Simulation and assessment of agricultural biomass supply chain systems

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Abstract

Agricultural biomass supply chain consists of a number of interacted sequential operations affected by various variables, such as weather conditions, machinery systems, and biomass features. These facts make the process of biomass supply chain as a complex system that requires computational tools, e.g. simulation and mathematical models, for their assessment and analysis. A biomass supply chain simulation model developed on the ExtendSim 8 simulation environment is presented in this paper. A number of sequential operations are applied in order biomass to be mowed, harvested, and transported to a biorefinery facility. Different operational scenarios regarding the travel distance between field and biorefinery facility, number of machines, and capacity of machines are analyzed showing how different parameters affect the processes within biomass supply chain in terms of time and cost. The results shown that parameters such as area of the field, travel distance, number of available machines, capacity of the machines, etc. should be taken into account in order a less time and/ or cost consuming machinery combination to be selected.

Keywords: agricultural biomass, supply chain management, simulation model, agricultural machinery, operations management.

1 INTRODUCTION

A biomass supply chain can be described as a multiple-segment chain which can be characterized by prominent complexity and uncertainty, and as such, it requires increased managerial efforts. The efficiency level of the supply chain relies on the organization and integration of the resources, along with efficient flow of products and information (Beamon, 1998; Simchi-Levi, 2003). In its full extent, biomass supply chain consists of the production of biomass, the process of harvesting and in-field handling, transportation (which potentially can include intermediate transportation, intermediate storage, and additional transportation), pretreatment, storage, and conversion. Moreover, there are cases where the storage and distribution of the generated bio energy are also connected to the biomass supply chain (An et al., 2011). Improvements in biomass supply chain should be done for minimizing not only the cost but also time consumption. The demand and the use of biomass can be increased by several ways, such as new conversion technologies, better planning and handling systems etc. (Sambra et al., 2008). It is clear that the level of complexity is high and so is the need for systems and models which can be utilized as decision support systems that can be used for increasing the efficiency of the biomass supply chain.

An agricultural biomass supply chain consists of a number of sequential operations, which might interact with each other, and it is affected by many variables, such as weather, moisture content, and cooperation between agricultural machines, making the entire process of biomass supply chain a complex system. By using computational tools, simulation mathematical models can be created for the assessment and analysis of supply chain systems.

There are numerous approaches in literature tried to analyze different features of the biomass supply chain. Sokhansanj et al. (2006) developed a model (IBSAL) which simulates the flow of biomass from a field to a biorefinery facility. Tatsiopoulos and Tolis (2003) worked on a model which simulates the problem of organizing a cotton biomass supply chain and the economic aspects of logistic procedures such as collecting and warehousing. Hansen et al. (2002) created a simulation model for the sugar cane harvesting and delivery systems. Pavlou et al. (2016) created three individual simulation models that were used for the analysis and assessment of different biomass harvesting, handling, and transport chains in terms of varying machinery configuration. Nilsson (1999) created a simulation model for wheat straw in order to analyze the performance of the entire process for minimizing the handling costs and energy needs. Sopegno et al. (2016) developed a computational tool for the estimation of the energy requirements of bioenergy crops on individual fields based on a detailed analysis of the involved in-field and transport operations. The results of the latter work shown the effect of the multiple parameters involved in agricultural production systems on the accounting of any economic or environmental measure of a biomass chain. Parameters that affect the output of the production system, in terms of monetary cost or energy requirements cost, includes, for example, the various different distances between the field, the storage facility, and the processing facility, material input dosages such as fertilizers and pesticides, different cropping management practices, and variations in the machinery systems (Bochtis et al., 2014). Such an approach can provide individualized results for a selected production system, where the configuration of different systems and the operational efficiency (Sørensen and Bochtis, 2010; Orfanou et al., 2013; Berruto et al., 2013; Bochtis et al., 2013a), as well diversify the performance of the biomass supply chain.

The aim of the presented paper is to show the effect of different parameters in a simulation environment regarding an agricultural biomass supply chain. Parameters such as the number of machines or the travel distance between field and biorefinery facility are implemented in the simulation model, and they are used for assessing the total operational time and variable cost of biomass supply chain. For the simulation, different scenarios have been chosen in order to show that the optimal solution in terms of time and/ or cost could be different according to the different parameters.

