural equipment, Automation, Decision support, Operations research, Robotics, Operational planning, Path Planning, Assessment Tool, Data-mining, Activity Recognition

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Abstract

The report describes the current project activities on the development of optimization methods for planning agricultural field operations and on the estimation of the potential benefits for farmers by comparing optimized plans with conventional ones. The complete activities include:

1) The GNSS-based monitoring and recording of 5 large scale harvesting operations executed by fleets of agricultural machinery (E.g. Maize harvesting executed by 1 forage harvester and 5 transport carts and grain harvesting executed by 3 combines and 3 transport carts).

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1 Introduction to the field of research

Cooperative field operations are executed by one or more primary unit/s (PU/s) performing the main work task and one or more service unit/s (SU/s) supporting the PU/s Bochtis and Sørensen (2009; 2010). For example, in a harvesting operation a self-propelled harvester may be supported by transport wagons used for out-of-the field removal of harvested grain.

As far as it concerns the operational planning of single units (exclusively for single PU) a significant amount of research has been recently carried out in the areas of field coverage planning (Bochtis, 2008a), field representation (Hameed et al., 2010; de Bruin et al., 2009), and control architectures and systems (Garcia-Perez et al., 2008; Coen et al., 2008). Furthermore, at the commercial level, a number of computerized navigation systems have been developed for PU's (harvesters), ranging from guidance aiding to full auto-steering systems based on satellite, mechanical (touch sensors) and optical (Laser, 3-D cameras) technologies (cf., CLAAS Steering systems: "A perfect line", 2009 brochure).

Regarding the operational planning of multiple PU's, Bochtis (2008b) has presented a method for on-line traffic re-planning for multiple harvesters. The main task of field coverage was structured and therefore it was expressed as the traversal of a weighted graph, where each swath represents a node and the problem of finding optimal traversal sequences is equivalent to the multiple travelling salesman problems (m-TSP).

Regarding the operational planning of heterogeneous cooperating units (PUs and SUs), there is a limited amount of research available. Bochtis et al. (2007) presented an algorithmic approach for on-line cooperation of combines and transport carts during grain harvesting operation. The method regards a real time optimization with criterions involving the minimization of the distance travelled by the SU and the minimization of the probability that a combine will interrupt its operation while waiting for a SU to unload its temporary grain hopper. Bochtis and Sørensen (2010), using the abstraction that PU's are the ''customers'' in the vehicle routing problem with time windows (VRPTW) methodology, showed that operational planning problems related to cooperating PUs and SUs can be cast as instances of the VRPTW and consequently, can be solved by adopting algorithmic approaches developed within this domain.

2 Aim of project

- The aim of the project is to develop algorithms for optimization of operational planning of units.
- Furthermore as the project is an Industrial PhD.-project, the aim is to disseminate knowledge to the involved company, CLAAS Agrosystems.
- To gain practical knowledge of the field operations, it has been the aim to record various operations with GPS loggers.

3 Methods, results and conclusions so far

3.1 Conceptualizing a path planning system for transport units

A paper has been published in the peer-review journal “Computers & Industrial Engineering” (Jensen et al, 2012). The paper presents a concept of using a path planning algorithm to optimize the path traveled of a transport unit in a harvest operation.

The main scientific contribution of the work is the formal representation of the fields and road network as a mathematical graph. The work is applicable to the Controlled Traffic Farming system or field operations where crossing of tracks, other than along them, is prohibited.

Software was written in MATLAB in order to illustrate the concept. Figure 1 shows the optimized path that a transport unit should take to minimize the distance (Figure 1a) or time (Figure 1b) of the travel between two fields.

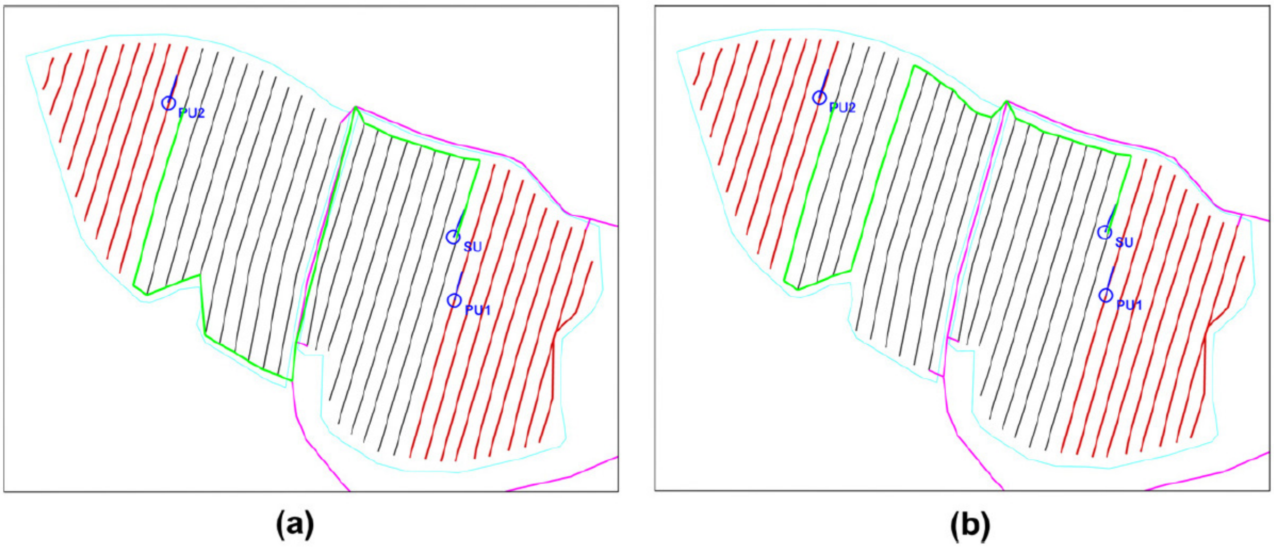

Figure 1 - The location of the SU (transport unit) and PU (harvester) are the same but optimality criterion is in a) time and b) distance, which gives two different paths.

The abstract of the paper is:

“Path planning in agricultural field operations involving cooperating machines (e.g. combine harvesters and transport units) has to satisfy both the objectives of the individual mobile unit and the team of the cooperating mobile units. Especially, the planning and execution efficiency for transport units can significantly affect the productivity of the whole system. In this paper a path planning method for transport units in agricultural operations involving in-field and inter-field transports was presented. The approach incorporated 1) the optimization criterions of time or travelled distance; 2) the generation of paths for both in-field and between fields movements of the transporting units; and 3) the adoption of restricted movements as imposed by the controlled traffic farming concept. A "Metric Map" is generated involving the creation of a geometric description of the different fields, the followed fieldwork pattern by the harvester, and the road network associated with the coupled operation. The topology of the Metric Map is then represented by a graph on where the single-source path planning problem is solved by implementing the Dijkstra's algorithm. Based on the results provided by selected scenarios, alteration between optimality criterions provides discrepancy between solutions in the range of 2-10% indicating that identification of the appropriate criterion suited to the specific operational conditions is of significant importance. Furthermore, the low computational requirements of the planer, taking into consideration the realistic demands of the harvesting operation system indicating that it is feasible to use the planner for on-line planning efforts."

