Advances in agricultural machinery management: A review

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ADVANCES IN AGRICULTURAL MACHINERY MANAGEMENT: A REVIEW

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Abstract

The introduction of intelligent machines and autonomous vehicles in the agricultural operations domain will allow for increased efficiency as well as for reduced environmental impact. Currently, innovative sensing and actuating technologies together with improved information and communication technologies provide the potential for such advancements. However, the full exploitation of these engineering advances requires the traditional agricultural machinery management process to be revisited. As a result, the traditional agricultural operations planning methods, especially the job-shop planning methodology, must be supplemented with new planning features, such as route planning and sequential task scheduling.

The objectives of this review are to outline current and required advances in agricultural machinery management to prepare for future intelligent manned and/or autonomous sustainable operations in agriculture. In the following sections, five key management tasks for agricultural machinery management are selected that span the various management phases and levels. These tasks are i) capacity planning (strategic level), task times planning (tactical level), scheduling (operational), route planning (operational level), and performance evaluation (evaluation level). For each of the management tasks, the definition is provided, and then, the most recent related literature is presented. Finally, the future requirements which will facilitate and set the framework for the development efforts necessary for fully implementing future agricultural management models and tools are discussed.

Keywords: capacity planning; scheduling; task times planning; route planning; performance evaluation; field robots.

1 INTRODUCTION

Physical optimisation has been the primary driver for improving agricultural machinery productivity and efficiency. This evolution has been caused by the archived benefits from economies of scale providing improved mechanical functionality; however, this trend is currently being impeded by environmental and biological factors that constrain the size and weight of the machinery (e.g., soil compaction) (Day, 2011). Thus, only marginal improvements to the effectiveness of modern agricultural machinery are possible. In this sense, further improvements to effectiveness are not available, but current engineering advances in innovative sensing and actuating technologies together with improved information and communication technologies hold the potential for significant improvements in the efficiency of these advanced machines. However, the full exploitation of these engineering advances requires the traditional agricultural machinery management process to be revisited. As a result, the traditional agricultural operations planning methods, especially the job-shop planning methodology, must be supplemented with new planning features, such as route planning and sequential task scheduling. Moreover, agricultural machinery management must be viewed in a different way than machinery management in the general industrial domain. Compared with the industrial setting, the bio-production domain is subject to a greater role of the environment and the inherent uncertainty and risk (e.g., crop growth or weather conditions) that characterise any farm process. Additionally, the domain variables have relatively large variances, and the planning procedures have large time constants. In general, risky decisions are the norm for agricultural machinery operations.

The objectives of this review are to outline current and required advances in agricultural machinery management to prepare for future intelligent manned and/or autonomous sustainable operations in agriculture. This will facilitate and set the framework for the development efforts necessary to fully implement future agricultural management models and tools.

In the following sections, five key management tasks for agricultural machinery management are selected that span the various management phases and levels: capacity planning, task times planning, scheduling, route planning, and evaluation. For each of the management tasks, the definition is provided, and then, the most recent related literature is presented. Finally, the future requirements are discussed.

2 MANAGEMENT PHASES AND LEVELS

According to ASABE Standards (ASAE S495.1, 2005), the following four phases are identified in the management of operations and tasks for agricultural machinery:

- **Planning**: System components are selected and the expected performance of the system is predicted
- **Scheduling**: The time when the various operations are to be performed is predicted taking into account factors such as availability of time, labour supply, job priorities, and crop requirements

- **Operating**: Executing the operations using labour and machines
- **Controlling**: The systems is controlled by utilizing various productivity measures and standards

Although the above mentioned processes are not aligned with the ones generally defined in engineering management discipline, it will be abided by in this review for the sake of recognisable historic categorisation schemes within the realm of agricultural machinery management. Such categorisations involve that different management tasks for agricultural machinery operate at different management levels (Sørensen et al., 2010). The following gives a description and a structuring of the agricultural production management activities within the different defined levels:

- **Strategic**: Design of production system for a period of 1-5 years or 2 or more cropping cycles – and specifically the labour/machinery system in connection with the selected types of crops
- **Tactical**: Setting up a production plan for a period of 1-2 years or 1-2 cropping cycles narrowing down the resource usage, i.e. labour input and machinery input adjusted to the current crop plan
- **Operational**: Determining activities in the current cropping cycle. It includes a short term timing of the activities, and the formulations of jobs and tasks
- **Execution**: Controlling the executed tasks and the work-sets performance
- **Evaluation**: Comparing planned and actual executed tasks

From the above listed agricultural production management levels, the examination of the execution level has been excluded from the present review since there is not a considerable work on related management tasks in the agricultural machinery domain (such as dynamic decision making and planning, reactive planning based on fault diagnostic systems, etc.). Furthermore, a number of decision making tasks on this level are overlapped with control tasks and covering such issues is beyond of the scope of the presented review.

3 AGRICULTURAL MACHINERY MANAGEMENT TASKS

Five key management tasks for agricultural machinery management were selected that span the various management phases and levels (Fig. 1). These management tasks are capacity planning, task times planning, scheduling, route planning, and performance evaluation. These selected management tasks cover the majority of the topics that have been addressed by ASABE Standards (ASAE EP496.3, 2006), including tractor performance, power requirements, field machine performance, reliability, cost of use, and selection of field machine capacity. However, the topic of “replacement” was not included in the present review, as it purely addresses economical attributes[1].

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[1] The authors are aware of only one recent study on the generalised topic of replacement: Aurbacher et al., (2011).

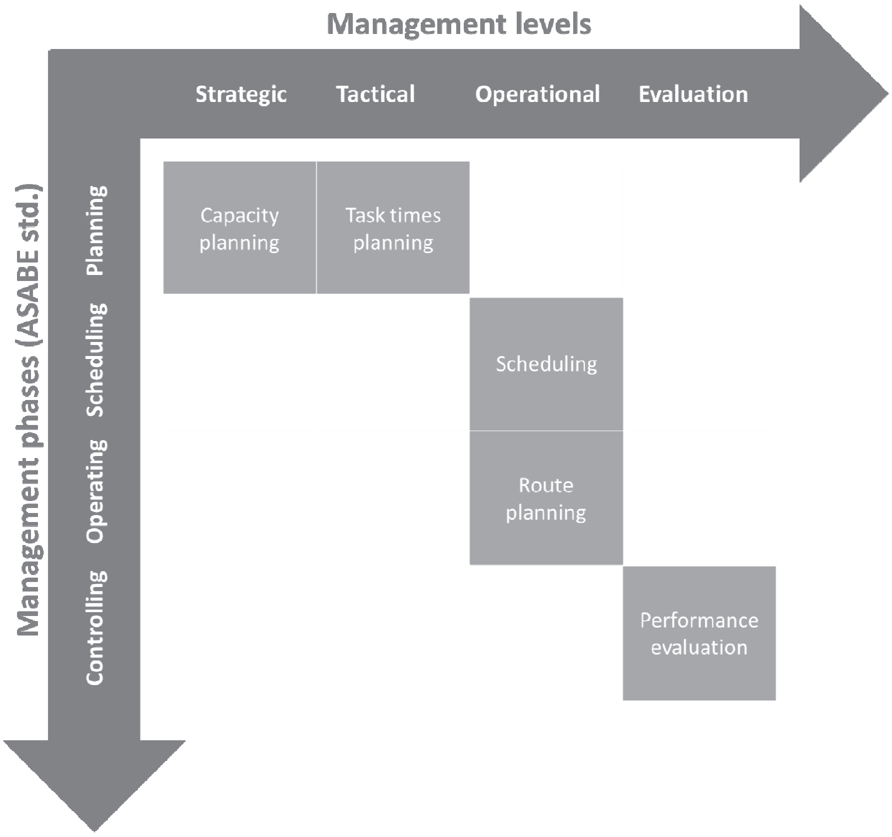

Figure 1 – The five selected management tasks for agricultural machinery to be reviewed and their relation to the general management phases and levels