2 MATERIALS AND METHODS

Biomass is used for making biofuels, bioproducts and biopower. The challenge is to secure and maintain a reliable supply of biomass which keeps up with quality specifications at a reasonable cost. The creation and use of simulation models can assist with the assesment of the supply chain design and of the operational parameters.

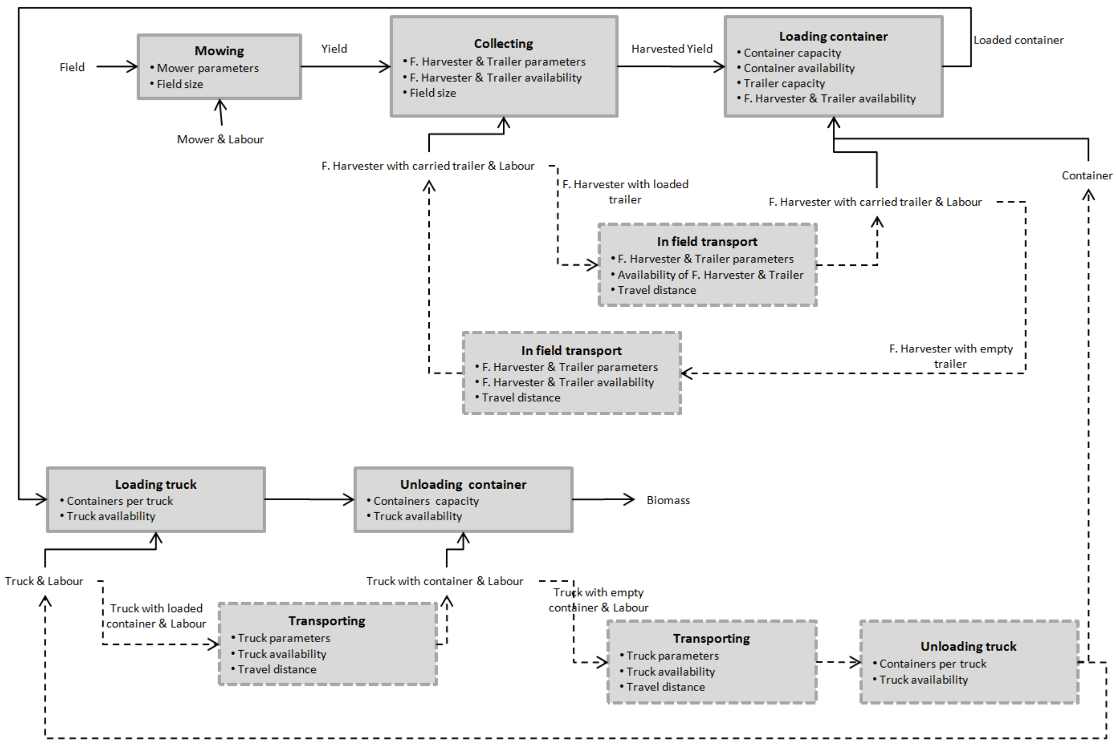
A simulation model of biomass supply chain, which consists of a number of sequential operations, i.e. mowing, collecting, loading, transporting and unloading, was developed on ExtendSim 8 simulation environment. ExtendSim is a stand-alone software for simulating discrete, continuous, and mixed systems. The simulation model was built by using pre-built blocks contained in the basic ExtendSim 8 software package.

Each one of the operations is well presented in the simulation model through different blocks and libraries from ExtendSim, showing analytically the flow of biomass from the field to the biorefinery facility. The operations and their resources are simulated by the blocks of the library "Item". Several different blocks from the library "Value" were used for importing the inputs of the system, for creating equations regarding the entire process and for controlling each operation separately in correlation with the others that interact. The graphical representation of the results was created by using blocks from the "Plotter" library.

Field, machinery and cost input data are required for the simulation of biomass supply chain. The inputs might differ based on the chosen scenarios. The output of the simulation model provides the bottlenecks of each machine, the total operational time and the variable cost of the agricultural biomass supply chain based on different scenarios. Each scenario is a combination of several parameters such as a) the travel distance between the field and the selected biorefinery facility, b) the capacity of the forage harvester's trailer, c) the capacity of the containers, d) the capacity of the truck, i.e. the number of containers per truck and e) the number of available containers in the field.