3.2 Collection and playback of GPS recordings of Agricultural Field Operations around Denmark

Field operations were recorded using GPS receivers mounted in the window of the vehicles (See Figure 2). The GPS receivers have memory and battery for about 24 hours of driving with a recording frequency of 1Hz. The receivers are cheap, costs about 300DKK, and very easy to mount on the vehicles.

The accuracy of the receivers seems to be adequate for measurement of the operation efficiency.

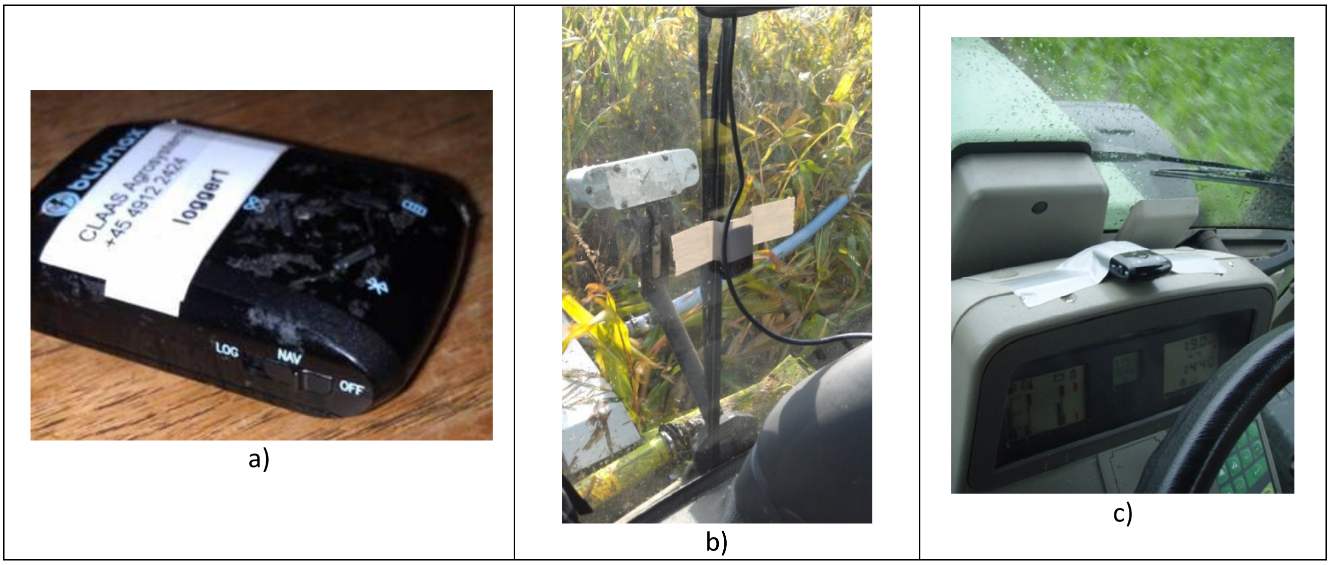

Figure 2 – a) Close-up photo of the GPS receiver and of the receiver taped to the window of a forage harvester and on the dash board of a tractor.

a)

b)

c)

Figure 3 – Examples of recorded vehicles: a) Forage harvester next to a maize field. b) Tractor pulling a trailer filled with chopped maize plants. C) Offloading of material at a farm.

Table 1 – Overview of recorded Agricultural Field Operations during the project.

Place	Time	Field operation	Vehicles recorded
Eskilstrup Maskinstation, Falster	September 2011	Maize silage harvest	1 forage harvester 5 tractor+trailer pairs
Vittrup Maskinstation, Jylland	Oktober 2011	Maize silage harvest	1 forage harvester 3 tractor+trailer pairs
-	July 2012	Grass mowing	1 tractor with mower implement.
-	-	Grass raking	1 tractor with raking implement.
Hverringe Gods, Fyn	September 2011	Wheat harvest	3 combine harvesters 3 tractor+trailer pairs

The GPS receiver writes the position measurements to a log-file in the NMEA standard. In order to play back the operation a script was made that converts the NMEA log-file to a KML file readable by Google Earth.

a)

b)

Figure 4 – Screenshots from the Google Earth application. Google Earth makes it possible to playback the operations. In a) only the boundary of the fields has been harvested. Later in b) most of the interior field has been harvested.

3.3 Automatic extraction of performance statistics from GPS recordings of multi-machinery operations

Monitoring of machinery field operations for a subsequent performance evaluation requires either the off-line manually registration and decomposition of the recorded data into relevant time elements (e.g. Sørensen & Nielsen, 2005), or the direct extraction of operations data from different logging devices (Grisso et al., 2002; Taylor et al., 2002). The former option is very time consuming while the latter requires special recording equipment.

The aim of this work is to create algorithms or *classifiers* that can automatically classify the operational time elements based on recordings from inexpensive and easily applicable GNSS loggers. This will make it possible to compare results of operational planning algorithms compared to conventional practices of farmers.

I have developed the algorithms for a forage harvest operation with one forage harvester and any number of transport units. The classifier for the forage harvester is called HARVESTER, and the classifier for the transport units is called TRANSPORT. The required inputs to the algorithms are:

- *GPS log-files of all involved vehicles*. In the study I use cheap GPS loggers, around 300kr per logger. They have moderate accuracy, which is sometimes visible in the data. For example in areas of the field where the harvester is covering parallel lines, there are situations where the position is *measured* to overlap previously covered lines. This is not due to bad driving by the harvester, but errors in position measurements.
- *Working width of forage harvester.*
- *Coordinates of field boundaries.* These boundaries should make sure to contain all movement of the harvester and transports related to the harvest. So rather make the boundaries a little too large than too small. The main purpose of the boundaries is to distinguish between classes involving in the collection of crop and travel on the rural roads. Retrieving the field boundaries can for example be done in Google Earth, as was done in this study.
- *Coordinates of the drop-*off *area boundary*. This is the area where cropped material is drop-off.
- *Time periods of longer personal breaks should be provided e.g. lunch break etc.* The software cannot discriminate between some kinds of situations. For example a situation where all vehicles are stopped for a lunch break will be classified identically to a situation where vehicles are stopped temporarily because maize is stuck in the header.

