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#### Functional modeling for green biomass supply chains

This is a pre print version of the following article:	
Original Citation:	
Availability:	
This version is available http://hdl.handle.net/2318/1618986	since 2016-11-30T12:15:45Z
Published version:	
DOI:10.1016/j.compag.2016.01.014	
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1	Functional modeling of biomass supply chains
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13	6 tables, 13 figures
14	Topic: Agricultural engineering

### 16 Abstract

17 The biomass supply chain is a multiple-segment chain characterized by prominent 18 complexity and uncertainty and as thus requiring increased managerial efforts as compared 19 with the case of single operation management. This paper deals with the operations 20 management within the supply chain of green (e.g. grass) and yellow (e.g. straw) biomass. 21 Specifically, three different supply chain systems, in terms of machinery configuration, were 22 analyzed and evaluated in terms of task times and cost performance. By using a function 23 modelling methodology, the structural representations of the systems in terms of activities, 24 actions, processes, and operations were generated and implemented by the ExtendSim® 25 simulation software. It was shown that the models can identify the bottlenecks of the systems 26 and can be further used as a decision support system by testing various alternatives, in terms 27 of resources used and their dimensioning. Finally, the models were evaluated against their 28 sensitivity on input parameters which are known with a level of uncertainty, i.e. the expected 29 yield and the expected machinery performance.

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Keywords: Biomass harvesting, logistics, operations management, simulation.

32

## 33 **1. INTRODUCTION**

34 The biomass supply chain is a multiple-segment chain characterized by prominent 35 complexity and uncertainty and as thus requiring increased managerial efforts as compared 36 with the case of single operation management. In its full extent, biomass supply chain includes production of biomass, harvesting and in-field handling, transportation 37 38 transportation, inter-mediate storage, (occasionally, inter-mediate and additional 39 transportation), pre-treatment, storage, and conversion, while some times the storage and 40 distribution of the generated bioenergy also is connected to the biomass supply chain (An et al., 2011). To that effect, numerous studies have been dedicated to analyze and elaborate 41 42 decision making and planning approaches associated with the different segments of this 43 specialized supply chain, including approaches for the initial network design (e.g. Zhang, F., 44 et al., 2012; Mafakheri and Nasiri, 2014; Rentizelas et al., 2014; Grigoroudis et al., 2014), 45 biomass storage planning (e.g., Rentizelas et al., 2009; Ebadian ET AL., 2013), and different 46 planning levels such as operational (e.g., Zhang and Hu, 2013), tactical (e.g., Shabani et al., 47 2014), and strategic level (e.g., De Meyer et al., 2015).

48 A specific characteristic of biomass supply chains is that the upstream decisions affect 49 the subsequent links of the chain. On the other hand, the selection of biomass processing 50 technologies, and the size and location of the conversion plant determine the type of all prior 51 operations (De Meyer et al., 2015). This characteristic is attributed to the fact that the 52 delivered biomass must fulfill specific requirements in terms of timeliness for delivering, 53 correct quantity, and desired shape, size and quality (Iakovou et al., 2010). Furthermore, the 54 upstream segments should be robust and flexible in order to adapt to the uncertainties 55 inherent in the biomass supply chains (Kim et al., 2011). To that effect, the availability of 56 different systems and the operational efficiency of field operations (e.g. harvesting and 57 handling of biomass) are key factors within the biomass supply chain considering that this 58 part accounts for more than 50% of the total cost.

59 In order to increase operational efficiency, improved methods and managements tools are required (Sørensen et al., 2010). This requirement is especially important in complicated 60 61 production systems which involve large scale operations. During large scale harvesting, 62 where biomass is used as a bioenergy resource, a number of sequential tasks are executed 63 which are dependent on different factors, such as the type of biomass (plant residues, grass, 64 and grain), the moisture content, and the final usage of the biomass (Sokhansanj, 2006). The 65 duration of the tasks is based on factors such as machinery and labor availability, machinery capacity, agronomical factors, etc. Advanced management models are required, such as fleet 66 67 management tools for operations of multiple machines in multiple fields (Sørensen and Bochtis, 2010; Orfanou et al., 2011), in order to analyze the process and understand the inner
working elements.