3.1 Capacity planning

3.1.1 Definition

Capacity planning is part of the system design and concerns both a qualitative and a quantitative selection of production components (i.e., in the particular case, machinery and supporting equipment) as related to the demand. As in the case of the industry floor production, the objective is a generic optimisation of the use of the components (including their dimensions). Capacity planning is governed by 1) demands of the operation to be performed, 2) availability of equipment, 3) possible working methods, 4) dimensions and capacity, and 5) cost, in addition to the consideration of functions such as available labour, timeliness, and workability. Compared with industry, capacity planning is performed within a domain characterised by many uncertain factors relating to biological plant growth, weather, etc.

3.1.2 Related work

In the following, only the most recent research (i.e., applied during the last decade) on capacity planning is presented; the main features of the approaches are presented in Table 1. Sørensen (2003a) adapted models to predict harvesting workability hours as governed by the hourly pattern of the crop moisture after maturity under different historic weather conditions. This workability prediction based on 30-year weather data was integrated into a farm-level optimisation model to predict the optimal machinery size for harvesting. de Toro & Hansson (2004) also measured workability by developing a simulation model for field machinery operations using a discrete event simulation technique to analyse machinery performance based on the daily status of soil workability. A more location-specific extension of the previous work was presented in de Toro (2005) to address cereal farms in Sweden.

A system-specific model for capacity planning was developed by Søgaard & Sørensen (2004). The optimisation model was based upon a least-cost concept involving all expected fixed and variable costs (including timeliness costs) of a particular farm size and crop plan. The output from the model is the sizing of each machine, including the tractor power and number of tractors required. Specifically, for the case of tillage, Sahu & Raheman (2008) developed a decision support system for matching tillage implements with tractors and for predicting the performance of the system. The conditions that are taken into account include the operating conditions, depth of tillage, speed of tillage, soil conditions, density and texture.

Regarding the capacity planning based on the timeliness cost, de Toro et al., (2012) developed a simulation model in which several combinations of harvester sizes and grain moisture ceilings were assessed in terms of overall costs (machine - labour - timeliness - drying) and annual variations. Gunnarsson et al., (2009) presented a method for estimating timeliness costs depending on dry-matter yield and nutritive value of forage to examine different harvesting systems and to present conclusions of machinery selection when harvesting silage for dairy cows in Sweden.

Table 1 – Capacity planning approaches and their funcionalities

	Optimisation method	**Criterion**	**Timeliness**	**Workability**	**Targeted operations and crops**
Sørensen , (2003a)	Simulation and analytical optimisation	Harvesting cost (fixed and operational machinery cost and timeliness)	YES	YES	Harvesting of arable crops
de Toro & Hansson, (2004)	Discrete event simulation	Fixed and operational machinery cost, timeliness cost, and labour cost	YES	YES	Whole farm system
Søgaard & Sørensen, (2004)	Analytical model of non-linear programming	Minimisation of the total annual Costs (fixed and operational)	YES	YES	Whole farm system
de Toro, (2005)	Discrete event simulation	Fixed and operational machinery cost, timeliness cost, and labour cost	YES	YES	Whole farm system
Sahu & Raheman, (2008)	Simulation	performance of the tractor-implement system (tractive performance, power utilisation, turning time, fuel consumption, overall efficiency)	NO	NO	Tillage of arable crops
Gunnarsson et al, (2009)	Simulation	Fixed and operational machinery cost, timeliness cost, transportation and storage cost, and labour cost	YES	YES	Forage harvesting
de Toro et al., (2012)	Discrete event simulation	Fixed and operational machinery cost, timeliness cost, drying cost, and labour cost	YES	YES	Grain harvesting

3.2 Task times planning

3.2.1 Definition

Task time planning refers to the assignment of time durations to activities. Activities could be field operations ("operation" here is used in its agronomical sense, e.g., harvesting) or work elements (e.g., transport). Task time planning is a prerequisite for scheduling.

Table 2 – Task times planning approaches and their functionalities

	Modelling approach:	Criterion	Case study	Operational features included	Time horizon
Sørensen et al., (2003)	Analytic modelling of farm operations, and simulation	Task duration, partial costs (for specific tasks)	Whole manure handling chain	Labour input, and capacity performance	Task specific
Sørensen, (2003b)	Analytic modelling of farm operations, and simulation	Task duration	Manure application in the field	Labour input, and capacity performance	Task and machine specific
Buckmaster & Hilton (2005)	Analytic modelling of cycle times for farm operations, system analysis	Task duration, capacity, efficiency measures	Grain harvesting and transport	Labour input, and capacity performance	Task specific
Sørensen & Nielsen, (2005)	Analytic modelling of farm operations, and simulation	Task duration, energy	Tillage operations	Inclusion of energy requirements	Task specific
Sørensen et al., (2014)	Analytic modelling of farm operations, and simulation	Task duration, energy	Tillage operations with varying intensity	Labour input, and capacity performance	Task and machine specific

3.2.2 Related work

Sørensen et al., (2003) developed an assessment tool that covers the entire chain of the manure handling system from the animal houses to the field. The tool enables a system-oriented evaluation of labour demand, machinery capacity and costs related to the handling of manure. The task time modelling and analysis refer to different technologies, i.e., the continuous flow of transport and application of organic fertiliser using umbilical transportation systems and the traditional tanker transport. Sørensen (2003b) developed a task time modelling framework for evaluating the operational performance of manure-handling machinery given specific external and internal conditions on the farm. The knowledge base encompasses capacity and labour requirements for the application of organic fertiliser using injection or trailing hoses. Finally, Sørensen & Nielsen (2005) used task time planning as the basis for comparing different tillage systems in terms of energy inputs, CO_2 emissions, and cost. Generalised task models fitted with parameters from farm studies were beneficial for evaluating the operational performance and incurred costs of using different tillage systems. Buckmaster & Hilton (2005) developed a computerised system for analysing the interaction of equipment and task times in dynamic operations systems. Outputs included system capacity, idle machine time, and efficiency measures (e.g., hours of work per hours of real time). Sørensen et al., (2014) used specific task models for labour and machinery input as the basis for estimating energy inputs and greenhouse gas emissions of different tillage systems. Task times were estimated for a number of constrained machinery systems and tillage scenarios across a modelled crop rotation. Table 2 summarises the above-mentioned works.