Figure 1 shows the architecture of the simulation model. Each box in the Figure 1 represents an operation of the agricultural biomass supply chain. These operations are "Mowing", "Collecting", "Loading container", "In-field transport", "Loading truck", "Unloading container", "Transporting", and "Unloading truck". Each one of the operations consists of constraint parameters that are presented with bullet points inside the respectively box. For example, the constraint parameters of "Loading container" are "Container capacity", "Container availability", "Trailer capacity" and "Forage harvester and trailer availability". The arrows show the flow of the product from the field to the biorefinery facility. Inputs and outputs are shown by arrows on the left and on the right side of each operation's box respectively. The arrow on the left side of each box represent the form of the product that inserts into the operation as an input while the arrows on the right side of each box show the form that the products exits as an output. For instance the input of the "Collecting" process is "Yield" while the output is "Collected Yield". The arrows at the bottom of each block present the physical aspects of each activity. This means that those arrows describe the resources, i.e. machines, labour etc. that are necessary in order the operation to be active. So, in order the "Mowing" operation to be achieved there is a need of at least one mower and a labour. Furthermore, the dashed arrows show the flow of the resources, more specifically, the transportation from one operation to another. An example is the in-field transportation of the forage harvester to the container when the trailer is loaded in order to be emptied.

Figure 1. Architecture of biomass supply chain simulation model



3 IMPLEMENTATION

In the presented case study a simulation model, which was developed for demonstrating a supply chain of crops for bio-energy production purposes, is shown. The system consists of eight sequential operations, i.e. mowing the field, collecting the yield, in-field transport, loading the yield to container, loading container to truck, transporting, unloading container and unloading truck. Each one of them is described in more details in Table 1.

Table 1. Sequential operations of the agricultural biomass supply chain system and description of them

Operation	Description
Mowing the field	The operation of mowing shows the activity of transforming the standing biomass to cut biomass that lies on the field. As it is shown on the architecture of the model, for a given field (input) the mowing activity is affected by the parameters of the mower and also by the field size. Moreover, the operation of mowing is controlled by the type of mower and by the operator of the machine. The operation is over when the whole field has been mowed. The output of mowing is the quantity of biomass which means the yield that lays on the field surface in pre-arranged swaths.
Collecting the yield	When mowing is over, the following operation regards the collection of the yield from the field. The yield that was the output of the previous operation (mowing) it turns into input. The collection of the yield is affected by the parameters of the forage harvester and the carried trailer. The former is used to collect the biomass while the latter to carry it. The trailer's capacity, as well as its availability, and the field size affect the whole operation. In case that the forage harvester is allocated to the following operation (loading the yield to container), the continuity of the operation of collecting stops until the forage harvester becomes available again. In general, the operation is controlled by the forage harvester with the carried trailer and the operator of the machine. The operation has as output a full load of the harvested yield.
In-field transport	When the trailer that is carried by the forage harvester is fully loaded, the forage harvester has to travel to the boundary of the field, where the containers are located in order the trailer to be unloaded. Then the forage harvester with the carried trailer returns back to the field and the operation of collecting the yield continues. The operation of the in-field transport is affected by the parameters of the forage harvester and the trailer, the availability of the forage harvester and the trailer, and the travel distance from the location of the field that the forage harvester stopped collecting yield to the location that the containers are located. The process of the in-field transportation which affects both the collection and the loading of biomass into the containers, basically shows the movement of the fully loaded trailer to the operation of loading the yield to container or the empty trailer, after being unloaded, to the previous operation (collecting the yield).
Loading the yield to container	The harvested yield is being unloaded to the containers located at the boundary of the field. This operation is affected by the capacity of the containers as well as by their availability. In case that there is no container available, due to the fact that they could be occupied within any of the following operations (loading container to truck, transporting, unloading container and unloading truck), then the continuity of the operation of loading is interrupted until a container becomes available again. The forage harvester with the carried trailer, the operator, and the number of the containers affect the performance of the process. The output of the loading is a fully loaded container. The operation is finished by the time that the whole yield from the field is loaded into the containers.
Loading container to truck	A container is loaded onto the truck by the time that the container is full and the truck is present and available. In case that the truck is not

