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AGRICULTURAL FLEET MANAGEMENT: AN OPERATIONAL RESEARCH APPROACH

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ABSTRACT Most agricultural field operations involve a number of highly interconnected tasks executed by co-operating heterogeneous agricultural machines. Agricultural machinery systems involved in ‘‘output material flow’’ operations, such as harvesting, as well as in ‘‘input material flow’’ operations, such as spraying and fertilising, include a number of primary units supported by a number of service (mainly transport) units. The characteristics of such operations require considerable efforts in terms of the managerial tasks of scheduling and planning. Here, an approach representing the planning and scheduling tasks for agricultural machines using basic well-known operational research problems is presented. A dedicated classification of field operations is given as the basis for the mapping of operational research problems.

Keywords: Field logistics, B-patterns, biomass supply chain, farm management.

INTRODUCTION In the context of the agri-food supply chain, four main functional areas can be identified (Ahumada and Villalobos, 2009), namely, production, harvest, storage, and distribution (Figure 1).

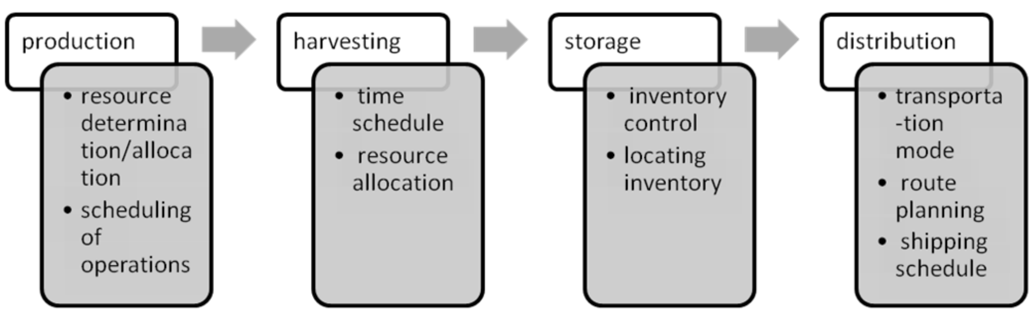

Figure 1. The four main functional areas in the context of the agri-food supply chain (according to Ahumada and Villalobos, 2009).

Decisions made in the production regards the whole growing season including the recourse (land, machine, labour) determination (strategic planning) and in-season allocation (operational planning) as well as the scheduling of the field operations (cultivation, sowing, fertilising, etc.) dedicated to the specific crop and production 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, medium and high capacity 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 agri-food 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 machine performance). Furthermore, the harvesting costs make up 30% of the total machinery costs (Sørensen, 2003). 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. Agricultural 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 agricultural machinery system.

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. Søgaard and Sørensen (2004) presented an approach involving the development of a non-linear programming optimisation model based on a level of aggregation consistent with the accessible and existing data related to machinery sets, crops, weather and timeliness of operations. Berruto and Busato (2008) developed a dynamic discrete-event simulation model combined with linear programming in order to evaluate and optimise biomass supply chain.

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 a single or multiple machinery systems operating in one or multiple geographically dispersed fields. *B-patterns* are the result of an algorithmic approach, according to which, field coverage 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 et al., 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 inclued a number of different types of agricultural operations (involving field area coverage), (Bochtis and Sorensen, 2009) showed that agricultural operations can be cast as a 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 section, a classification of the field operations involving single or multiple machinery systems is devised and tailored to the identifications of the characteristics necessary for choosing the appropriate problem modelling and solving method from the operational research area.

CLASSIFICATION OF THE AGRICULTURAL FLEET MANAGEMENT PROBLEMS The agricultural field operations can be classified according to five generic themes. These five themes specify the characteristics of the planning problem as far as it concerns the machines, the facilities used by the machines, 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, and the objective of the optimisation.

Machines This theme defines the characteristics of the machines 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 machines, the machines' features, and the existence of temporal constraints on an operation's part. The first subtheme specifies the number of the machines 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, the fleet can be homogeneous (all vehicles have the same capacity) or heterogeneous, i.e. all machines have identical capacities or there are machines with different capacities. The third subtheme regards the presence of temporal constraints. There can be availability intervals for the machines and lower and upper bounds on the duration of their routes in the case of the presence of capacity constraints. The latest bounds could be identical for all of the machines or different for some machines.