3.3 Scheduling

3.3.1 Definition

Scheduling concerns the allocation of resources (e.g., machines, labour, processing units) to tasks (e.g., operations in a production process) over given time periods; the goal is to optimise one or more objectives (e.g., makespan, total weighted completion time, maximum lateness). In an agricultural context, scheduling is defined as "*determining the time, when various operations are to be performed. Availability of time, labour and machinery supply, job priorities and crop requirements are some important factors*" (ASABE Standards, 1974). Two general types of scheduling problems can be found in the bio-production systems domain, namely (van Elderen, 1980):

a. pure scheduling problems where the start time and end time must be decided for each task (e.g., in the seasonal planning of field operations) and
b. sequencing problems where tasks that compete for the use of shared resources must be ordered (e.g., in the operational planning of large-scale harvesting).

3.3.2 Related work

The first scientific approaches that supported the scheduling process in agriculture appeared in the early 1980s, e.g., van Elderen (1980), and were mainly based on linear programming and simulation methodologies. These early approaches regarded pure scheduling problems, whereas a number of approaches dealing with sequencing planning have appeared only recently in the literature. Guan S., Nakamura, Shikanai, & Okazaki (2008) introduced hybrid Petri nets into modelling farm work flow, which describe the farming process and reallocation resources in the presence of uncertainties. As a continuation of this work, Guan et al., (2009) proposed resource assignment and scheduling based on a metaheuristic approach. Foulds & Wilson (2005) developed an approach for scheduling the harvest of renewable resources. An extension of the techniques developed in the previous work from the single-farm level to the multi-farm was presented in Basnet et al., (2006).

Typical operational research formulations for scheduling problems applied in industrial manufacturing, such as the job shop scheduling problem (JSSP) or the flow shop scheduling problem (FSSP) have been proposed for casting sequencing scheduling problems in agricultural field operations (Bochtis, 2010). Based on this concept, Bochtis et al., (2013b) formulated the problem of finding a permutation schedule for a number of geographically dispersed fields where several sequential biomass handling operations must be performed as a flow shop with a sequence-dependant set-up time scheduling problem. This approach regards the case of a single machine per operation type. An extension to the case of multiple-machinery available per operation type was presented in Orfanou et al. (2013).

Table 3 presents the above-mentioned works and their functionalities.

Table 3 - Scheduling approaches and their funcionalities

	Modelling approach:	**Criterion**	**Case study**	**Operational features included**	**Time horizon**
Foulds & Wilson, (2005)	Integer programming formulation. Solving algorithm: two targeted case-specific heursitcs	Completion time of the last task (makespan)	Rape seed harvesting Hay harvesting	Inclusion of minimum and maximum time lags	Harvesting period season
Basnet et al., (2006)	Integer programing formulation. Solving algorithm: greedy heuristic combined with tabu search	Completion time of the last task in the last field (makespan)	Rape seed harvesting and handling	Minimum and maximum time lags	Harvesting time of the fields under consideration
Guan et al., (2008)	Hybrid Petri nets combined with mixed integer non-linear programming	The maximum of the starting times of all of the tasks	Sugarcane production	Cooperative work and uncertainties	Not specified
Guan et al., (2009)	Hybrid Petri nets combined with a two-phase metaheuristic based on simulated annealing and genetic algorithms	Idle time between tasks	Sugarcane production	Cooperative work, and uncertainties	Whole cropping season
Bochtis et al., (2013)	Formulation as a flow shop with sequence dependant set up times scheduling problem	Completion time of the last task in the last field (makespan)	Cotton residues harvesting and handling	Incorporation of task time prediction models	Harvesting time of the fields under consideration
Orfanou et al., (2013)	Integer programing. Algorithm: Greedy heuristic combined with tabu search (as in Basnet, Foulds, & Wilson, 2006)	Completion time of the last task in the last field (makespan) and operational cost	Grass harvesting and handling	Incorporation of task time prediction and operational cost estimation models	Harvesting time of the fields under consideration

3.4 Agricultural vehicles routing

3.4.1 Definition

Agricultural vehicles can be categorised as primary or supporting units. According to the acknowledged definitions (Bochtis & Sørensen, 2009), the term “primary unit” refers to an agricultural machinery unit that performs the main work task (e.g., a tractor-sprayer combination), whereas the term “supporting unit” refers to a unit supporting one or more primary units (e.g., grain carts in a harvesting operation).

The work of a primary unit is related to the area coverage plan which encompasses the problem of determining how the carried implement of the unit passes over all points in a targeted spatial environment under criteria such as minimising cost, time, and overlap. Different approaches have been developed that deal either partially or completely with the problem of area coverage in agricultural operations. Two types of approaches can be distinguished in the related literature.

The first type of approach deals solely with the process of *spatial configuration planning*. Spatial configuration planning can be defined as the process of generating a geometrical representation of a field area to provide a concise representation of the operational environment that can be readily used for subsequent planning efforts (e.g., a route plan or area coverage plan). In principle, spatial configuration planning includes three tasks: the division of the entire field area into sub-field areas (when necessary), the determination of the driving direction within each of the sub-fields, and the determination of the fieldwork tracks that completely cover each one of the sub-field areas.

The second type of approach addresses the process of *route planning*. Route planning concerns the task of the optimal connection of the entities defined previously by a spatial configuration plan; this includes the optimal sequencing of the fieldwork tracks and/or the optimal sequencing of the sub-field areas. Typically, the route planning approaches also include a spatial configuration approach.

The core aspect of the above-mentioned approaches is that agriculture field operations include working distance elements (i.e., fieldwork tracks) and non-working distance elements (i.e., headland turnings). This fact diversifies area coverage planning for field operations, with the general notion of area coverage planning as it appeared in other scientific disciplines (e.g., robotics) in which several path planning based approaches have been developed. A third type of approach is that in which a continuous path is generated that covers the entire area under question. In this case, a distinction is not made between the tasks of spatial configuration and route planning.

In the case of supporting units, the planning task regards the optimal connection between two positions: the current position of a supporting unit and the position when the servicing of a primary unit must occur.

3.4.2 Related work

3.4.2.1 Area coverage planning for primary units

The related studies on area coverage planning are presented for the following four categories. The features of all planning approaches are listed in Table 4. In terms of the route planning process, field operations that involve a full coverage of the field area can be diversified as capacitated and non-capacitated. Capacitated refers to the operations in which a quantity of a “commodity” is either transported out of the field area (output material flow, e.g., harvesting) or transported and distributed in the field area (input material flow, e.g., spraying); the agricultural machine has to execute more than one route to complete the operation. Non-capacitated refers to the operations in which there is neither material addition nor material removal to/from the field (neutral material flow, e.g., tillage or mowing). Note that operations in which the primary unit is serviced on-the-go, from the primary unit area coverage point of view, are considered without capacity restrictions.