	present at the loading site, then the operation cannot continue. The input in this operation is the full containers that are loaded onto the truck. Moreover, the operation is affected by the capacity of the truck (i.e. containers per truck). The truck and the operator of it are the physical aspects that affect the whole process. The output of the process is a loaded truck with one container or more which travels to the selected place (biorefinery) where biomass is going to be unloaded. The operation comes to an end when the last loaded (it does not have to be full) container is loaded onto the truck.
Transporting	By the time that the designated number of containers has been loaded onto the truck, the operator drives it to the storage facility in order the container/s to be unloaded. When the container/s is/ are unloaded, the truck returns back to the field where the empty container/s are available again. Furthermore, the truck is present and available one more time for the operation of loading the container/s onto it. The travelling distance that the truck has to cover and the truck parameters affects the transporting operation. Moreover, the operator controls the whole process. The output of the operation is the container which includes the quantity of biomass.
Unloading container	When the truck with the loaded container/s arrives to its final destination (biorefinery facility), the following operation of unloading the container/s takes place. The travel distance that needs to be covered between the field and the delivery facility, the truck's availability as well as, the capacity of the container/s affect the operation. The output of the operation is the biomass which is unloaded at the processing facility.
Unloading truck	After the truck returns back to the field with the empty container/s, the container/s are unloaded from the truck. In case that there are more containers to be loaded onto the truck, then the whole process continues. When all of the biomass is delivered to the biorefinery, all functions terminate.

For the implementation of the simulation model, a field of 8 ha located in Denmark and two biorefinery facilities at 6 km and 22 km far away from the field were chosen. A number of machines is necessary in the simulation model for each one of the operations of the agricultural biomass supply chain to be examined in this study. Those machines are a 150 hp tractor, a mower, a forage harvester, a trailer and a truck. The parameters of the selected machines are shown in Table 2.

Table 2. Parameters of the machines

Machines	**Repair factors[a]**		**List Price[b] (€)**	**Fuel Cost (€/h)**	**Accum. Use (h/y)**	**Productivity (min/ha)**	**Travel speed (km/h)**
	RF1	**RF2**					
Tractor (150 hp)	0.003	2.0	60,000	-	1,000	-	-
Mower	0.44	2.0	15,000	11.89	400	42.00	-
Forage Harvester	0.03	3.0	3,000	67.52	800	92.00	15.0
Trailer	0.4	1.7	40,000	-	800	-	-
Truck	0.003	2.0	110,000	Full: 17.92 Empty: 12,46	1,750	-	51.5

DAAS (2009)

Different scenarios were examined in this study. Those scenarios concern a combination of different parameters, i.e. the travel distance between field and biorefinery facility (6 km, 22 km), the capacity of forage harvester trailer (4,600 kg, 5,700 kg, 6,800 kg), the capacity of container (5,500 kg, 6,900 kg, 8,300 kg), the number of trucks (1, 2), and the number of the available containers (1 – 6). Each combination is described with letters (SD, LD) and four numbers. The sequence of the combinations is explained in Table 3.

Table 3. Explanation of the combination sequence

Sequence		Abbreviation	Explanation
(1)	Travel Distance between field and biorefinery facility	SD	Short Distance: 6 km
		LD	Long Distance: 22 km
(2)	Capacity of Forage Harvester Trailer	0	Low Capacity Trailer: 4600 kg
		1	Medium Capacity Trailer: 5700 kg
		2	Large Capacity Trailer: 6800 kg
(3)	Capacity of Container	0	Low Capacity Container: 5500 kg
		1	Medium Capacity Container: 6900 kg
		2	Large Capacity Container: 8300kg
(4)	Capacity of Truck	1	1 Container per Truck
		2	2 Containers per Truck
(5)	Number of Available Containers in the Field	2	2 Available Containers
		3	3 Available Containers
		4	4 Available Containers
		5	5 Available Containers
		6	6 Available Containers

4 RESULTS

In this section, the results of total operational time, variable cost, and bottlenecks of the simulation model are presented. Figure 2 presents a graph of the total operational time based on the travelling distance. The blue line represents the short distance (SD = 6 km) and the red line represents the long distance (LD = 22 km) between the field and the biorefinery facility. On the y axis, the time (min/ ha) that was needed for finishing the operations is shown. The total operational time varies from 120 min/ ha to 180 min/ ha based on the machinery combination which is presented on the x axis of the graph. In general the combinations in the short distance need less time to complete the operation of biomass supply chain than the combinations in the long distance. The combination “SD2212” (i.e. 6 km distance between field and biorefinery facility, 6800 kg capacity trailer, 8300 kg capacity container, 1 container per truck and 2 available containers) needs the least time for completing the operation, while the combination “LD0012” (i.e. 22 km distance between field and biorefinery facility, 4600 kg capacity trailer, 5500 kg capacity container, 1 container per truck and 2 available containers) needs the most time for completing the operation.

