Machinery management in bio-production systems: planning and scheduling aspects

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Abstract: Most operations in bio-production systems involve a number of highly interconnected tasks executed by co-operating machinery systems operating in series or in parallel. An envisioned future team of identical field-robots could represent an example of the former case, while machinery systems including a number of primary units supported by a number of service (mainly transport) units involved in "output material flow" operations, such as harvesting, as well as in "input material flow" operations, such as spraying and fertilising, could represent examples of the later. the efficient execution of such operations requires considerable efforts in terms of scheduling and planning. Here, a classification scheme for the management task of planning and scheduling for bio-production machinery systems is proposed, as a first step towards implementing appropriate management tools used in industrial management domain. The identifications of the characteristics of the decision problems related to the management of these systems can provide the basis for their mapping to the appropriate operational research approaches.

Keywords: agricultural machinery management, field logistics, B-patterns, biomass supply chain, farm management, farm machinery

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1 Introduction

Operations management in the bio-production domain characterised by short operational time windows, wide spatial distribution, trafficability and workability issues, while sustainability aspects have also taken into consideration. Furthermore, additional demands on the precision and integration of the scheduling, planning, and control functions require that the planning tasks allocated to the machinery team and corresponding labour, needs to consider the dynamic interaction of machine, biological, and meteorological factors. The decision process on the examined operational system should adjust for changes in weather, seasonality, biological factors, legal and political regulations, competition issues, and customer's demands.

Bio-production systems constitute the first links, namely the production and selection (harvest), of the argi-food supply chain and the biomass supply chain. Nevertheless, although the supply chain of agricultural products and biomass, have received a great deal of attention due to issues related to public health and bioenergy production, respectively, adopting formalised management tools from the industry domain, in the bio-production machinery management there is only a sparse tradition for using such tools (Bochtis et al., 2007; Sørensen and Bochtis, 2010).

In the context of the agri-food and biomass supply chain, four main functional areas can be identified (Ahumada and Villalobos, 2009), namely, production, harvest, storage, and distribution (Figure 1). Decisions made in the production regards the whole growing season including the recourse (land, machine, labour) determination and in-season allocation, as well as the scheduling of the field operations (cultivation, sowing, fertilising, etc.) dedicated to the specific crop and production system and finally the planning of these operations in terms of their optimal execution by the

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available/selected machinery system. The link of harvesting includes the in-field harvesting, out-of-field removal of crop/biomass, and the rural road transportation in the case of an intermediate storage, while the corresponding machinery system includes harvesters, transport units, transport trucks, and unloading equipment between each pair of successive stages. Although that harvesting is the last link of the production function, it is identified as a separate function within the supply chain due to the complex planning efforts that are concerned with this operation, caused by the uncertainties that it is subjected to (*e.g.*, yield, weather, and machinery and system performances). Furthermore, the harvesting costs make up 30% of the total machinery costs (Sørensen, 2003b). This emphasizes the need for developing robust planning tools for choosing and operating the optimal harvesting and in/inter-field transport equipment. The third function is storage, which is related with the inventory control and the fourth is the distribution related to the selection of the transportation mode, the route planning of the involved transport units, and the shipping schedule to deliver the product to the consumers.