3.3.1 Low level classifiers

The HARVESTER and TRANSPORT classifiers are built by combining results from the following lower level classifiers:

- LOCATION: Using the field and drop-off boundaries, identify which points are inside a field, outside and inside the drop-off area.
- COVERAGE: Is applied to the trajectory of the forage harvester to identify where it is covering new area thus harvesting, and where it is covering previously covered area thus not harvesting.

- STOP: Identify where a vehicle is stopped and where it is driving.
- SERVICE: Identify which transport unit is servicing the harvester and which transports are waiting in queue behind the servicing transport.

3.3.1.1 COVERAGE classifier

The COVERAGE classifier tells whether the area covered by the vehicle in each time element has been covered in a previous time element or not. In a maize harvest operation this can be used to infer whether the harvester is harvesting crop or not.

The algorithm works by building a polygon of covered area by going through the trajectory iteratively called the *worked polygon*. If the covered area in a time element overlaps the worked polygon with less than 20%, the vehicle is said to be harvesting. The algorithm requires the *working width* as input. To increase computational speed without sacrificing accuracy much, the Douglas-Peucker Polyline Simplification algorithm is applied to the worked polygon at every 200th trajectory point.

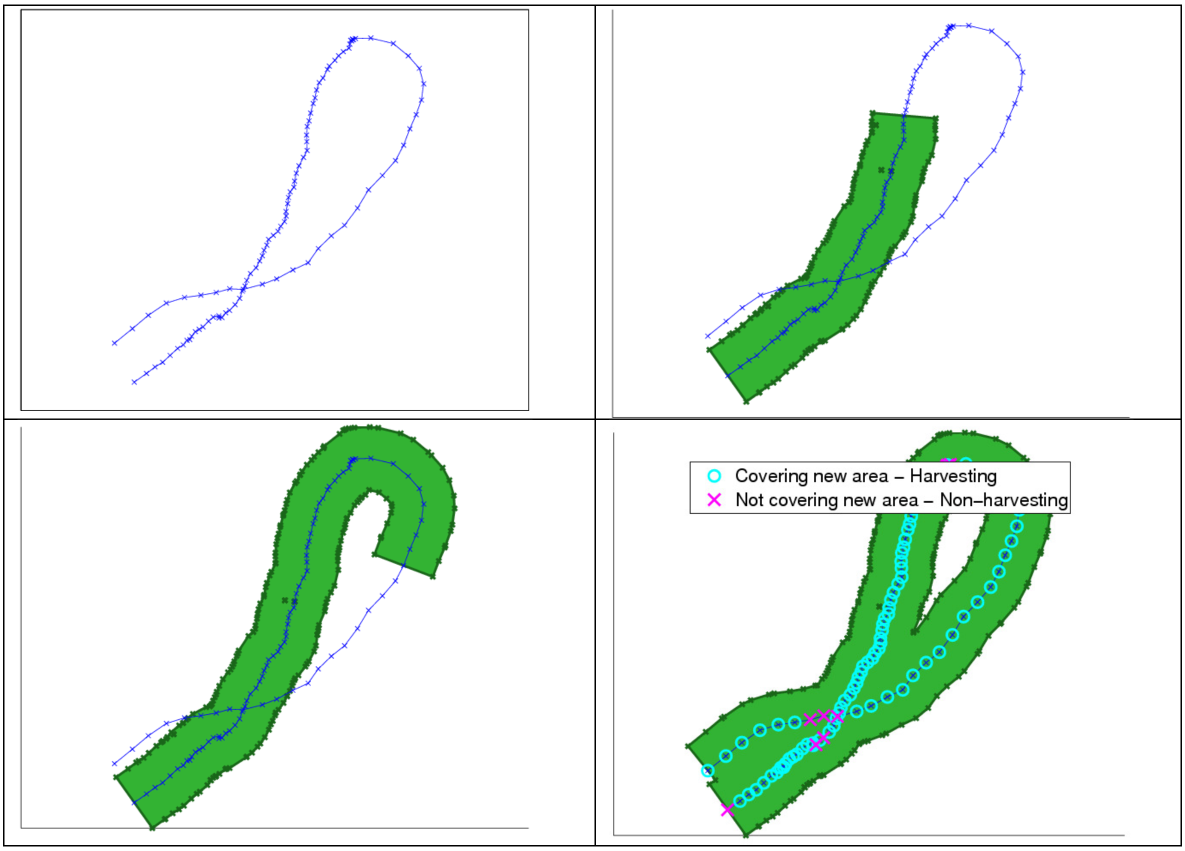

Figure 5 - From upper left to lower right, the plots show how the worked polygon is built iteratively from the trajectory (upper left plot). The points where new area is covered are classified as "Harvesting" otherwise "Non-harvesting".

3.3.1.2 STOP and SERVICE classifiers

The STOP classifier predicts whether the vehicle is in a stopped state or driving. This state is detected by requiring the vehicle to have had a very low speed for at least a given duration. The speed is estimated at each trajectory point. A point is "stopped" if the speed is below a threshold of 0.3 m/s and if it is a period of stopped points for at least 10 seconds.

The SERVICE classifier predicts whether transport wagons are within service distance of the harvester and whether they are close to another transport being close to the harvester. First it is found out if transport unit is servicing the harvester, and in that case which one. This is the closest machine with distance below *d_servicing*. Next we check if any of the other transport units are within *d_queue* distance from the servicing transport unit. Following this logic, it is established for each time point, which transport unit is servicing the transport unit, q0, which one is in queue position 1, q1, queue position 2, q2, etc. d_queue is set to 20 meters. *d_servicing* is set higher, because the transporter units usually keeps a larger distance from each other.

An example is shown in Figure 6. Here transport unit, T3, is servicing the harvester, H1, and transport unit T1 is driving in queue. Circles are drawn around H1 and T3 with a radius of respectively *d_servicing* = 20m and d_queue = 2 * *d_servicing* = 40m.

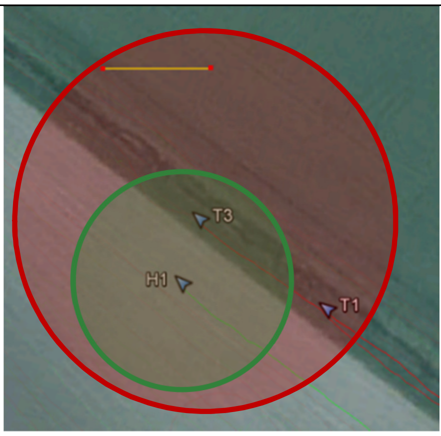

Figure 6 - Snapshot of a maize harvest with transport unit 3 servicing the harvester and transport unit 1 driving in queue to service.