3.4.2.1.1 Pure spatial configuration planning approaches

Many studies have been presented for spatial configuration planning that take into account either specific operations or the entire set of operations for a cropping system. Because the headland pattern is almost exclusively the adopted strategy for the coverage of a field area by an agricultural machine, all of the developed methods dedicated to spatial configuration address the generation of set(s) of parallel field work tracks. The most challenging task of the related research is the treatment of complex non-convex field shapes. Several methods have been developed over the last decade that implement a variety of different optimisation criteria to deal with two-dimensional or three-dimensional search spaces and with free-obstacle areas or areas with physical obstacles, whereas some of the methods can be used in real-time planning systems.

The first attempt was introduced by Palmer et al, (2003) in which a method to generate pre-defined field work tracks under the criterion of reducing overlapped and missed areas was presented. de Bruin et al., (2009) presented a method for optimising the spatial configuration of field work tracks while modifying field margins to provide space for biodiversity. The approach relocates areas of inefficient machine manoeuvring to boundary strips by minimising the costs of area loss and additional field work tracks minus any subsidy received for field boundaries. Bochtis et al. (2010b) presented an approach to evaluate the consequences, in terms of machinery performance of different driving directions, of establishing tramlines in a controlled traffic system under the criterion of minimising the total cropping period operational cost. The main result from this work was that the general rule of establishing field work tracks parallel to the longest edge of the field does not hold in the case of a controlled traffic system. The same conclusion was also derived by Oksanen & Visala (2009). Hameed et al., (2010) presented a spatial configuration method for the generation of both straight and curved field work tracks. In Hameed et al., (2013), the method was expanded to three dimensions for the case of material input operations to provide optimal field work tracks configuration under the criterion of minimising the energy requirements. The case-based results showed an energy requirement reduction of up to 6.5%, which was the average for all the examined scenarios compared with the case of assuming 2D field areas. Jin & Tang (2010) developed an approach for field area decomposition and coverage direction determination within each sub-area for 2D field areas. The results showed that in the most extreme cases, the developed algorithm saved up to 16% in the number of turns and 15% in the headland turning cost. Jin & Tang (2011) developed an approach to deal with 3D terrain maps of field areas. Each field was decomposed into sub-regions based on its terrain features. Compared with the 2D planning results, the experimental results of 3D coverage path planning was superior in reducing both headland turning cost and soil erosion cost. On the tested fields, on average, the 3D planning algorithm saved 10.3% of the headland turning cost, 24.7% of the soil erosion cost, 81.2% of the skipped area cost, and 22.0% of the weighted sum of these costs.

3.4.2.2 Pure route planning approaches

As previously mentioned, route planning methods provide a traversal plan of the distinct geometrical entities constituting the spatial configuration of a field area. Because fieldwork tracks are the main entity for defining field area spatial configuration (in terms of area coverage), the optimal sequencing of these tracks is the centre of the route planning task for agricultural vehicles. Based on this routing approach, a new type of optimal field work pattern, B-pattern, has been recently introduced (Bochtis, 2008). B-patterns are defined as (Bochtis, et al., 2013): "*algorithmically-computed sequences of field-work tracks completely covering an area and that do not follow any pre-determined standard motif, but in contrast, are a result of an optimisation process under one or more selected criteria*". The optimal sequences are the unique result of the optimisation approach to the specific combination of the mobile unit kinematics and dimensions, the operating width, the field shape, and the optimisation criterion-criteria. The optimisation process involves the expression of the field coverage as the traversal of a weighted graph, where the weight of the graph arcs could be based on one or more optimisation criteria. Criteria include the minimisation of the total non-working travelling distance, total or non-productive operational time, total operational time, and a soil compaction measure. In the case of a non-working distance minimisation, a reduction of up to 50% in the total non-working travelled distance has been achieved by implementing the B-patterns approach (Bochtis & Vougioukas, 2008). In Bochtis et al., (2012), the reductions of the risk for soil compaction based on a selected risk factor were 23% and 61% for two experimental cases.

3.4.2.3 Combined spatial configuration and route planning approaches

Oksanen & Visala (2009) presented a greedy algorithm based approach for dividing a single field area into sub-fields that are simple to operate. The approach was based on a trapezoidal decomposition algorithm that takes into account practical aspects, such as the presence of under drainage in the field. Regarding the route planning aspects, the method also considers the functions of refilling or empting the machine's tank in the case of capacitated operations. Hameed et al., (2011) developed a two-stage approach, where the optimal driving direction is derived based on the minimisation of the overlapped area in the first stage and a sub-optimal generation of B-patterns is derived in the second stage. However, these sub-optimal solutions still proved more efficient than the conventional field work patterns based on the experimental results. A method for combining spatial configuration and B-pattern generation was presented by Spekken & de Bruin (2012).

3.4.2.4 Path planning approaches

Due to the specific features of the area coverage task in field operations, as mentioned previously, only a limited number of path planning approaches have appeared in the literature. A complete approach has been presented by Ali et al., (2009), who presented continuous coverage of the field area without explicitly considering field work tracks. This work was specific to the case of harvesting. However, it can be applied in the case of input material flow operations because it covers the case of out of the field travel of the primary unit to unload (to re-fill in the case of input material flow).

Table 4 – Area coverage planning approaches and their related features

	Planning type			**Geometric features**							
	Spatial configuration	**Route planning**	**Path planning**	**Dimensions**	**Sub-field division**	**Curved lines**	**In-field obstacles**	**Optimisation method**	**On-line capability**	**Criterion**	**Operations**
Palmer et al., (2003)	X			2D	NO	NO	YES	Exhaustive enumeration	Off-line system – manual interventions are needed	Minimisation of the overlapped and missed areas	Specifically for spraying
Bochtis et al., (2008)		X		2D	NO*	YES	NO	Generation of B-patterns. VRP formulation (as binary integer programming optimisation problem) implementation of the Clarke–Wright savings algorithm	Yes	Minimisation of the total non-working travelled distance	Non-capacitated operations
de Bruin et al., (2009)	X			2D	NO	NO	NO	Exhaustive enumeration (“brute force”)	Computational requirements are not mentioned	Minimisation of the cost of the lost area	Non-specific
Oksanen & Visala, (2009)	X	X		2D	YES	YES	YES	Greedy algorithm for the division of the area into sub-areas / Heuristic algorithm for the selection of the driving direction	Off-line system (4 min computational time is reported for an example case)	Three criteria in a weighted cost function: the relative efficiency (operated area divided by total time), the normalised area (area of a generated sub-area divided into the remaining area) and the normalised distance (travelled distance in a sub-area excluding the travelled distance in the headland area)	Both non-capacitated and capacitated operations
Ali et al., (2009)			X	2D	NO	NO	YES	Two approaches were presented: a) VRP with additional turn penalty constrains (integer linear programming), and b) modified minimum cost network flow problem	For fields of area higher than 5 hectares, the computational time tend to increase substantially	Non-working time	Harvesting operations for both on-the-go unloading (continuous harvesting) and out-of-the-field