Figure 3 refers to the total cost of the operations for the short distance combinations in blue colour and long distance combinations in red colour. The y axis represents the cost (€/ ha) of the selected operations for each one of the selected machinery combinations presented on the x axis. The cost values vary from 240 €/ ha to 380 €/ ha. The short distance combinations consume less cost in comparison the long distance ones. The lowest cost consumption combination is the “SD2224” (i.e. 6 km distance between field and biorefinery facility, 6800 kg capacity trailer, 8300 kg capacity container, 2 container per truck and 4 available containers) and the highest one is the “LD0012” (i.e. 22 km distance between field and biorefinery facility, 4600 kg capacity trailer, 5500 kg capacity container, 1 container per truck and 2 available containers).

In the case that the field is located 22 km far away from the biorefinery facility, there are created some bottlenecks in the simulation model and some operations are forced to stop due to the absent of the resources. When the resources are available again, those operations continue. In this case the bottleneck phenomena are related to the forage harvester and the truck. Figure 4 shows the bottlenecks of the forage harvester and the truck for each one of the machinery combination (Figure 4(a)) and how those bottlenecks affect the total operational time and the variable cost of biomass supply chain for each one of the machinery combinations (Figure 4(b)).

Figure 2. Total operational time of biomass supply chain

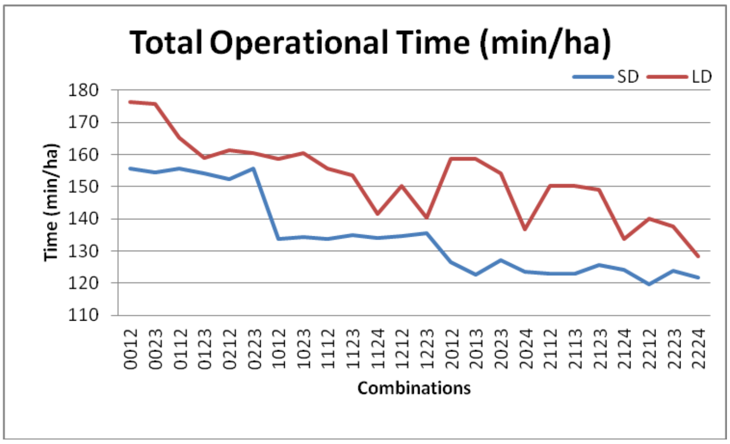
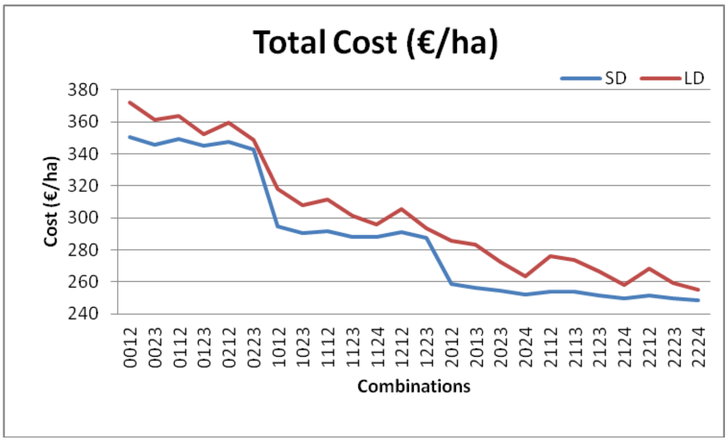