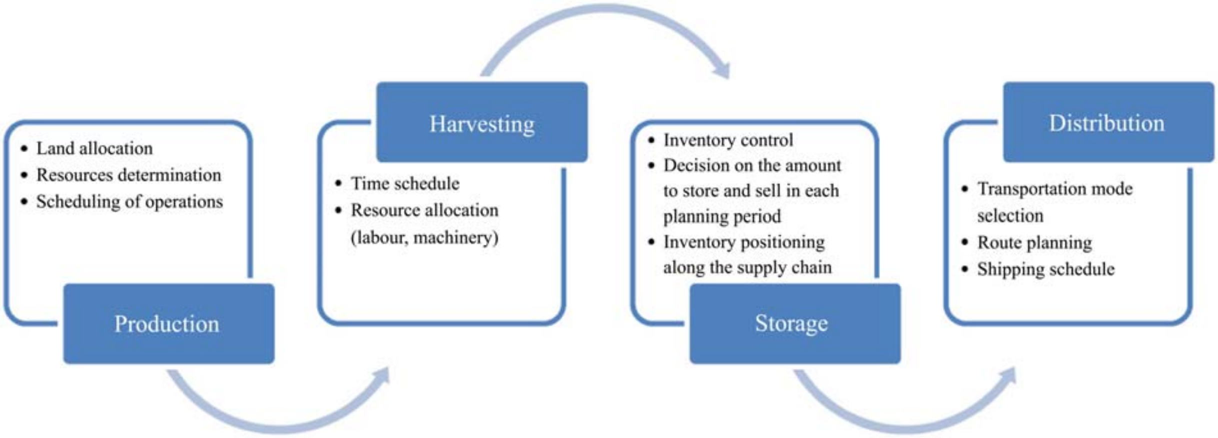

Figure 1 Four main functional areas in the context of the agri-food supply chain (according to Ahumada and Villalobos, 2009)

Bio-production machinery management is related with the first two functions (production and harvesting) and with issues of the third function (storage) such as the facility network design in the case that the optimisation model takes into consideration the interaction between the storage location and the machinery system. Furthermore, bio-production machinery management includes a number of "vertical" supply chains to the previous mentioned one. These supply chains relate to the "input material flow" operations, such as spraying and fertilising, which include a complete logistics system (Sørensen, 2003a).

Emerging planning and scheduling approaches and tools based on advanced methods and techniques from the operational research area have been presented recently dealing with optimisation issues inherent in agricultural fleet management (*e.g.*, Basnet, Foulds and Wilson, 2006; Berruto and Busato, 2008).

Bochtis (2008), introducing a new type of algorithmically computed optimal fieldwork patterns (*B-patterns*), showed the potential for the implementation of combinatorial optimisation as part of the optimal operational planning for single or multiple machinery systems operating in one or multiple geographically dispersed fields. *B-patterns* are the result of an algorithmic approach, according to field coverage which is expressed as the traversal of a weighted graph, and the problem of finding optimal traversal sequences is transformed into finding the shortest tours in the graph. The implementation of the *B-patterns* for conventional agricultural machines with auto-steering systems was presented in Bochtis and Vougioukas (2008). The experimental results showed that by using *B-patterns* instead of traditional fieldwork patterns the total non-working distance can be reduced significantly by up to 50%. The same approach has been implemented for the mission planning of an autonomous tractor for area coverage operations such as grass mowing, seeding and spraying (Bochtis，Vougioukas and Griepentrog, 2009).

The above approach revealed the equivalency, in terms of the nature of the optimisation problem, between the agricultural field coverage operations and the well-known combinatorial optimisation problem referred to as the vehicle routing problem (VRP). The equivalency is based on the abstractive representation of the fieldwork tracks as the “customers” in the (VRP) methodology. By using this abstraction, and expanding it to include a number of different types of agricultural operations (involving field area coverage), (Bochtis and Sorensen, 2009) showed that agricultural operations can be cast as VRP instances (VRP with stochastic demands, VRP with time windows, dynamic VRP, distance constrained VRP, etc.) and, consequently, can be solved using developed methods for the solution of these instances.

Furthermore, by using the abstractive representation of the supported primary machines as the “customers” in the VRP with time windows methodology, Bochtis and Sørensen (2010) showed that agricultural field operations involving service units (e.g., transport wagons in a harvesting operation) can be cast as instances of this specific constrained type of VRP. The abstraction was motivated by the fact that in agricultural operations involving co-operating machines, a number of service units are required to fulfil requests for on-site service of a number of primary units in a given field region and at a specific time. Furthermore, service requests are generated by a spatial-temporal process which may be deterministic (*e.g.*, seeding), stochastic (*e.g.*, harvesting) or dynamic (*e.g.*, sensor based site-specific spraying).

In the following sections, a classification scheme for the management task of planning and scheduling for bio-production machinery systems is proposed, tailored to the identifications of the characteristics necessary for choosing the appropriate management tools used in industrial management domain.

2 Planning

Planning for bio-production machinery units can be classified according to five generic themes. These five themes specify the characteristics of the planning problem as far as it concerns the (mobile) units, the facilities used by the units, the costumers that are served by the machines (the meaning of the term costumer will become self-evident in the subsequent section), the optimisation problem itself, and the objective of the optimisation.