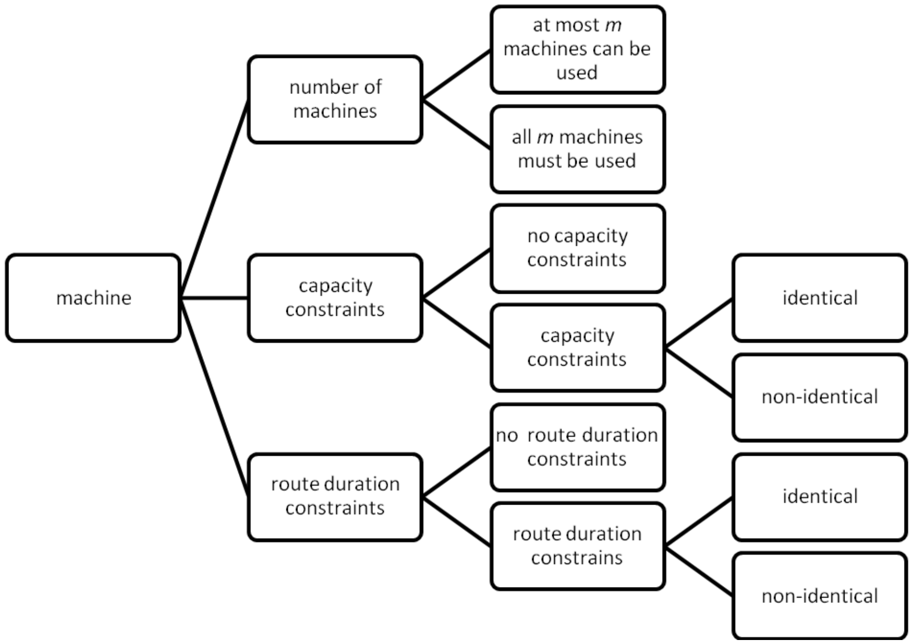

Figure 2. Classification of the AFOs based on the machinery characteristics

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

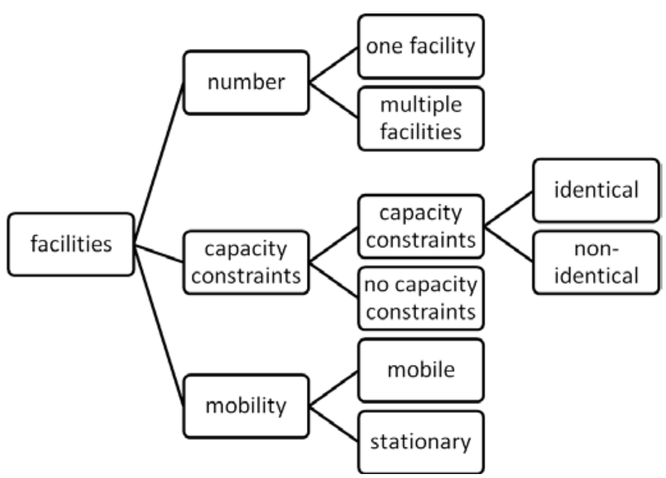

Figure 3. Classification of the AFOs based on the facilities characteristics

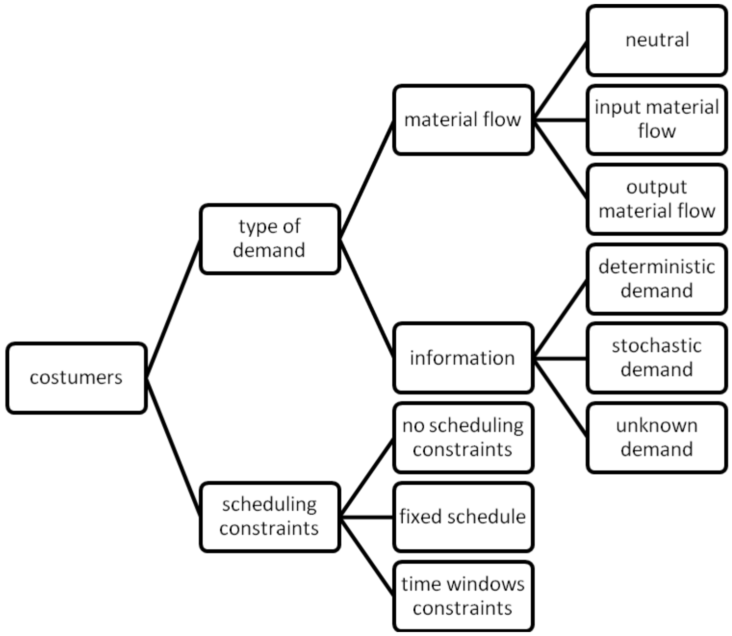

Figure 4. Classification of the AFOs based on the costumers characteristics

Costumers The term "costumer" refers to two different abstractions and consequently, to two different problem types. According to the first abstraction (Bochtis and Sorensen, 2009), the tracks worked in the field are represented as the ''customers'', and according to the second abstraction the supported primary machines (i.e. combines) 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. 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. The second subtheme specifies the costumer scheduling constraints. Either there are no temporal constraints, or the there is a fixed schedule, or the starting time of the service of a costumer is restricted to intervals called a time window determined by factors like timeliness and workability..

Problem The first subtheme of the theme "problem" defines the network (or graph) underlying the planning or scheduling 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 machine/s must visit one customer before visiting the other.

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 machines and the facilities. Consequently, the restrictions are of the following types: costumer-facility, costumer-machine, and facility machine. As for example, a restriction could be that a costumer must be served from a given facility (e.g., caused by request for different fertilizer 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 machine. 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 subtheme in the problem's theme.