								(mixed integer programming)			unloading (intermitted harvesting)
Bochtis et al., (2010b)	X			2D	NO	NO	NO	Exhaustive enumeration combined with simulation	Off-line system	Operational cost	The entire set of operations in controlled traffic farming systems
Hameed et al., (2010)	X			2D	YES	YES	YES	None	Case-dependent; in general, an off-line system	None	Non-specific
Jin & Tang, (2010)	X			2D	YES	NO	YES	Depth-first graph search for finding all possible lines that divided the entire field into two sub-regions. For the generation of the sub-areas and the driving direction, an algorithm based on the divide-and-conquer strategy was developed	The complexity of the algorithm was $O[n^3\log(n)]$ for a field with n edges in total. For all tested fields with no more than 20 vertices and five interior obstacles, the optimal solutions were found by the algorithm software within 60 s.	Minimising number of headland turns	Non-specific
Jin & Tang, (2011)	X			3D	NO	YES	NO	A heuristic-based approach where edge segments and contour lines are used as candidates, and a “seed” curve is generated	Computational requirements are not mentioned	Weighted function including headland turning cost, soil erosion cost, and skipped area cost.	Non-capacitated operations
Hameed, et al., (2011)	X	X		2D	NO	NO	NO	Three stages. Exhaustive enumeration of driving direction determination. A genetic algorithm for the other two stages (B-patterns generation and block sequence optimisation)	Computational time app. 20 min for two relatively simple shaped fields of app. 8 ha and 17 ha.	Minimisation of overlapped area (for the driving direction determination). Minimisation of total travelled distance	Non-capacitated operations
Bochtis, et al., (2012)		X		2D	NO[*]	NO	NO[#]	Generation of B-patterns. Implementation of a case – oriented brute force algorithm	Very low computational time requirements (on the scale of ms)	Minimisation of the risk of soil compaction	Capacitated operations. In general, when the agricultural vehicle carries time-dependent loads
Spekken & de Bruin, (2012)	X	X		2D	NO	NO	NO	Implementation of traveling salesmen problem (TSP) for the track sequence generation (Clarke–Wright savings algorithm)	Computational requirements are not mentioned	Non-working time during headland turnings	Non-capacitated operations and capacitated operations in which servicing occurs on the headlands
Hameed et al., (2013)	X			3D	NO	NO	YES	Exhaustive enumeration combined with an object-oriented simulation	High computational time requirements. Based on the case studies, the computational time ranged between 60 min and 380 min for two field areas of app. 11 ha and 21 ha	Minimisation of energy requirements (fuel consumption)	Capacitated operations

3.4.2.5 Route planning for supporting units

The topic of planning tasks for supporting units has been theoretically addressed by Bochtis & Sørensen (2010), who discussed the related planning and scheduling tasks as examples of the vehicle routing problem with time windows (VRPTW). The concept involved the case of field operations with co-operating machines; a supporting unit is required to fulfil a request for on-site service from a primary generated by a spatial–temporal process. A number of VRPTW instances were suggested, such as multiple depots instance, for the case of input material flow operations and availability of several refilling facilities, the VRPTW with a schedule horizon when the operation is constrained by certain time periods during which refilling units can use the facility unit, the VRPTW instance with stochastic demands, for the case of harvesting operations in which a predicted yield distribution is available, and the dynamic version of the VRPTW that can be applied (e.g., in the case of sensor-based variable precision spraying).

The problem of route planning for supporting units was first investigated in Bochtis et al., (2010). The planning method was based on an abstraction of a field as a two-dimensional grid and implementing a breadth-first search algorithm to generate optimal in-field paths to be followed by service units for either stationary or on-the-go unloading. Jensen et al., (2012) presented a route planning method for transport units involving in-field and inter-field transports as well. The approach was based on the generation of a ‘‘metric map’’ that involved the geometric description of the different fields, the subsequent fieldwork pattern by the harvester, and the road network associated with the coupled operation. Dijkstra’s algorithm was implemented to solve the corresponding problem. This extended approach incorporates the criterion of time beyond the criterion of travelled distance for the generated paths to thus provide the possibility of alternate optimal criterion to adapt the plan to the case-specific operational conditions and requirements. Both of the above-mentioned approaches are applicable to the case of controlled traffic farming systems. Furthermore, their computational time requirements deem them appropriate for real-time applications.

3.5 Performance evaluation

3.5.1 Definition

Machinery performance evaluation regards the final step in planning and control cycle for a field operation. A key point is the comparison between the planned operation and the actual executed operation. The result of this comparison has to be integrated in the subsequent repeated planning cycle and will enable the manager to adapt to the operations planning process. According to Sorensen et al., (2010) the evaluation of a field operation involves four main decision processes, namely: (a) data processing for documentation, (b) compliance with standards check, (c) summarising of operation’s performance, and (d) comparison with target.

3.5.2 Related work

Nikkilä et al., (2012) and Nash et al., (2011) developed service information management systems for automated compliance control with existing farm data. The case involved precision fertilisation and demonstrated how compliance to a number of fertilisation restrictions and norms could be controlled automatically. It is worth noting that the developed tool can also be applied to controlling and evaluating the task plan before execution as well as to evaluating the executed work.

Although a variety of ICT have been developed for monitoring agricultural machinery performance, due to the heterogeneous data structures of many existing systems for data acquisition the numerous data formats and interfaces, usually manual steps are required for processing data (e.g. for converting data from one format to another), (Steinberger, et al., 2009). To this end, a number of off-line evaluation systems have been appeared in the literature concerning the evaluation of agricultural machinery performance. Hansen et al., (2007) presented a study for analysing path patterns for single combines with particular emphasis on turns in the headland of the field. The turns were mathematically described in order to be able to create a model that can be used to provide comparisons between different harvesting scenarios. Grisso et al., (2004) developed four traffic pattern indices to indicate the steering behaviour made during field operations for combines and planters based on geo‒referenced data.

Regarding the on-line performance evaluation systems, Amiama, et al., (2008) developed an information and documentation system for the performance data of forage harvesters. The recorder information includes performance data (e.g., operation speed and harvested yield), machine settings, and machine warnings (e.g., oil pressure, oil temperature). The system provided also the off-line functionality of comparing the field capacity value collected by the system with the field size and the crop yield. Yahya et al., (2009) developed an on-board data acquisition system comprising a differential global positioning system for mapping of tractor-implement performance with geographical location displaying and recording in real-time among others, tractor's theoretical travel speed, actual travel speed, fuel consumption rate, rear drive wheel slippage, rear drive wheel torque, pitch angle, and roll angle and also implement's PTO torque, drawbar force, three-point hitch forces, and tillage depth.