2.1 Units

This theme defines the characteristics of the units and of their followed routes for the completion of a specific allocated operation (Figure 2). There are three types of information in this theme: the number of units, the units’ features, and the existence of temporal constraints on an operation’s part. The first subtheme specifies the number of the units involved in the execution of a field operation, which can be a constant number specified beforehand, or a variable specified as part of the problem instance. The second subtheme specifies the presence or not of capacitated constraints. In the case of the presence of capacity constraints (that is the case of input or output material flow operations) the team of the units (fleet) can be homogeneous (all units have the same capacity) or heterogeneous (i.e. there are machines with different capacities). The third subtheme regards the presence of

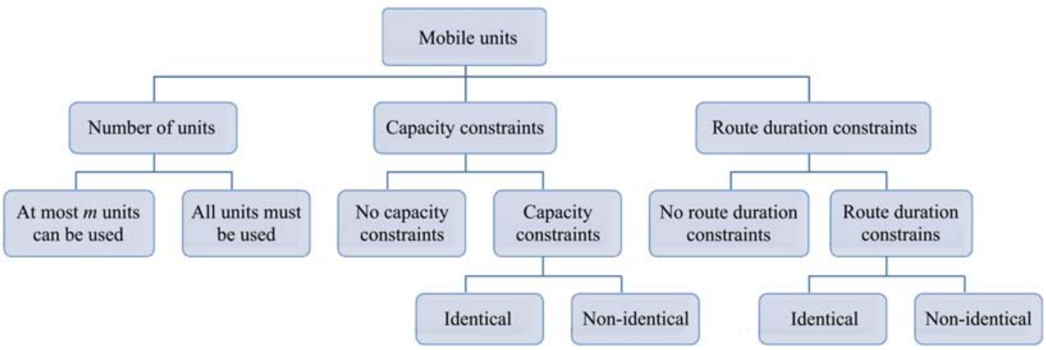

Figure 2 Classification of the bio-production machinery planning problems based on the characteristics of the mobile units

temporal constraints. There could be availability intervals for the units, as well as lower and upper bounds on the duration of their tasks in the case of the presence of capacity constraints. The latest bounds could be identical for all of the units or different for some of them.

2.2 Facilities

This theme defines the characteristics of the facility units that mobile units use as refilling or unloading locations and/or as their depot. There are three types of information in this theme: the number of facility units, their capacity and their mobility features (Figure 3). The first subtheme specifies the number of the facility units. There are planning problems with a single facility unit and problems with multiple facility units which can be fixed or given as part of the problem instance. Analogously to the units theme, the second subtheme specifies the presence or not of capacitated constraints and if, in the former case, the facility units have the same or different capacities. The third subtheme specifies the mobility of the unit, that is, if the facility unit is stationary or mobile.

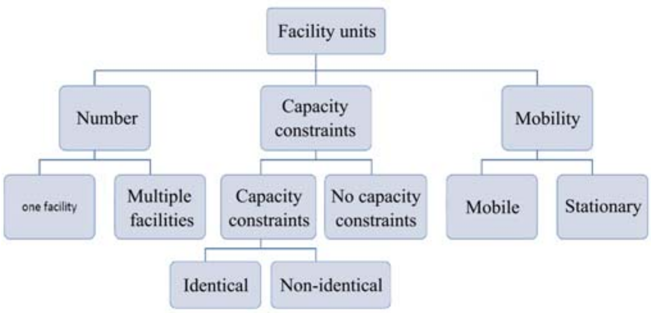

Figure 3 Classification of the bio-production machinery planning problems based on the characteristics of the supporting facility units

2.3 Costumers

The term "costumer" refers to two different abstractions and consequently, to two different problem types. According to the first abstraction (Bochtis and Sørensen, 2009), well-defined part of the field area (for example, field tracks worked in the field) are represented as the "costumers", and according to the second abstraction (Bochtis and Sørensen, 2010) the supported primary units (i.e., combines in a harvesting operation) by the service units (i.e., in-field transport wagons) are the "customers". There are three types of information in this theme (Figure 4). The first subtheme specifies the flow of the material at the operation under question which can be neutral, input material flow, or output material flow (Bochtis, Vougioukas and Griepentrog, 2009). The second one relates to the perspective of *a-priory* available information and classifies the problems as deterministic, stochastic, and with un-known demands, according to the certainty of the value of the "costumers" demand. In the first abstraction the demand regards the quantity of material that has to be removed from, or distributed in, a field area, while in the second abstraction regards, i.e., the quantity of the material that is carried by a unit and has to be refilled with. The second subtheme specifies the costumer scheduling constraints. Either there are no temporal constraints, or there is a fixed schedule, or the starting time of the service of a costumer is restricted to intervals called time windows determined by factors like timeliness and workability in the first abstraction and by machinery restrictions (e.g., temporary grain tank volume) in the second abstraction.