Figure 3. Total variable cost of biomass supply chain

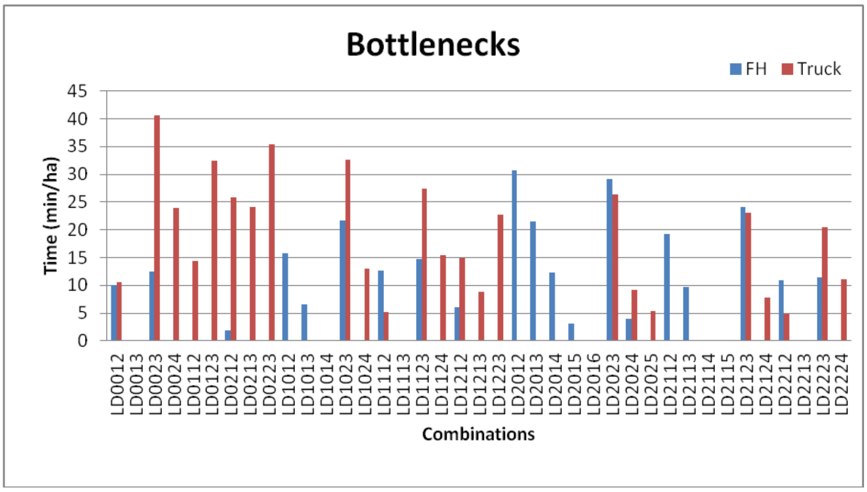


The blue bars in Figure 4(a) show the bottlenecks of the forage harvester and the red ones the bottlenecks of the truck. The machinery combinations are on the x axis and the time (min/ ha) that the bottlenecks last for each one of the machines (truck and forage harvester) and machinery combinations is shown on the y axis. There are cases that there are no bottlenecks and cases that the bottlenecks last up to 40 min/ ha. In most of the cases the bottlenecks of the truck last longer than the bottlenecks of the forage harvester. The machinery combination “LD0023” (i.e. 22 km distance, 4600 kg capacity trailer, 5500 kg capacity container, 2 containers per truck and 3 available containers) has the longest bottleneck of the truck, while the machinery combination “LD2012” (i.e. 22 km distance, 6800 kg capacity trailer, 5500 kg capacity container, 1 container per truck and 2 available containers) has the longest bottleneck of the forage harvester. There are no bottlenecks of either of the machines in the machinery combinations “LD0013” (i.e. 22 km distance, 4600 kg capacity trailer, 5500 kg capacity container, 1 container per truck and 3 available containers), “LD1014” (i.e. 22 km distance, 5700 kg capacity trailer, 5500 kg capacity container, 1 container per truck and 4 available containers), “LD1113” (i.e. 22 km distance, 5700 kg capacity trailer, 6900 kg capacity container, 1 container per truck and 3 available containers), “LD2016” (i.e. 22 km distance, 6800 kg capacity trailer, 5500 kg capacity container, 1 container per truck and 6 available containers), “LD2114” (i.e. 22 km distance, 6800 kg capacity trailer, 6900 kg capacity container, 1 container per truck and 4 available containers), “LD2115” (i.e. 22 km distance, 6800 kg capacity trailer, 6900 kg capacity container, 1 container per truck and 5 available containers), and “LD2213” (i.e. 22 km distance, 6800 kg capacity trailer, 8300 kg capacity container, 1 container per truck and 3 available containers). There are cases that bottlenecks of only one of the machines occur.

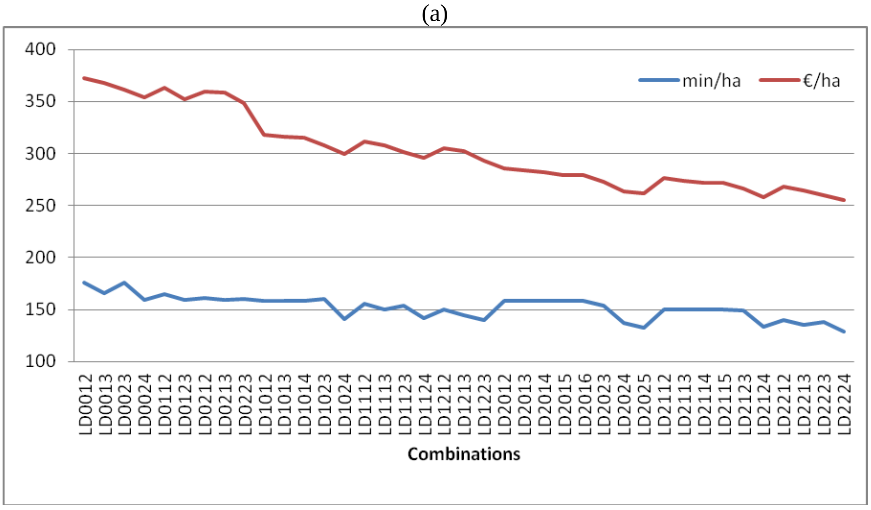
In Figure 4(b) a graph of the total operational time (min/ ha), in blue colour, and variable cost (€/ ha), in red colour, for each one of the machinery combinations is presented in order to show how they are affected by the bottlenecks phenomena that occur during the process. There are cases that even if there are no bottlenecks at all, it is needed more time (min/ ha) and more variable cost (€/ ha) for the completion of the biomass supply chain than cases with bottlenecks. An example is the combinations