4 FUTURE REQUIREMENTS

In the following sections, the future requirements for each of the five selected management tasks are presented. Fig. 2 provides an overview scheme of these requirements, their connection, and the external requirements for their development.

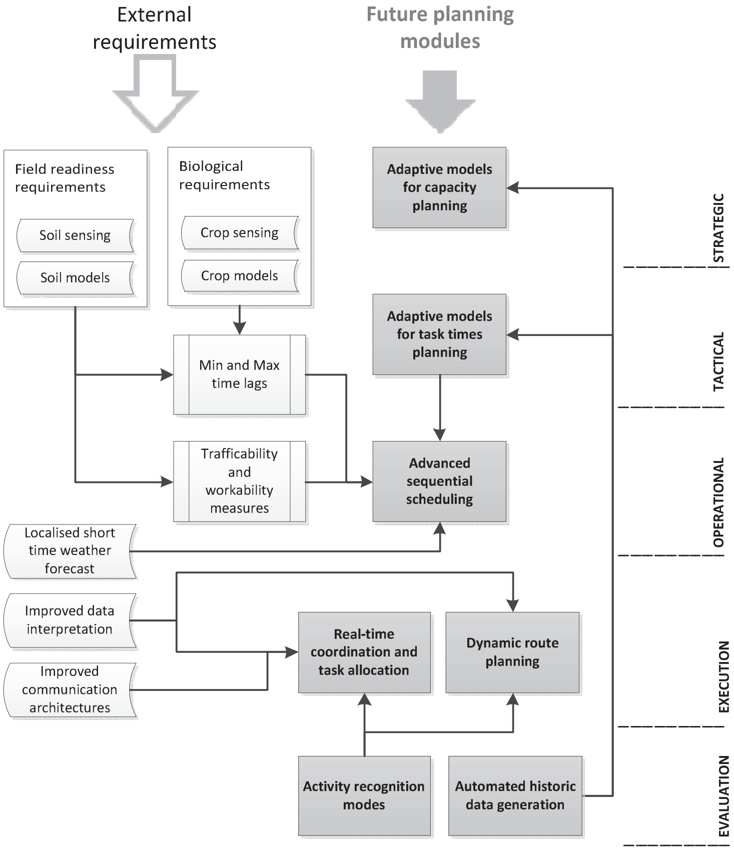

Figure 2 – Future requirements for agricultural machinery management tasks

4.1 Capacity planning

Strategic capacity planning is based on the average norm data covering a multiple-year planning horizon. Therefore, the data are uncertain and could benefit from being more highly adapted to the actual farm enterprise. Improved capacity planning measures will require adaptable models that are cooperating to receive feedback from the evaluation management level of the planning cycle. This requires improved automatic data connectivity between the different planning levels.

4.2 Task times planning

The reliability of field operations that take place in a stochastic environment is also an important aspect to be included in task times planning. However, the difficulty in dealing with stochastic measures, such as availability and reliability, concerns the practical implementation of these measures in terms of quantification and task time prediction. A precise task time prediction cannot only be based on off-line estimation using average norms (such as the approach presented here) but should preferably include models that are adaptable. Then, the model-recorded parameters could be updated so that they precisely reflect the conditions at the specific field based on automatic data collection from historical operations.

4.3 Scheduling

Based on the previously presented works, it is evident that the focus is shifting from pure scheduling approaches to sequential scheduling approaches. This shift is due to the increased capacity and availability of machines compared to the past and the available information on the operational conditions (e.g., weather prediction), which allows for short-term decision making just prior to an operation's execution. However, the intensification of agricultural production involves large-scale field operations that use machinery fleets for which decisions on shared resource allocation are required (i.e., the exact task of sequential scheduling). The inclusion of non-identical machines allocated to a specific task type (e.g., different operating width or power), the consideration of the non-continuous nature of field operations (daytime work), the incorporation of biological requirements (e.g., minimum and maximum lags caused by crop field drying) and field readiness requirements (e.g., trafficability) are factors that will drive more complex, yet more reliable and applicable, scheduling approaches.

4.4 Route planning for agricultural vehicles

In a field operation, an agricultural vehicle produces work while moving. Due to this nature of field operations, the notion of the "mission" of an agricultural vehicle is inextricably connected to the traversing route because the actions to be taken (e.g., raising or lowering of the implement, the starting or stopping of the PTO) are well defined in relation to the location and positioning of the vehicle. Therefore, mission planning for agricultural robotic vehicles will be a logical extension of the route planning efforts presented previously. Complete mission planning approaches for agricultural machines have already appeared in the literature. In Bochtis et al., (2009), a mission plan for a deterministic behavioural agricultural robotic tractor was presented. In Johnson et al., (2009), a mission plan for a team of autonomous tractors based on hybrid behaviour (deterministic and reactive) was presented.

Dynamic route planning is also a topic that is expected to attract interest in the near future because this type of routing is well suited to the variability of the parameters that describe the operational environment in biological systems. Deterministic route planning cannot address factors such as yield variability and soil physical properties variability in terms of trafficability. Furthermore, due to the outdoor environment of the field operations, unexpected events are extremely common and deterministic planning can only provide the basis for an off-line predetermined execution plan.

Finally, route planning for field operations that involves co-operating machines (e.g., harvesters and grain carts) has been addressed separately for each unit type (primary or supporting). The next step in route planning efforts is to combine planning for both types of units to satisfy the objective of the team work optimisation.

4.5 Performance evaluation

All developed approaches are lacking an automated performance evaluation process. The prediction of operating modes for agricultural machines based on automated activity recognition, as observed in other domains (e.g., public transportation safety, [Liao, Patterson, Fox, & Kautz, 2007]), is expected to be a future research topic in the agricultural machinery management domain. Furthermore, all of the current approaches are focused on single machine monitoring. Monitoring of systems of co-operating machines (e.g., harvesters and transport units) is also a future research topic.

The development of fault detection and diagnosis systems for agricultural machines is also needed for the automated evaluation and real-time re-planning of tasks. Systems used in greenhouse production, e.g., climate control (Linker et al., 2000) and irrigation control (Coates et al., 2006), must be developed for open-air production where research is currently lacking. The only scientific work that has appeared regarding agricultural machines, based on the authors' knowledge, is the work of Craessaerts et al., (2010) in which a system for the detection and isolation of sensor failures for harvesters is presented.

5 CONCLUSIONS

The most recent advances in agricultural machinery management were reviewed, and aspects of future requirements were identified in this study. The following general conclusions can be extracted.

- The focus is shifting towards the implementation of industrial engineering approaches. Planning approaches such as vehicle routing, job-shop scheduling, floor shop scheduling, and optimisation approaches beyond the typical linear programming used in the past (e.g., binary and integer programming) and entire system analysis methodologies (such as Petri nets) are increasingly employed for formulating and solving agricultural machinery planning processes.
- The latest developments in agricultural management provide the framework for planning operations executed by co-operating multiple-machinery systems, which are a stepping stone for future fully autonomous systems.
- Real-time decision support systems must be further developed to close the loop of sensing-data interpreting-decision making-actuating in real-time machine control (e.g., in controlling inputs).
- A lack of integration exists between the different management levels, which prevents the full exploitation of the precision and accuracy of the developed approaches and prevents their adaptation to location-specific conditions.