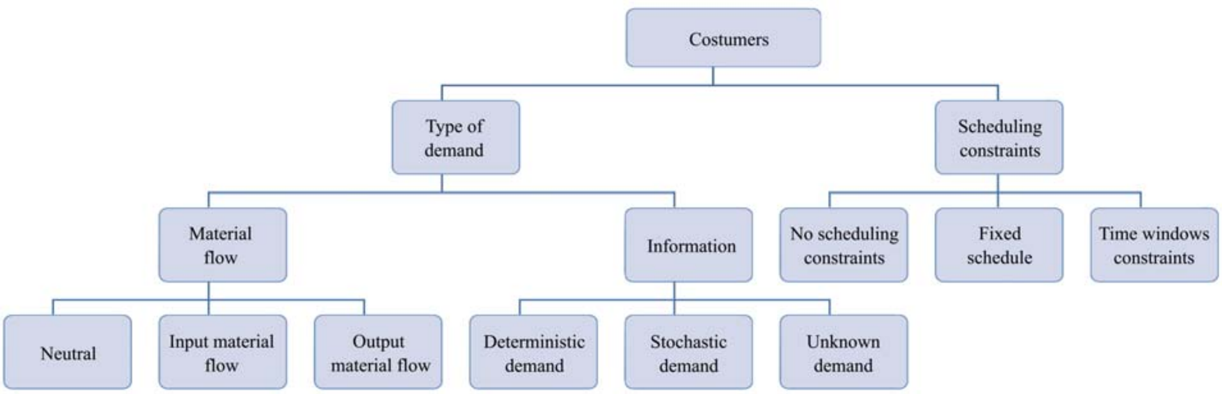

Figure 4 Classification of the bio-production machinery planning problems based on the characteristics of the customer (specified field areas or mobile service units)

2.4 Problem

The first subtheme of the theme “problem” defines the network (or graph) underlying the planning problem under question. The cost can satisfy the triangular inequality or not, and the problem’s graph can be either directed or undirected. The second subtheme relates the information of the presence of precedence constraints between costumers, that is, the unit/s must visit one customer before visiting the other (for example in the case where the unit has to follow a fixed fieldwork pattern).

The third subtheme specifies the restrictions between different pairs of entities that are parts of the problem. The term entities refer to the costumers, the units and the facilities. Consequently, the restrictions are of the following types: costumer-facility, costumer-machine, and facility machine. For example, a restriction could be that a costumer must be served from a given facility (*e.g.*, caused by request for different fertiliser type, or in the case of traceability in grain harvesting, caused by different loads corresponding to harvested areas of different crop varieties), or a costumer must be allocated to the same route as another costumer (as previous on the different variety case), or must be visited (in the case where costumers represent field tracks or areas) or served (in the case where the costumers represent primary units) by a given service unit. The opposite situation also occur, that is, a costumer should not be served from a given facility, or should not be allocated to the same route of a machine as another costumer, or finally, should not be visited/served by a given primary/service unit. Figure 5 presents the subthemes in the problem’s theme.