70 This paper deals with the operations management within the supply chain of green (e.g. 71 grass) and yellow (e.g. straw) biomass. Specifically, three different supply chain systems, in 72 terms of machinery configuration, are analyzed and evaluated in terms of task times and cost 73 performance. By using a function modelling methodology, the structural representations of the systems in terms of activities, actions, processes, and operations are generated. Based on 74 75 this modelling approach, three individual simulation models are built and implemented by 76 the ExtendSim® simulation software. Finally, a sensitivity analysis is performed in order to 77 assess the impact of the uncertainty of the yield and machinery productivity on the 78 simulation models output.

79

## 80 **2.** Methodology

81 2.1 Systems description

The three examined systems of biomass supply chain are shown in Figure 1. Systems 1 and 2 regard chains where the cut biomass is physically dried prior to its transportation to the process facility (bio-energy generation plant or any intermediate storage facility). System 3 regards a supply chain system of wet biomass where the biomass is cut and transported directly to the designated location with high moisture content without any prior physical drying.

88

### 89 2.2 MODELLING OF THE WORK PROCESS

90 For modeling the process of the tasks and operations in the previously described three 91 systems, the IDEF0 (Integrated Computer Aided Manufacturing definition for Function 92 Modeling) modelling scheme was implemented. IDEF0 is a function modeling technique for 93 the analysis of manufacturing functions and the description of the workflows as an ordered 94 sequence of events and involved objects. IDEF0 has been implemented to describe processes 95 in supply chains of agricultural products, such as grain supply chains (Thakur and Hurburgh, 96 2009; Busato, 2015) and vegetable supply chains (Hu et al., 2012), and processes in 97 agricultural production systems (van 't Ooster et al., 2013; Peres et al., 2011). The IDEFO 98 diagram follows a "box and arrow" structure representing functions as boxes and the 99 interfaces between functions as arrows inputting or outputting a box. Functions operate 100 either sequentially or simultaneously with other functions with the interface arrows

101	"constraining" the various operations by triggering or controlling them. The basic syntax for
102	an IDEF0 model is shown in Figure 2.
103	The architectures of the IDEF0 models for the three systems are presented in
104	
105	Figure 3, Figure 4, and Figure 5, respectively, while the analytical descriptions of each
106	model are given in Table 1, Table 2, and Table 3, respectively.
107	
108	2.3 The simulation model
109	2.3.1 SIMULATION ENVIRONMENT
110	The ExtendSim® programming environment (Imagine That Corporation, San Jose,
111	CA, USA) has been used for creating the three simulation models that represent the three
112	different systems of biomass harvesting operations. ExtendSim® is a stand-alone software
113	for simulating discrete, continuous, and mixed systems. The simulation model was built by
114	using pre-built blocks contained in the basic ExtendSim® software package.
115	2.3.2 INPUT PARAMETERS
116	The input parameters of the simulation include:
117	Field configuration:
118	- Area of the field
119	- Yield of the field
120	- Dry loses during physical drying
121	- Distance between the field entry/exit point and the container's location
122	Machinery inputs:
123	- Number of labor in each task
124	- The in-field travelling speed for machinery carrying biomass
125	- Capacity of machines
126	- The repair and maintenance factor for each tractor and for each implement
127	- Power of each tractor (or self-propelled machine)
128	- Time of loading and unloading processes involved in the chain
129	- The travelling speed of the truck from field to the storage facility
130	- Accumulated use of each machine
131	Cost inputs
132	- Labor cost rate

The unit fuel cost (in the case where the fuel consumption is estimated within the
simulation model) or the hourly fuel cost for each task in the case where these values
are available (form experimental or historical data)

- 136 The list price of each machine
- 137

#### 138 2.3.3 Pre-processing

A pre-processing of the input data takes place in order to estimate the task times and the cost per time unit of each task within the supply chain. The estimation of the task times is based on the machine type, the corresponding task type specifications, and the area of the field. The estimation of the cost is based on the machinery system specifications for each machinery type and regards the implement and tractor variable unit costs, the fuel consumption and labor unit cost. The tractor variable cost is the summation of the repair and maintenance cost and the fuel that is consumed:

146 
$$c_{Th} = c_f + c_{rm} \rightarrow \mathcal{E} / h$$

147 where,  $c_{Th}$  refers to the hourly tractor variable cost,  $c_f$  is the fuel cost, and  $c_{rm}$  is the 148 accumulated repair and maintenance cost in a typical field.