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Figure

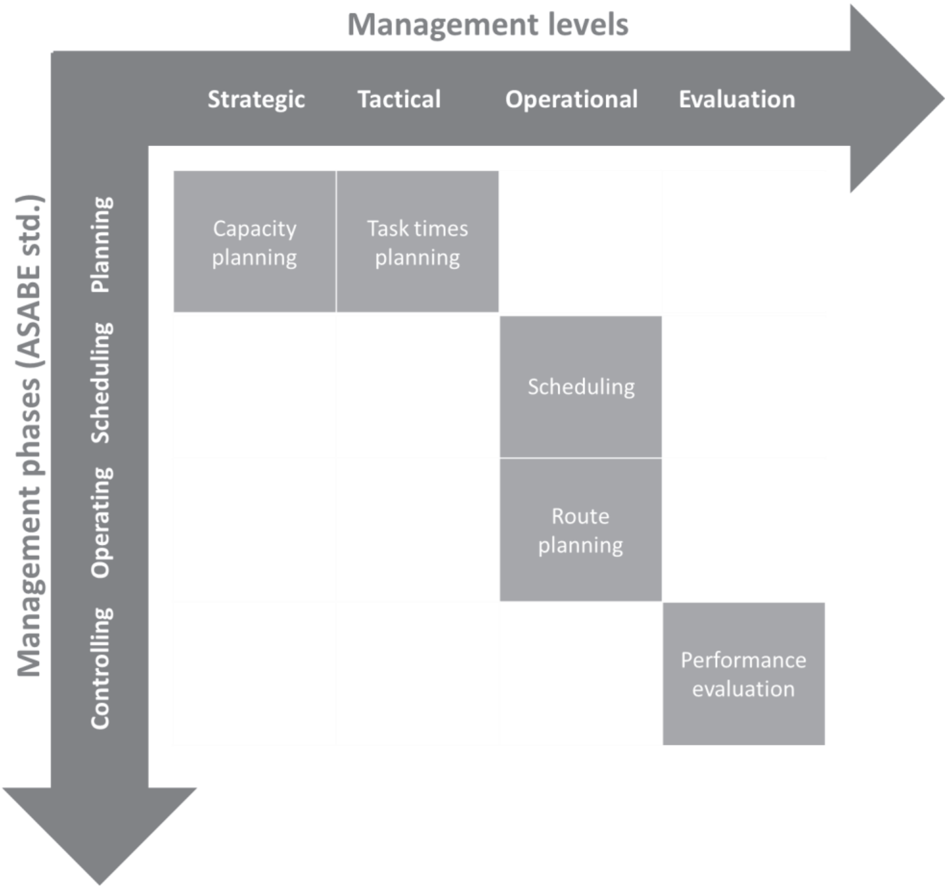

Figure 1 – The five selected management tasks for agricultural machinery to be reviewed and their relation to the general management phases and levels

Figure

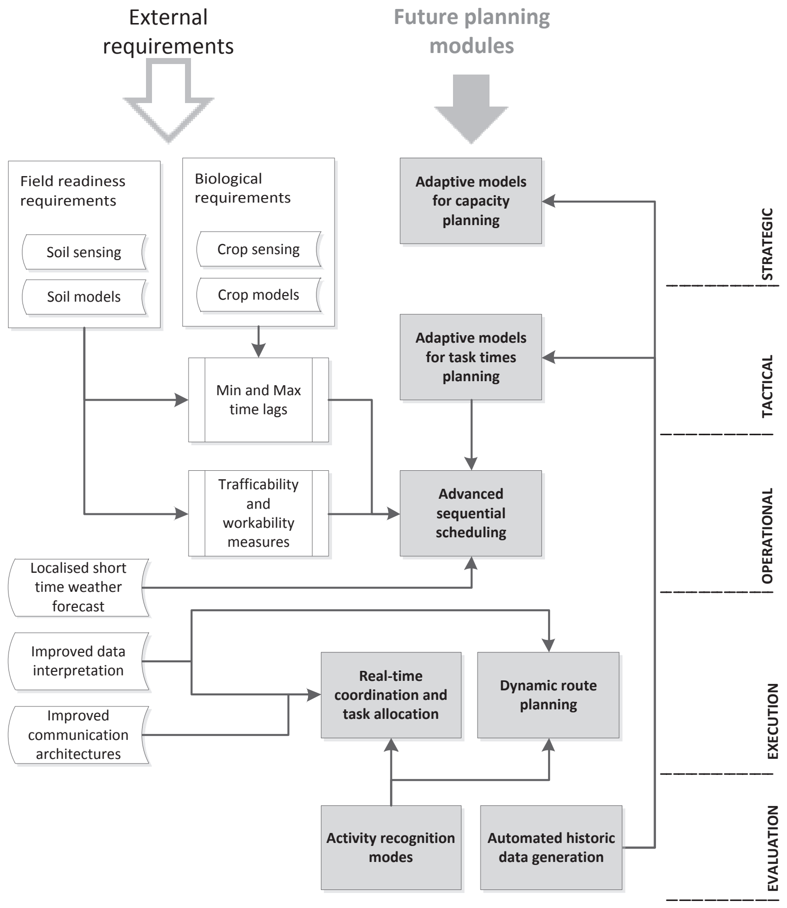

Figure 2 – Future requirements for agricultural machinery management tasks

Table

Table 1 – Capacity planning approaches and their funcionalities

	Optimisation method	Criterion	Timeliness	Workability	Targeted operations and crops
Sørensen , (2003a)	Simulation and analytical optimisation	Harvesting cost (fixed and operational machinery cost and timeliness)	YES	YES	Harvesting of arable crops
de Toro & Hansson, (2004)	Discrete event simulation	Fixed and operational machinery cost, timeliness cost, and labour cost	YES	YES	Whole farm system
Søgaard & Sørensen, (2004)	Analytical model of non-linear programming	Minimisation of the total annual Costs (fixed and operational)	YES	YES	Whole farm system
de Toro, (2005)	Discrete event simulation	Fixed and operational machinery cost, timeliness cost, and labour cost	YES	YES	Whole farm system
Sahu & Raheman, (2008)	Simulation	performance of the tractor-implement system (tractive performance, power utilisation, turning time, fuel consumption, overall efficiency)	NO	NO	Tillage of arable crops
Gunnarsson et al, (2009)	Simulation	Fixed and operational machinery cost, timeliness cost, transportation and storage cost, and labour cost	YES	YES	Forage harvesting
de Toro et al., (2012)	Discrete event simulation	Fixed and operational machinery cost, timeliness cost, drying cost, and labour cost	YES	YES	Grain harvesting