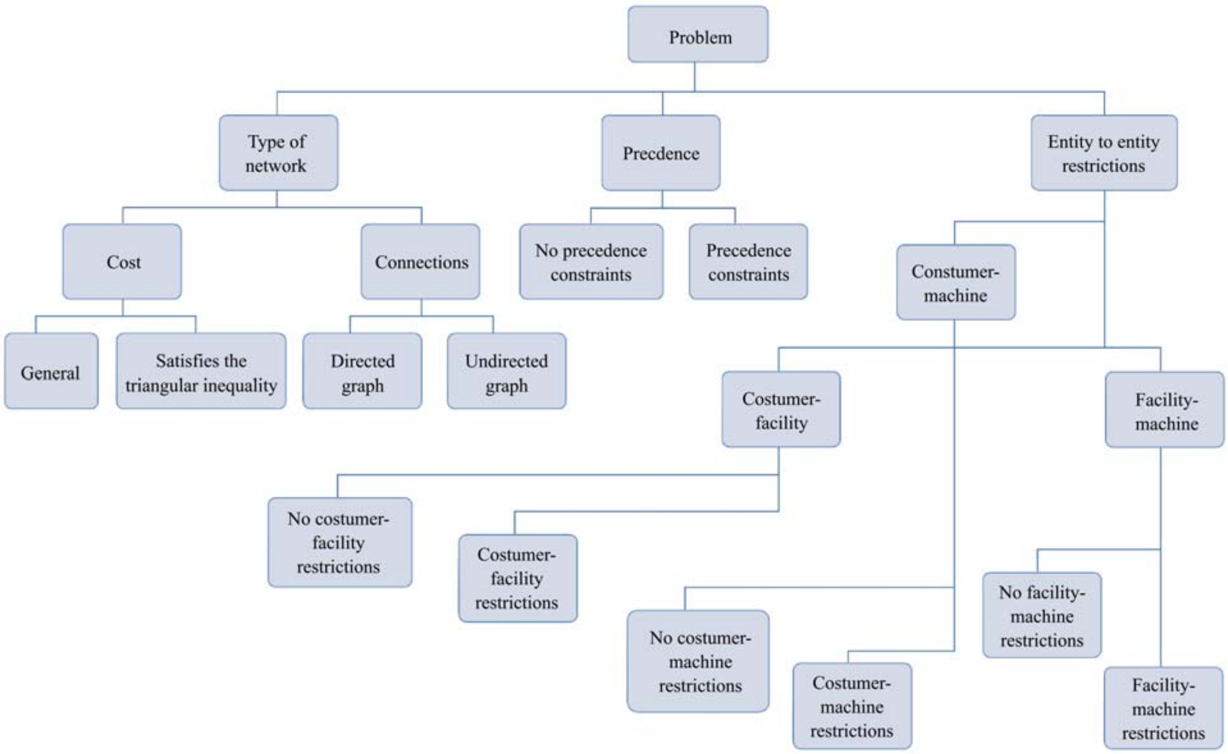

Figure 5 Classification of the bio-production machinery planning problems based on the characteristics of the optimisation problem itself

2.5 Objective

The fifth and final theme defines the objective function of the problem (Figure 6). The most common objectives in the machinery planning and scheduling problems are the minimisation of the total travelled distance or operational time. A cost function can be used to model situations where, in addition to optimal routing, it is also required to determine the fleet size and composition. The penalty functions enable the modelling of costs incurred due to the violation of soft constraints that may be violated at a certain cost. At the other end, there should be the possibility that no objective is specified, so that the problem is reduced to a question of feasibility measures.

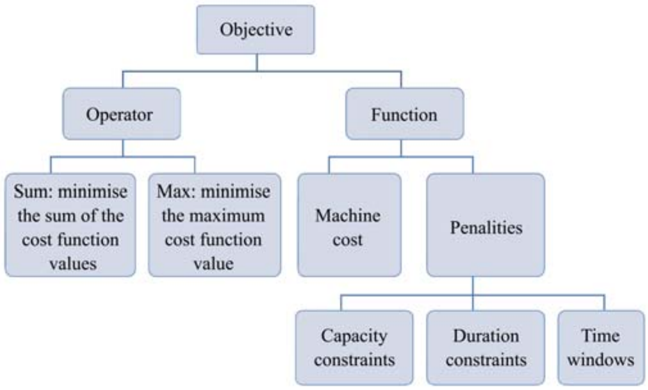

Figure 6 Classification of the bio-production machinery planning problems based on the characteristics of the objective

3 Scheduling

In the followings, a classification of the scheduling for bio-production machinery units according to three generic themes is presented. These three themes specify the characteristics of the scheduling problems as far as it concerns the (mobile) units, the constraints of the problem, and the objective of the problem. The themes "units" and "objective" have also presented on the case of planning, but with a different focus. Figure 7 depicts the summary of the following classification.

3.1 Units

The following themes providing categories of differrent scheduling problems in field operations regard the case of multiple-units, since the case of a single unit is the simplest of all possible scheduling cases and is a special case of all other more complicated types. There are two generic cases for multiple-machinery systems: operating in parallel and in series.