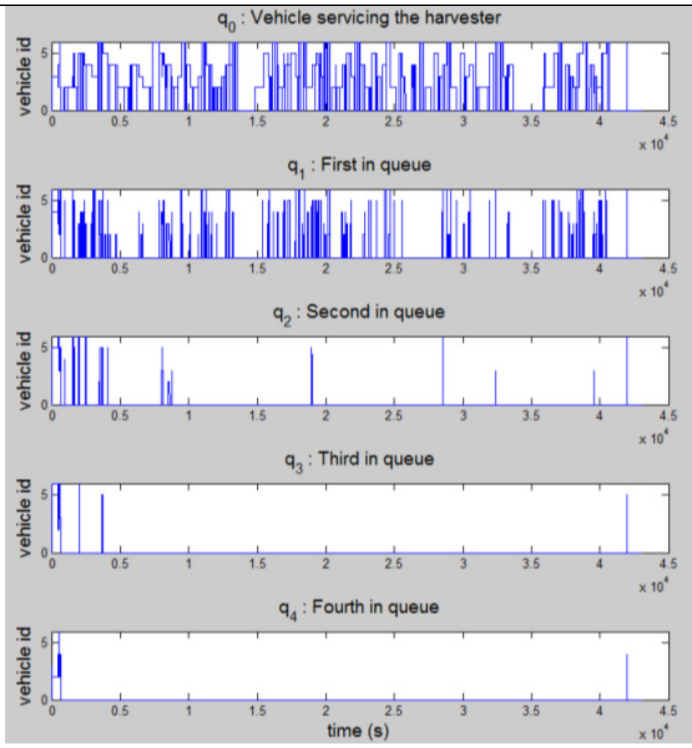

Figure 7 - Plot of q0,q1,..,q4. q0 > 1 means that one of the transport units are servicing the harvester. q1 > 1 means that one of the transport units are in queue position 1, driving in queue behind another transport unit.

The Figure 7 shows the functions q0, q1, q2, q3 and q4. As expected a lower number of transport units in queue is more frequent than a higher number in the queue.

To find out if a transport unit is driving in queue in a given time point, it is simply checked if either q1, q2, q3 or q4 equals that vehicle id.

The results of the STOP and SERVICE classifiers are seen in Figure 8. It seems that they are functioning well. Later this is verified using manually created reference data.

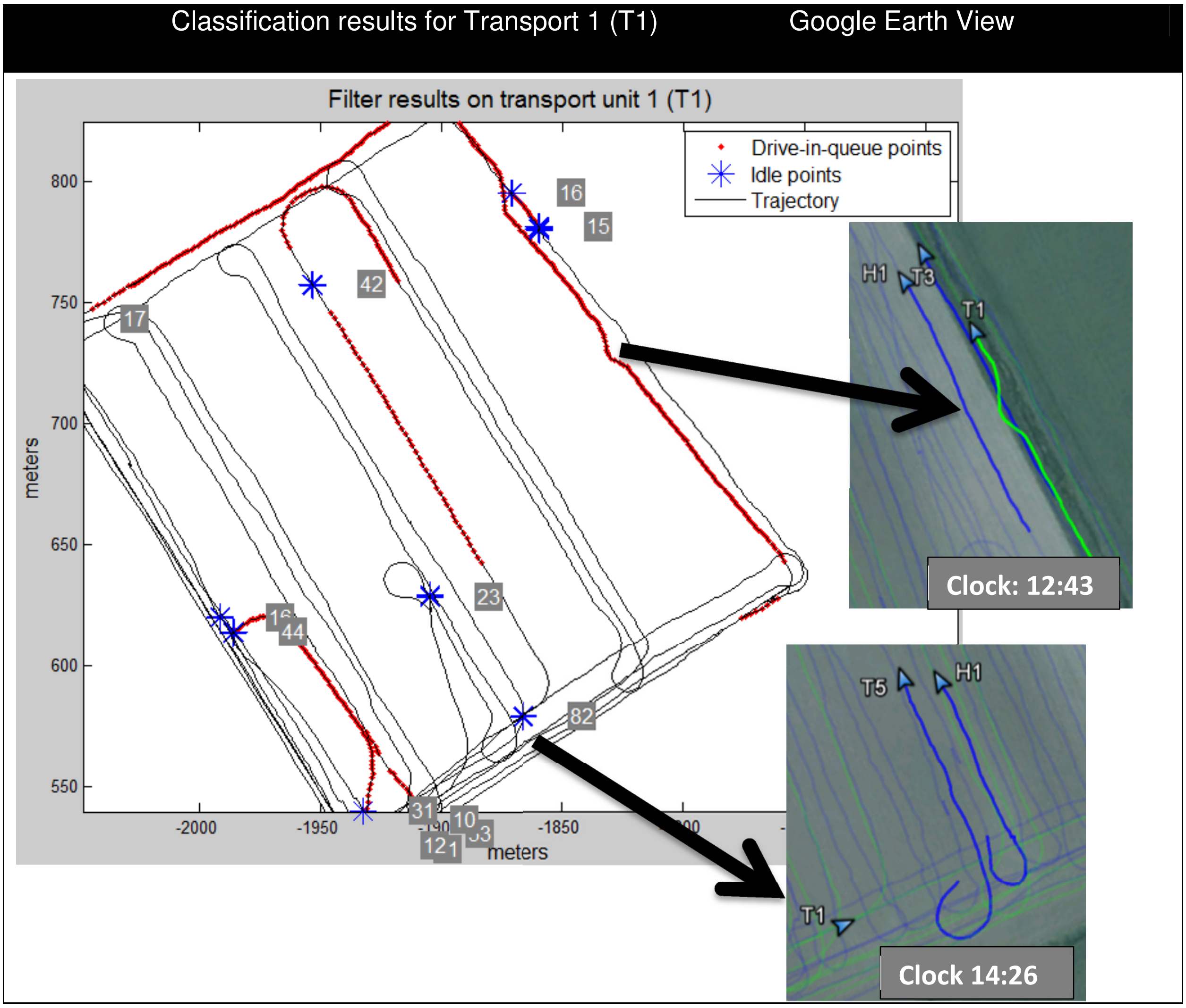

Figure 8 - (Right side) Trajectory of Transport unit 1 (T1) is plotted, along with idle points in blue colors and driving-in-queue points in red color. Numbers in squares are duration of the idle period in seconds. (Left side) Two parts of the trajectory of T1 is viewed in Google Earth along with the trajectory of the other vehicles. The thick part of drawn trajectories corresponds to 60 seconds.

3.3.2 Combining low level classifiers to create HARVESTER and TRANSPORT classifiers

The classifiers were designed by identifying requirements for the various situations in a forage harvest operation. When the harvester is harvesting for example, the harvester is inside a field and is covering new area. These requirements are seen in the upper left part of the Harvester Classification Tree in Figure 9 . When the harvester is making a non-productive turn where it is not able to harvest, it is driving inside a field and covering area previously covered. Or when the forage harvester header is blocked with maize, the harvester is stopped and there usually a stopped transport unit next to it. The requirements needed to classify all classes are identified using this logic and can be seen for the harvester in Figure 9. Likewise the transport classes are identified and can be seen in Figure 10.