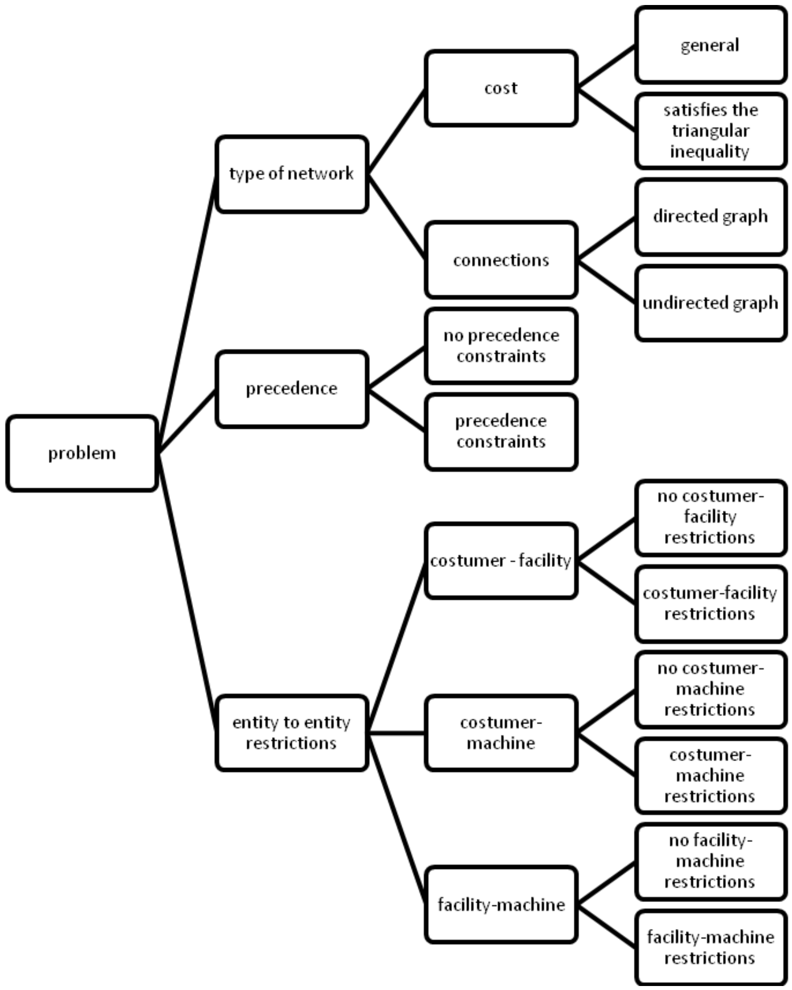

Figure 5. Classification of the AFOs based on the problem characteristics

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 and the minimization of the span of a plan. A machine cost function can be used to model situations where, in addition to routing and scheduling, 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..

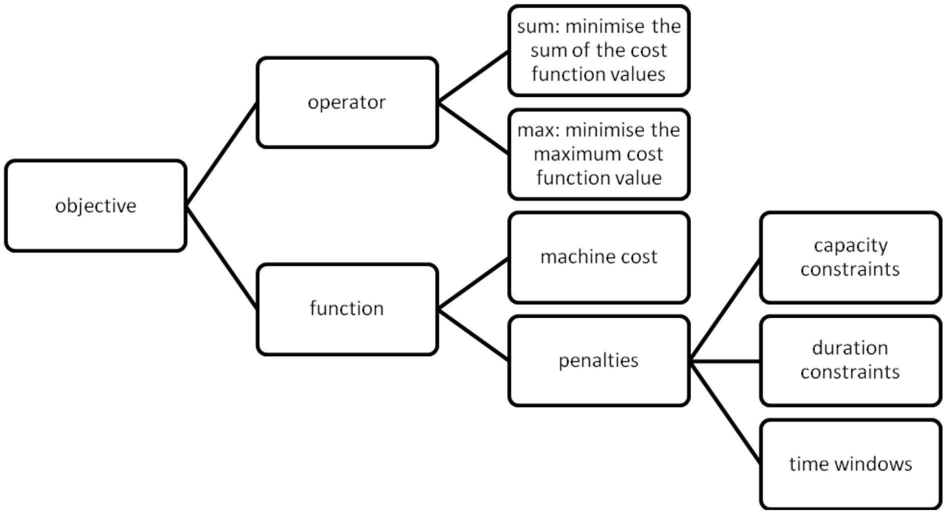

Figure 6. Classification of the AFOs based on the objective characteristics

DISCUSSION The classification of the decision problems involved in the fleet management in agricultural field operations can be seen as a stepping stone for the application or the development, when needed, of the appropriate operational research techniques for their efficient solution. Let us consider some examples of the usage of this classification for the mapping of agricultural fleet management problems to standard problems from the operational research domain. 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 the one of the travelling salesman problem 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 CO2 emissions was in the order of 18% (Bochtis et al., 2010).

CONCLUSIONS A classification of field operations as the basis for their mapping to operational research problems was presented. This classification is a prerequisite for the implementation of advanced operational research modelling and problem solving methods in the future agricultural machinery management systems.

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