3.1.1 In parallel

Identical units There is a team of identical units which operate in parallel. Each field requires a single operation which may be executed by any one of the available units or by any one that belongs to a given subset. There are cases where the operation in a field cannot be carried out by just any machine, rather only by any one belonging to a specific subset (for example due to traffic ability constraints a lighter unit is required).

Units in parallel with different capacities There is a team of units in parallel with different capacities (here, the term capacity refers to the ability of the unit to

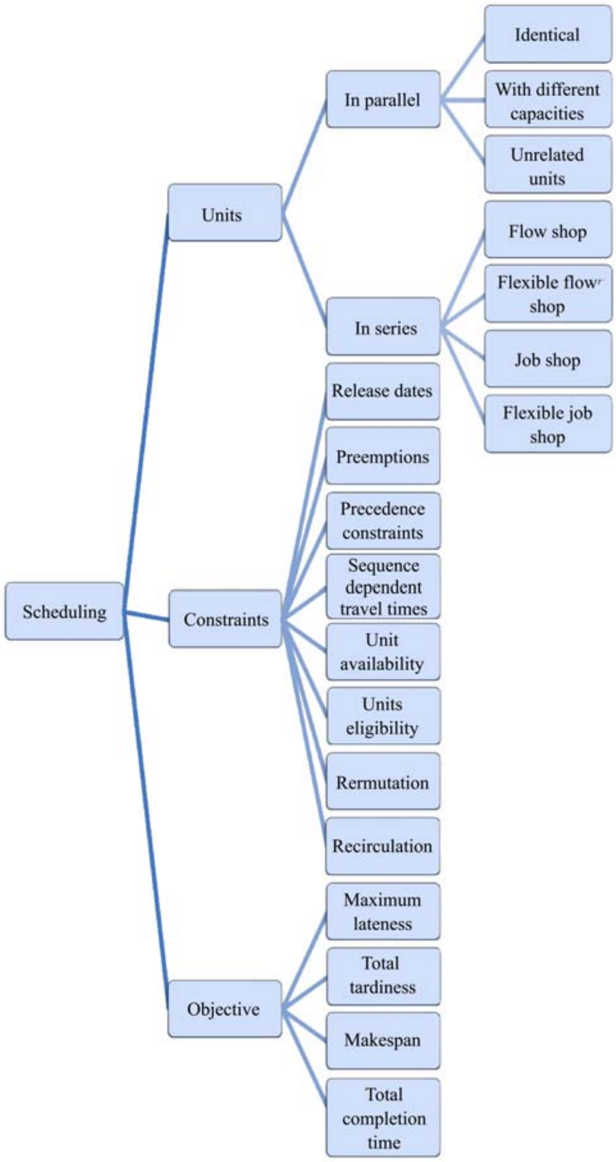

Figure 7 Classification of the bio-production machinery scheduling problems

perform). This category refers to the case where the capacities of the units are independent of the field.

Unrelated units in parallel This scheduling case is a generalization of the previous one where the capacity of each unit depends on the field in which it operates. 3.1.2 In series

Flow shop There is a team of units in series. Each one of the units has to operate in each field. The operations in all of the fields have to follow the same sequence, i.e., unit 1 has to be operated firslyt; unit 2 has to be operated secondly, and so on. After completion of the operation at a field the field joins the queue at the next unit. Usually, all queues are assumed to operate under the discipline, that is, a field cannot "pass" another in priority while waiting in a queue. If the first in first out (FIFO) discipline is in effect the flow shop is referred to as a *permutation* flow shop. As an example, the operations of raking, baling, and loading of crop residues for bio-energy production use.

Flexible flow shop A flexible flow shop is a generalisation of the flow shop where units both in parallel and in series are involved. Instead of a team of, e.g. *m*, units in series there are *m* sequential types of operations and for each one there a number of identical units to operate in parallel are available.

Job shop In a job shop scheduling for a team of units each field has its own predetermined sequence of operations that have to be carried out.

Flexible job shop A flexible job shop is a generalisation of the job shop where units both in parallel and in series are involved. Analogously to the case of the flexible flow shop, Instead of a team of, e.g. *m*, units in series there are *m* sequential types of operations and for each one there a number of identical units to operate in parallel are available.

3.2 Constraints

Release dates Some operation types in the field cannot start before a (not always deterministically known) specific data, while some others may start at any time.