"LD2016" (i.e. 22 km distance, 6800 kg capacity trailer, 5500 kg capacity container, 1 container per truck and 6 available containers) that there are not bottlenecks and "LD2023" (i.e. 22 km distance, 6800 kg capacity trailer, 5500 kg capacity container, 2 container per truck and 3 available containers) that bottlenecks exist.

Figure 4. (a) Bottlenecks of Forage Harvester and Truck, (b) Influence of bottlenecks on total operational time and variable cost of biomass supply chain



(a)



(b)

5 DISCUSSION

The inputs of this simulation model include field data (e.g. field size), machinery data (e.g. number and capacity of the machine used in each operation), and cost data (e.g. labor) which are used for providing the output of the simulation model created, i.e. the total time that was necessary for finishing all of the operations, from cutting and collecting the biomass until it is transferred and unloaded at the biorefinery facility, and the variable cost of the whole process.

Figure 2 and Figure 3 show how the different combinations affect the total operational time and the variable cost of the biomass supply chain in short and long distances. Based on the results, the travel distance between the field and the biorefinery facility affects the decision of machinery combination for the process of agricultural biomass supply chain in order to minimize the time consumption (Figure 2). For instance, the combination "2013" (i.e. 6800 kg capacity trailer, 5500 kg capacity container, 1 container per truck and 3 available containers), is a preferable choice for the short travelling distance (SD) between the field and the biorefinery facility but it is a relatively poor option for the long travelling distance (LD). On the other hand, the total variable cost is not affected on the same level as the total operational time by the different travel distances (Figure 3). It is shown that the process is influenced rather equally either for short or long distance, in terms of cost.

Furthermore, when there is a case of long travel distances, it is better to use a large capacity container in order to minimize the time consumption, instead of a large capacity forage harvester trailer (Figure 2). On the contrary, it is less time consuming to use a large capacity forage harvester trailer for short travel distances (Figure 2). Moreover, it .seems that large capacity forage harvester trailer affects positively the cost of the process regardless the travelling distance.

The simulation model provides the in-depth status of the material flow as a function of time for the different operations. When two operations interact, bottlenecks phenomena might occur which are the main causes for increasing the operating time of the operation. The bottlenecks occur due to the fact that there is imbalance of resources allocated in two or more interacting operations. More specifically, in the presented system, it seems that the capacity of the truck has no significant influence on time and cost consumption, in comparison with the capacity of forage harvester trailer and container (Figure 2, Figure 3). This occurs, because even if the truck travels less times to the biorefinery facility and back to the field, more bottlenecks of the truck are created during the process. However, when there are more available containers in the field and/ or large capacity forage harvester and container, the process becomes less time consuming because the bottlenecks are minimized (Figure 4).

A physical process that diversifies the whole operational configuraition and execution of the harvesting and handing of biomass, and consequently the whole supply chain, is drying. Drying directly affects the scheduling of the innvolved operations (Bochtis, 2010; Bartzanas et al., 2015). Furtermore, the machinery operational features, such as the coverage planning, affects the productivity of the whole chain. Different approaches on the operating plans diversify up to 20% the operating time and cost for both in-field activities (Bochtis et al., 2013b; Zhou et al., 2014) and inter-field travelling and transportation (Jensen et al., 2012).

6 CONCLUSION

In this paper, a simulation model of agricultural biomass supply chain was developed in ExtendSim 8 simulation environment consisting of sequential operations such as mowing, collecting, loading, transporting, and unloading. The purpose was to find out how the simulation model performs by comparing different operational scenarios in order to identify the differences on total operational time, variable cost, and inherent bottlenecks. Furthermore, the simulation model provides a better understanding of the parameters that could affect the process and influence the time consumed and the cost for each task and also all the temporary interruptions of various inter-connected processes. It is concluded that in each case, parameters, such as the area of the field, the travel distances between field and biorefinery, and the machinery system have to be taken into consideration in order to choose the best machinery combination (number of available machines, capacity of the machines) for minimising time and/or cost requirements.

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