The fuels and oil cost can be either a direct input based on the experimental or historical data available, or if not such data exist, the field machinery fuel cost can be estimated by implementing the specific volumetric fuel consumption formula and the process as it is described in ASAE D497.6 (2009) and has been implemented in the simulation model.

The repair and maintenance cost is estimated by using the formula of accumulated repair and maintenance cost according to Agricultural Machinery Management Data ASAE Standard (ASAE EP496.3, 2009):

157 
$$c_{rm} = RF1 \cdot P \cdot \left[\frac{a}{1000}\right]^{RF2}$$

where,  $c_{rm}$  is the accumulated repair and maintenance cost in typical field operating speeds ( $\epsilon/h$ ), *RF*1 and *RF*2 refer to the repair and maintenance factors, *P* is the machine list price ( $\epsilon$ ), and *a* is the accumulated use of machine (h/y).

161 The implement variable cost is the repair and maintenance cost of the implement. It 162 is estimated with the same procedure as it is described in tractor variable cost:

163 
$$c_{lh} = c_{rm} \rightarrow \mathcal{E} / h$$

164 where,  $c_{Ih}$  is the hourly implement variable cost.

165 The machinery variable cost is estimated by the costs of labor, fuels and oil, and 166 repair and maintenance. The hourly variable cost is the summation of labor, tractor and 167 implements variable cost:

168 
$$c_h = c_{Th} + c_{Ih} + c_{Lh} \rightarrow \mathcal{E} / h$$

169 where,  $c_h$  is the hourly variable cost,  $c_{Lh}$  is the hourly labor cost.

170

171 2.3.4 PROCESSING

172 As mentioned above, for the implementation of the three models, ExtendSim<sup>®</sup> simulation programming environment was used. ExtendSim<sup>®</sup> is a simulation software for 173 174 modeling discrete, continues and mixed systems. The simulation model works by simulating 175 the material flow and integrating the resources and the constraints throughout all sequential 176 and parallel activities-functions. When a discrete event takes place, the simulation model 177 allocates the corresponding time and cost to that part of the task that has been executed. A 178 number of pre-defined blocks stored in repositories, called "Libraries", were used. For the 179 main simulation part, two types of Libraries were used, namely "Item Libraries", which 180 simulate real world elements and resources that interact when specific events occur, and 181 "Value Libraries", which contain blocks that provide information to item blocks. Table 4 182 describes the functionality of the main blocks that were used for the implementation of the 183 three systems.

184

185 2.3.5 OUTPUT

The general output of the simulation model is the total time required for the completion of all tasks of a system and the cost of the whole operation (from cutting the biomass until its unloading to the processing facility. However, the model provides the possibility for an indepth decomposition of the individual sub-processes. The time consumed and the cost for each task and sub-processes are provided and also all the temporary interruptions of various inter-connected processes (bottlenecks).

192

### 193 **3. MODEL IMPLEMENTATION**

194 3.1 Case study description

For the demonstration of the simulation model, data from a real biomass production system located in Piedmont region, North Western Italy, was used. These data refers to the machinery features for each system, yield related data, and operational times data. The crop cultivated in the considered production system is grass (2<sup>nd</sup> cut) with an average yield of 10.2 t/ha. Based on experimental results in the system, yield losses, during the harvesting and handling operations, of an average value of 22% have to be considered. Furthermore, for systems 1 and 2, a mass loss of 75% has been considered (water) as an outcome of the field drying process from 80% to 18% MC w.b. This value corresponds to an average period of drying in the specific region. The machinery implemented for each system is provided in Figure 6. The machinery data are listed in Table 5.