Table

Table 1 – Task times planning approaches and their functionalities

	Modelling approach:	Criterion	Case study	Operational features included	Time horizon
Sørensen et al., (2003)	Analytic modelling of farm operations, and simulation	Task duration, partial costs (for specific tasks)	Whole manure handling chain	Labour input, and capacity performance	Task specific
Sørensen, (2003b)	Analytic modelling of farm operations, and simulation	Task duration	Manure application in the field	Labour input, and capacity performance	Task and machine specific
Buckmaster & Hilton (2005)	Analytic modelling of cycle times for farm operations, system analysis	Task duration, capacity, efficiency measures	Grain harvesting and transport	Labour input, and capacity performance	Task specific
Sørensen & Nielsen, (2005)	Analytic modelling of farm operations, and simulation	Task duration, energy	Tillage operations	Inclusion of energy requirements	Task specific
Sørensen et al., (2014)	Analytic modelling of farm operations, and simulation	Task duration, energy	Tillage operations with varying intensity	Labour input, and capacity performance	Task and machine specific

Table

Table 1 - Scheduling approaches and their funcionalities

	Modelling approach:	**Criterion**	**Case study**	**Operational features included**	**Time horizon**
Foulds & Wilson, (2005)	Integer programming formulation. Solving algorithm: two targeted case-specific heursitcs	Completion time of the last task (makespan)	Rape seed harvesting Hay harvesting	Inclusion of minimum and maximum time lags	Harvesting period season
Basnet et al., (2006)	Integer programing formulation. Solving algorithm: greedy heuristic combined with tabu search	Completion time of the last task in the last field (makespan)	Rape seed harvesting and handling	Minimum and maximum time lags	Harvesting time of the fields under consideration
Guan et al., (2008)	Hybrid Petri nets combined with mixed integer non-linear programming	The maximum of the starting times of all of the tasks	Sugarcane production	Cooperative work and uncertainties	Not specified
Guan et al., (2009)	Hybrid Petri nets combined with a two-phase metaheuristic based on simulated annealing and genetic algorithms	Idle time between tasks	Sugarcane production	Cooperative work, and uncertainties	Whole cropping season
Bochtis et al., (2013)	Formulation as a flow shop with sequence dependant set up times scheduling problem	Completion time of the last task in the last field (makespan)	Cotton residues harvesting and handling	Incorporation of task time prediction models	Harvesting time of the fields under consideration
Orfanou et al., (2013)	Integer programing. Algorithm: Greedy heuristic combined with tabu search (as in Basnet, Foulds, & Wilson, 2006)	Completion time of the last task in the last field (makespan) and operational cost	Grass harvesting and handling	Incorporation of task time prediction and operational cost estimation models	Harvesting time of the fields under consideration

Table

Table 1 – Area coverage planning approaches and their related features

	Planning type			Geometric features							
	Spatial configuration	**Route planning**	**Path planning**	**Dimensions**	**Sub-field division**	**Curved lines**	**In-field obstacles**	**Optimisation method**	**On-line capability**	**Criterion**	**Operations**
Palmer et al., (2003)	X			2D	NO	NO	YES	Exhaustive enumeration	Off-line system – manual interventions are needed	Minimisation of the overlapped and missed areas	Specifically for spraying
Bochtis et al., (2008)		X		2D	NO*	YES	NO	Generation of B-patterns. VRP formulation (as binary integer programming optimisation problem) implementation of the Clarke–Wright savings algorithm	Yes	Minimisation of the total non-working travelled distance	Non-capacitated operations
de Bruin et al., (2009)	X			2D	NO	NO	NO	Exhaustive enumeration (“brute force”)	Computational requirements are not mentioned	Minimisation of the cost of the lost area	Non-specific
Oksanen & Visala, (2009)	X	X		2D	YES	YES	YES	Greedy algorithm for the division of the area into sub-areas / Heuristic algorithm for the selection of the driving direction	Off-line system (4 min computational time is reported for an example case)	Three criteria in a weighted cost function: the relative efficiency (operated area divided by total time), the normalised area (area of a generated sub-area divided into the remaining area) and the normalised distance (travelled distance in a sub-area excluding the travelled distance in the headland area)	Both non-capacitated and capacitated operations
Ali et al., (2009)			X	2D	NO	NO	YES	Two approaches were presented: a) VRP with additional turn penalty constrains (integer linear programming), and b) modified minimum cost network flow problem (mixed integer programming)	For fields of area higher than 5 hectares, the computational time tend to increase substantially	Non-working time	Harvesting operations for both on-the-go unloading (continuous harvesting) and out-of-the-field unloading (intermitted harvesting)
Bochtis et al., (2010b)	X			2D	NO	NO	NO	Exhaustive enumeration combined with simulation	Off-line system	Operational cost	The entire set of operations in controlled traffic farming systems
Hameed et al., (2010)	X			2D	YES	YES	YES	None	Case-dependent; in general, an off-line system	None	Non-specific
Jin & Tang, (2010)	X			2D	YES	NO	YES	Depth-first graph search for finding all possible lines that divided	The complexity of the algorithm was $O[n^3\log(n)]$ for a	Minimising number of headland turns	Non-specific

								the entire field into two sub-regions. For the generation of the sub-areas and the driving direction, an algorithm based on the divide-and-conquer strategy was developed	field with n edges in total. For all tested fields with no more than 20 vertices and five interior obstacles, the optimal solutions were found by the algorithm software within 60 s.		
Jin & Tang, (2011)	X			3D	NO	YES	NO	A heuristic-based approach where edge segments and contour lines are used as candidates, and a “seed” curve is generated	Computational requirements are not mentioned	Weighted function including headland turning cost, soil erosion cost, and skipped area cost.	Non-capacitated operations
Hameed, et al., (2011)	X	X		2D	NO	NO	NO	Three stages. Exhaustive enumeration of driving direction determination. A genetic algorithm for the other two stages (B-patterns generation and block sequence optimisation)	Computational time app. 20 min for two relatively simple shaped fields of app. 8 ha and 17 ha.	Minimisation of overlapped area (for the driving direction determination). Minimisation of total travelled distance	Non-capacitated operations
Bochtis, et al., (2012)		X		2D	NO*	NO	NO$^\#$	Generation of B-patterns. Implementation of a case – oriented brute force algorithm	Very low computational time requirements (on the scale of ms)	Minimisation of the risk of soil compaction	Capacitated operations. In general, when the agricultural vehicle carries time-dependent loads
Spekken & de Bruin, (2012)	X	X		2D	NO	NO	NO	Implementation of traveling salesmen problem (TSP) for the track sequence generation (Clarke–Wright savings algorithm)	Computational requirements are not mentioned	Non-working time during headland turnings	Non-capacitated operations and capacitated operations in which servicing occurs on the headlands
Hameed et al., (2013)	X			3D	NO	NO	YES	Exhaustive enumeration combined with an object-oriented simulation	High computational time requirements. Based on the case studies, the computational time ranged between 60 min and 380 min for two field areas of app. 11 ha and 21 ha	Minimisation of energy requirements (fuel consumption)	Capacitated operations