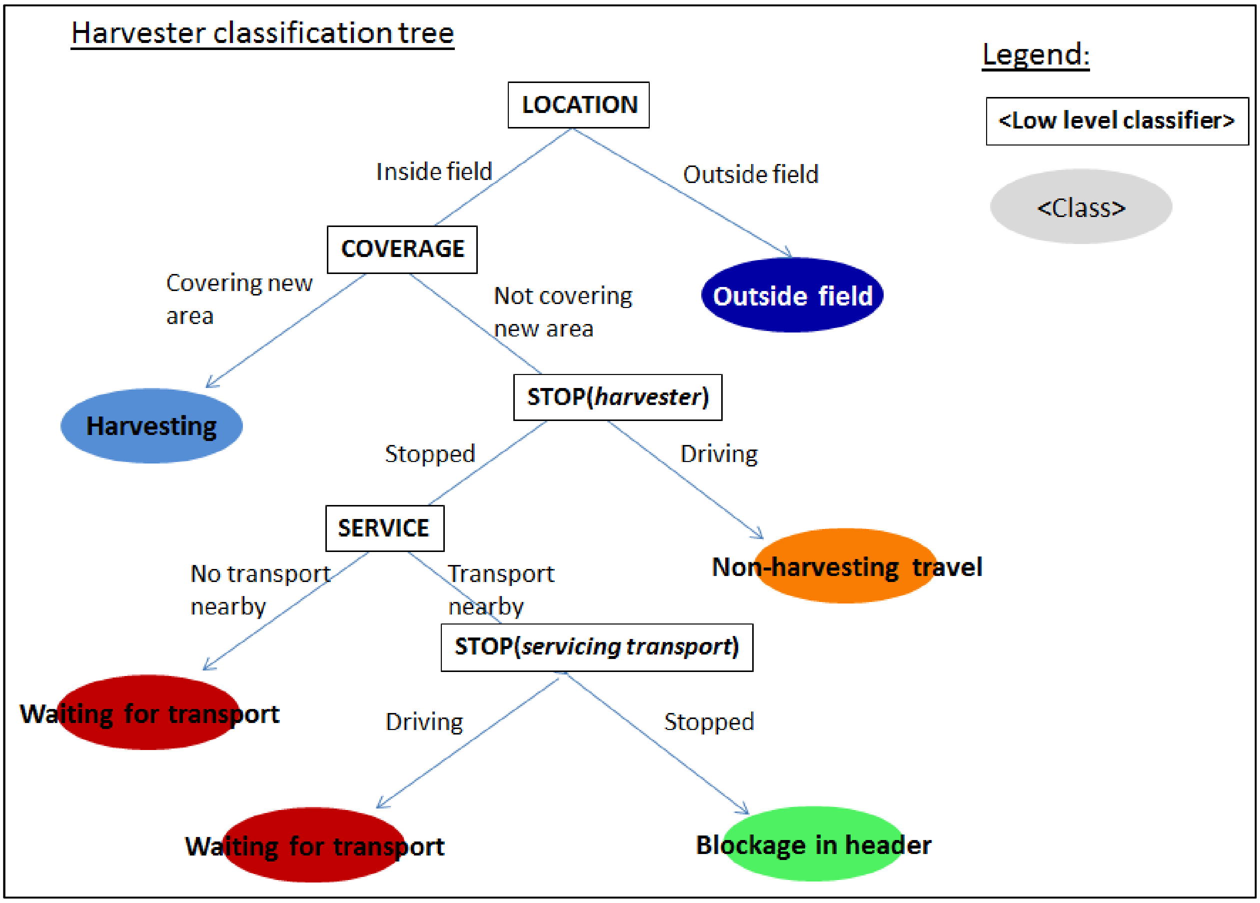

Figure 9 - The HARVESTER classifier is described by requirements to the results of the lower level classifiers LOCATION, COVERAGE, STOP and SERVICE.