Preemptions Preemptions imply that it is not necessary to complete an operation to a field once started. In contrast, it is allowed to interrupt the operation at a field and allocate another field (or field area) on the unit.

Precedence constraints Precedence constraints require that an operation at a field has to be completed before the same operation can be started to another field.

Sequence dependent travel times In the case of the field operations, the setup times correspond to the travel times that the units have to spend in order to travel from one field to another. These times depends on the distance between the fields as well as of the type and the characteristics of the unit.

Units availability Can be either deterministic (i.e., scheduled maintenance) or dynamic (breakdowns).

Units eligibility When not all units are capable of carrying out the operation in some fields.

Permutation According this constrain each unit operates according to the FIFO. This implies that the order in which the first unit operates at the fields is maintained throughout the family of operations.

Recirculation Recirculation occurs when an operation should or may be executed by one or multiple units in parallel more than once.

3.3 Objective

Following the most common objective functions to be minimised in a scheduling problem for field operations:

Maximum lateness In correspondence in the term of *lateness* in scheduling theory, in field operations the lateness can be defined as the difference between the completion time of an operation in a field and the due time of this operation which can be imposed by a request, or by biological and weather factors. The maximum lateness measures the worst violation of the due dates in the fields for which operations are scheduled.

Total weighted tardiness Operations can be completed either later (positive lateness) or earlier (negative lateness) than the due time. For an operation in a field, the tardiness is defined as the maximum between the lateness and 0.

Makespan The makespan is defined as the maximum competition time among the scheduled operations. It is equivalent to the completion time of the last field that is operated according the schedule.

Total weighted completion time The summation of the weighted completion times of all fields.

4 Discussion

The presented classification of the planning and scheduling problems in the fleet management in bio-production field operations can be seen as a stepping stone for the application of the appropriate operational research techniques for their efficient solution. Operations in arable farming such as, cultivation and mowing, according to the classification, in the machine theme are specified as operations for a single machine without capacity constraints, with potential route duration constraints (i.e., end of the day-time, forecasted weather conditions). In the theme of facilities, there is a single facility (farm depot), without any capacity constrain since it regards only the machinery parking and maintenance.

The “costumers” in these problems are the field tracks and there are not any demand constraints. The cost since it refers to the non-working distance travelled that is affected by the non-linear machine kinematic constraints does not satisfy the triangular inequity. Depending on the field, in terms of presence of traffic constraints, the graph of the problem can be either directed or undirected. Presence constraints could be imposed in the case where the operation under study is been carried out concurrently with operations of different types. Finally, since the planning regards a single machine, there are no entity to entity restrictions. As far as it concerns the objective of the optimisation problem, it regards the minimization of the summation of all the non-working activities of the machine (in terms of distance or time) and there are no penalty constrains.

All the previous specify that for the planning of the previous type of operations the appropriate model and, consequently, the appropriate solution methods, is one of the travelling salesman problems and its variations (e.g., symmetric, and asymmetric). As a generalization, the case of a seeding operation, for example, can be considered where there is capacity constraints related to the seed-tank capacity of the machine and the track-costumes have non-identical deterministic demands proportionally to their length. The problem then is modified to the capacitated vehicle routing problem. Other examples include the problem of planning for the operation of an application unit in a sensor-based variable rate precision spraying with some *a priory* information (e.g., satellite image) or the planning of a harvester (e.g., grain, cotton) that unloads its bin at a predetermined out-of-field location and which both can be cast as a vehicle routing problem with stochastic demands (a detailed description of the mapping between agricultural field operation problems and routing problems can be found in Bochtis and Sørensen, 2009 and 2010).

It has to be noted that the basis of the *B-patterns*, mentioned above in the introduction section, consists of the implementation of these techniques. Research into the potential savings from the implementation of these patterns has shown that the savings in the operational time ranged from 8.4% to 17.0%, while the mean savings in the fuel consumption, and consequently to the CO_2 emissions was in the order of 18% (Bochtis *et al.*, 2010).

5 Conclusions

A classification scheme for the management task of planning and scheduling for bio-production machinery systems was proposed, as a first step towards implementing appropriate management tools used in industrial management domain. The presented classification is a prerequisite for the identification of the characteristics necessary for the implementation of advanced operational research modelling and problem solving methods in the future bio-production machinery management systems.

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