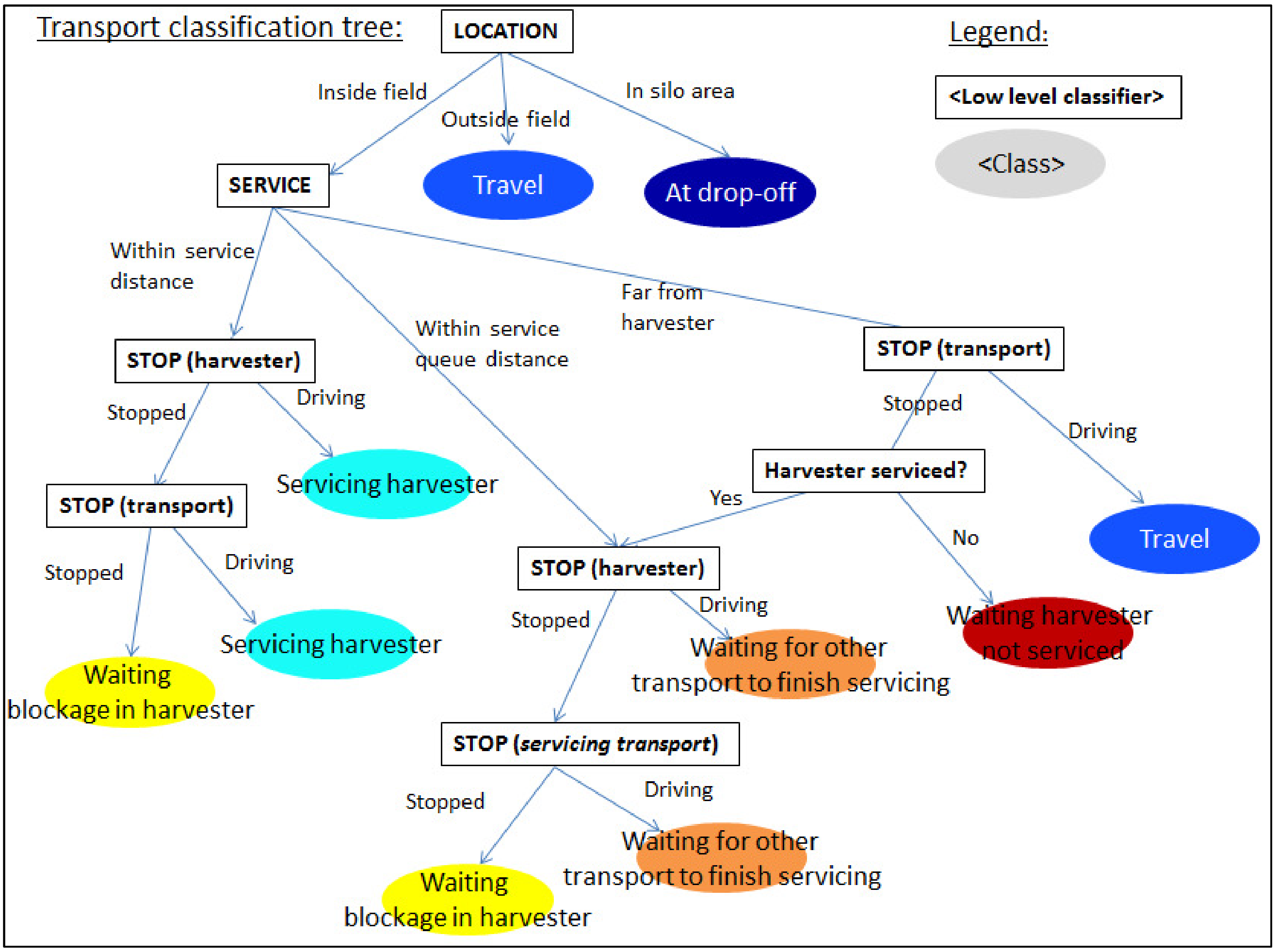

Figure 10 - The TRANSPORT classifier is described by requirements to the results of the lower level classifiers LOCATION, STOP and SERVICE.

3.3.3 Results

The classifiers are applied to the data from real forage harvest operations recorded at Eskilstrup and Vittrup Maskinstation. The classification results for a forage harvester and a transport unit can be seen in Figure 11 and Figure 12.

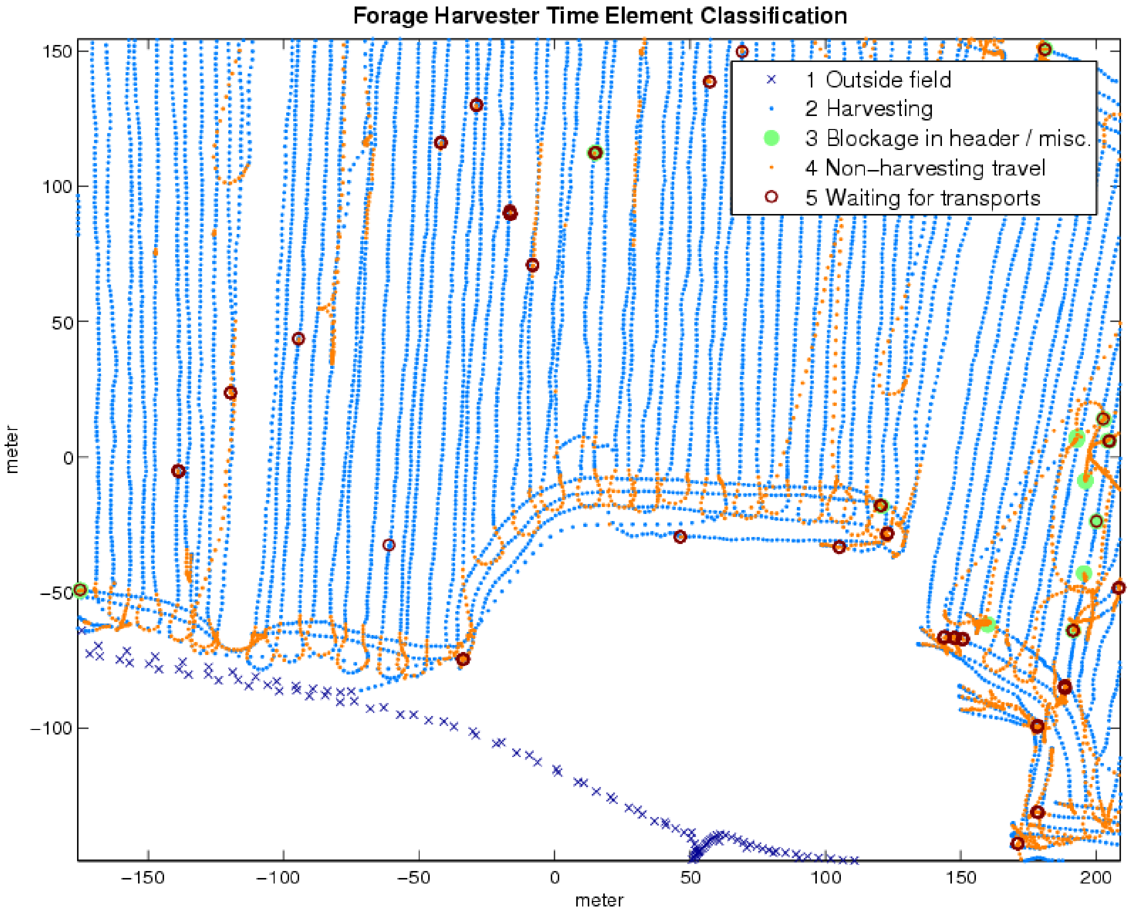

Figure 11 - Harvester classification results. The harvester initially harvests the boundary of the field to make room for the transport units and the later u-turns. Because of this the harvester will not harvest any material in the u-turns. In the figure it can be seen that the classifier successfully classifies points on the u-turns at the boundary of the field as "Non-harvesting travel".

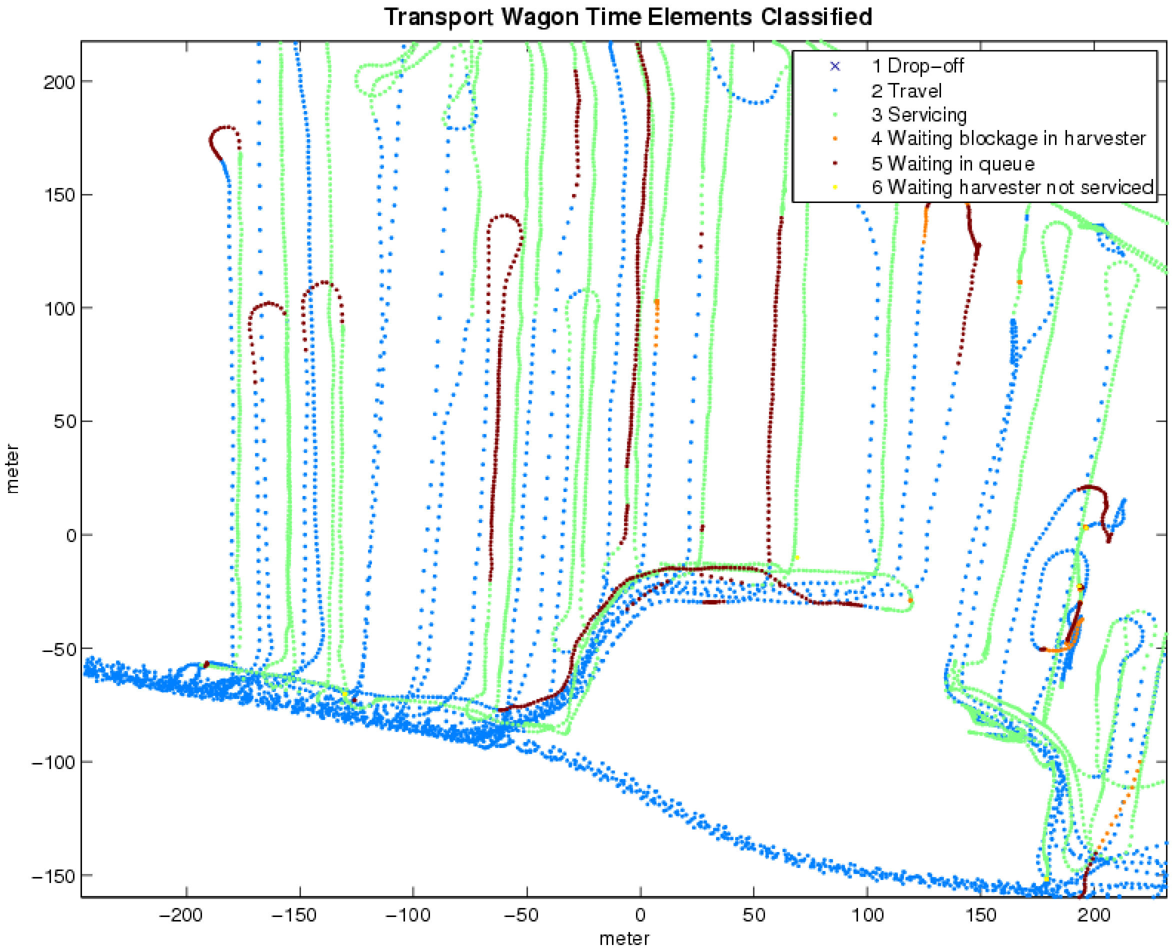

Figure 12 - Transport classification results. Notice that the transport unit must many times wait for another transport to finish servicing the harvester.

The classifier detection performance is evaluated by comparing predicted labels with a manual defined reference. The reference where made by playing back the operation in Google Earth and judging from experience what the respective vehicles are doing. In order to create an unbiased reference set, time elements of respective vehicles are manually classified at predefined points in time e.g. UTC 7:10, 7:30, 7:50, etc. This forced the reference set to contain random samples of the full data set thus creating an unbiased reference set. In another selection scheme a biased reference set could occur because only situations easily classified would be selected.

The detection performance of the two classifiers, HARVESTER and TRANSPORT, are reported with *error matrices* showed in Table 2 and Table 3. The use of error matrices is necessary when the occurrences of the classes are unbalanced as they can be in this case. Reporting purely a high accuracy does not reveal that there might be many errors of classifying to the minority class. Looking at the error matrices, the HARVESTER classifier seems to work satisfactory and the *Balanced Error Rate* is calculated to be 6%. The TRANSPORT classifier has relatively many errors when trying to predict the class "Waiting for other transport to finish servicing harvester". Investigating these errors in detail reveals that four of them were due to the field boundary being too tight. Another error was due to the manual created reference was wrong. Correcting these errors gives a Balanced Error Rate of 7%.

Situations occur which are not defined in the classifier like *personal breaks* and *towing of vehicles*. It seemed difficult to design the classifiers to segment out those classes from the rest.

3.3.4 Use of classifications

The classifications can be summed to create pie charts indicating the efficiency of operations. Comparing the pie charts from forage harvesters of two different operations can give a clear answer to which is most efficient (See Figure 13).

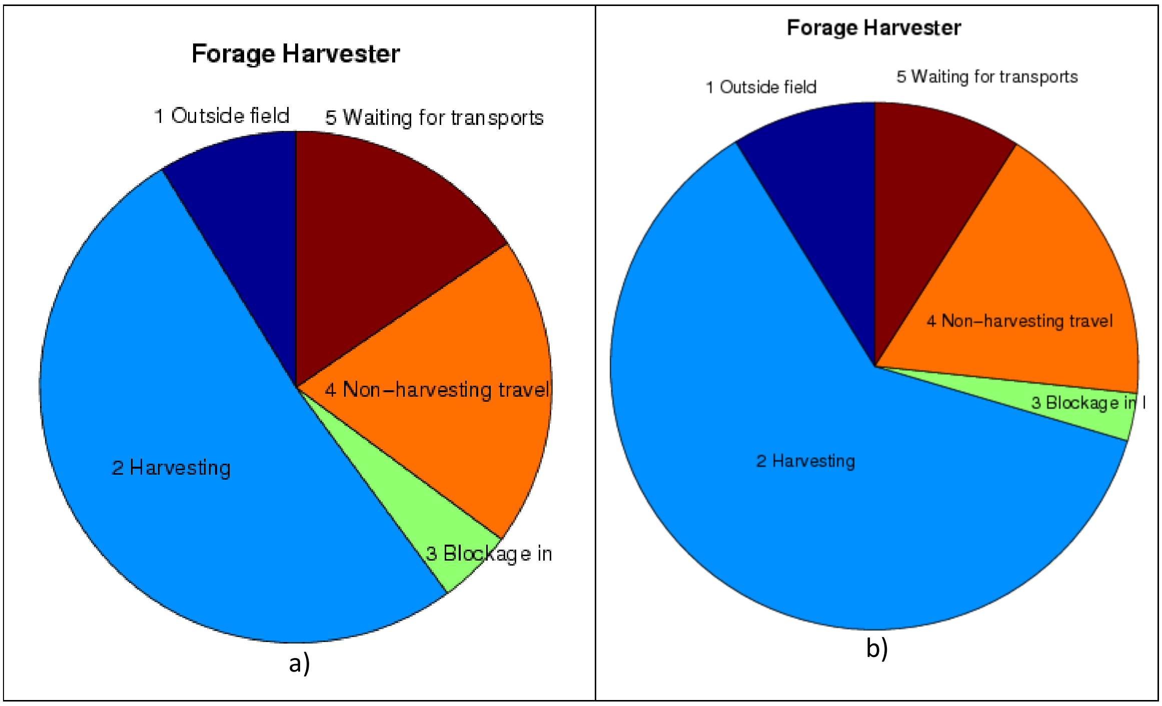

Figure 13 – Pie charts of harvester time elements from two different operations. b) is clearly more efficient having relatively less waiting time due to lack of available transport units and more harvesting time.

Table 2 - HARVESTER classifier error matrix. Few errors are present.

		Predicted class				
	HARVESTER error matrix	Outside field	Harvesting	Blockage in header, prep. for towing etc.	Non-harvesting travel	Waiting for transport
Actual class	Outside field	5	0	0	0	0
	Harvesting	0	63	0	1	0
	Blockage in header, prep. for towing etc.	0	0	7	1	0
	Non-harvesting travel	0	1	0	11	0
	Waiting for transport	0	0	1	0	9
	Personal breaks	*0*	*0*	*0*	*0*	*1*
	Towing of vehicles	*0*	*0*	*0*	*1*	*0*

Table 3 - TRANSPORT classifier error matrix. There are relatively many errors when classifying "Waiting for other transport to finish servicing harvester". Four of them can be removed by enlarging the field boundaries.

		Predicted class					
	TRANSPORT error matrix	At drop-off	Travel between harvester and drop-off	Servicing harvester	Waiting because of header blockage in harvester	Waiting for other transport to finish servicing harvester	Waiting while harvester not serviced
Actual class	At drop-off	18	1	0	0	0	0
	Travel between harvester and drop-off	0	43	0	0	0	0
	Servicing harvester	0	2	14	0	0	0
	Waiting because of header blockage in harvester	0	0	0	0	0	0
	Waiting for other transport to finish servicing harvester	0	7	0	0	11	0
	Waiting while harvester not serviced	*0*	*0*	*0*	*0*	*0*	*0*
	Personal break	*0*	*3*	*0*	*0*	*0*	*1*

4 Plan for remaining of study

The plan is to further mature topics within field coverage planning (Bochtis, 2008a). I call this "Track Sequence Optimization", because the main result of the technology is an optimized sequence of working the tracks in the field. An example of an optimize track sequence of an virtual field in Figure 14.

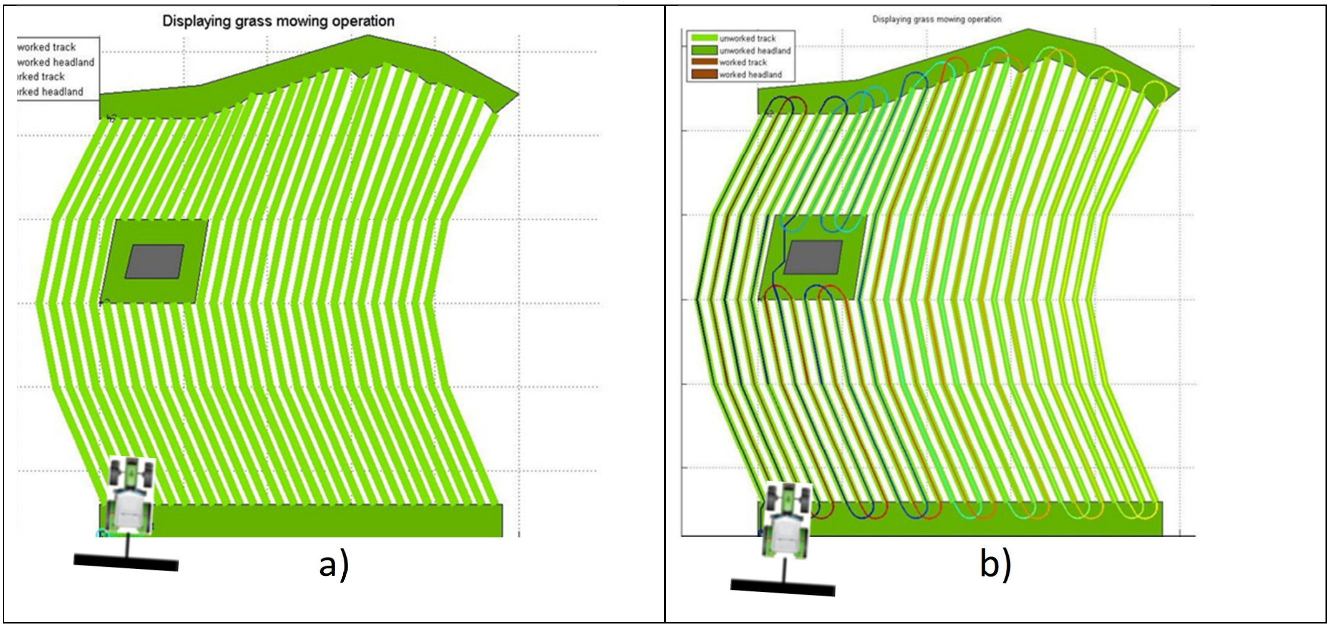

Figure 14 – a) A tractor is about to mow a grass field. The optimized track sequence, minimizing the non-working distance is shown in b).

Ultimo November 2012: **Submit paper** about the automatic extraction of performance statistics from multi-machine forest harvest operation.

December 2012 and January 2013: Concept development of Track Sequence Optimization for combine harvesters maximizing the possibility of on-the-go offloading to transport units while minimizing non-productive time.

February 2013 – May 2013: Prepare field tests of Track Sequence Optimization.

Complete 5 ECTS course on "Implementation of heuristics for the Travelling Salesman Problem".

Summer 2013: Attend conference.

Autumn 2013: Finish field tests of Track Sequence Optimization.

December 2013: **Submit paper** about experience with execution and implementation of real-time in-field Track Sequence Optimization.

January-April 2014: Write PhD-thesis.

5 Appendix: Other activities

5.1 Courses attended.

- **ACAI Summer School 2011**. Lectures in software for automatic planning and scheduling. Inspired by Artificial Intelligence research.
- **Department of Biosystems Engineering PhD-Summer School 2011**, "Operations Management in bio-production".
- **Industrial PhD-course 2011**, Copenhagen Business School. Introduction to organizations, intellectual property rights, innovation, business strategy.
- **Network & Integer Programming 2011**, Technical University of Denmark. Mathematical tools to solve Network problems and general Integer Programming problems.

5.2 Conferences attended:

- **ICAPS 2011,** International Conference on Automated Planning and Scheduling, Germany. Conference was attended in connection with ACAI summer school.
- **NJF 2011**, Nordic Association of Agricultural Scientists, Denmark. Gave talk about CLAAS Agrosystems. Presented poster from "Operations Management in bio-production" summer school titled "Analytical derived headland turning cost".
- **CIGR-AgEng 2012**, International Conference of Agricultural Engineering, Spain. Presented poster titled "Automatic extraction of transport unit performance statistics in multi-machinery harvest operation from GNSS recordings".

5.3 Activities related to CLAAS Agrosystems:

- Attended **Agritechnica 2011,** world largest exhibition for the agricultural machinery industry, with the purpose of making a review of available Route Planning technology.
- Further developed concept of Single Machine Track Sequence Optimization technology based on (Bochtis 2008a).
- Presented overview of research in Reference line and Guidance lines generation.
- Six months leave from PhD, Spring 2012. Full time employed at CLAAS Agrosystems to implement Single Machine Track Sequence Optimization technology.

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