205

#### 206 3.2 MODELS' FUNCTIONALITY

207 The simulation model provides the in-depth status of the material flow as a function of 208 time for the different operations. When two operations interacts bottlenecks phenomena 209 (imbalance of resources allocated in two or more interacting operations) might occur which 210 are the main causes for increasing the operating time and consequently, the total cost of the 211 operation. In the examined systems, bottlenecks occur in the operation of the unit of each system that executes the task of the out-of-field removal of biomass (that is in System 1 the 212 213 collector, in System 2 the pick-up machine, and in System 3 the forage harvester), and in the 214 transportation of the biomass to the processing facility.

215 Figure 7, Figure 8, and Figure 9 present the identified bottlenecks as a function of time 216 for both the out-of-field biomass removal unit (a) and the transport unit (b) for System 1, 217 System 2, and System 3, respectively. In these figures the various bottlenecks occurred in the 218 systems are presented as horizontal line segments (level 1 for the case of truck). As it was 219 expected, for the case of the out-of-field biomass removal units the total duration of 220 bottlenecks is higher for the long distance transportation compared to the one of the short 221 distance transportation, while the opposite holds true for the case of the total duration of 222 bottlenecks for the transport unit.

These bottlenecks are the result of the matching between different features of the system, for example the productivity of the biomass collection process and the capacity (or the number) of the available containers. In order to highlight the effect of the differentiation of the results in terms of the bottlenecks occurrence and duration a number of scenarios have been run implementing different containers number and capacities for the case of system 1 for a field of 5 ha and for two distances between the field and the processing facility (a short distance of 5 km and a longer distance of 26 km).

230 Starting from the basis scenario (two containers of 6,900 kg capacity) the number of 231 the containers was increased until the idle-time of the forage harvester was reached zero and in parallel, two underestimates and overestimates ( $\pm 20\%$  and  $\pm 40\%$ ) of the capacity basis value have been examined. The goal was to find an optimal combination between the number of containers and their capacity for minimizing the idle time of forage harvester.

235 Based on the results listed in Table 6, less idle time does not result to less total 236 operating time and/ or less total cost. In general, idle time is reduced in the case of higher 237 number of containers with higher capacity. However, the truck travels more times from the 238 field to the storage facility and back, getting as a result a more time and cost consuming 239 system. In the case of short distance, the best combination between capacity and number of 240 containers in terms of idle time is 4,100 kg - 3 containers, while in terms of total operating time and cost is 8,300kg - 2 containers. In the case of long distances, the best combination 241 242 between capacity and number of containers in terms of idle time is 6,900kg - 3 containers 243 and 5,500 kg - 4 containers, while in terms of time and cost is 8,300 kg - 3 containers. This 244 means that when the distance between the field and the storage facility is long, containers 245 with low capacity are not efficient in terms of time and cost expenses.

Another functionality of the simulation model is the estimation of the distribution of cost elements. For example, Figure 10 presents the distribution in terms of cost of the different operations involved in the examined systems for fields located at short distance (5 km) with the area of 5 ha. In the presented distributions, the cost of each operation regards the set of all tasks making up a complete operation, for example the cost of the collector in Figure 10a regards the laying biomass collection task, the in-field transport to and from the container, and the loading of biomass into the container.

253

#### 254 3.3 Systems comparison

255 The simulation models can be used for the comparison of the three different systems. 256 Figure 11 presents the total unit cost and the total unit operation time for the three systems 257 for different combinations of field area and distance between the field and the processing 258 facility. As expected, system 3 is the most cost- and time-effective system. However, the 259 biomass delivered to the processing facility by system 3 is wet biomass, and further cost is 260 required for the drying process. In other words, the margin between the cost values of system 261 3 and the other two systems represents the maximum additional cost allocated to drying (for 262 the quantity of biomass produced per ha) in order system 3 to still be the most economical 263 one. Based on the same logic, the margin between the total cost in systems 1 and 2, 264 represents the maximum additional cost for the wrapping of bales in order system 2 still 265 remain more economical compared to system 1.

266 The dominant role played by field distance should also be noticed. The increase in costs 267 is almost linear with the distance increase. It is more important for system 3 than for systems 268 1 and 2 since we transport wet material so there is a higher quantity to be transported and 269 this influence transport costs. Finally, it can be seen that when the area increases the total 270 operation unit cost is slightly decreased. This fact has to do with the increase of the 271 operational efficiency with the increase of the area of a field due to the reduction of the non-272 productive times. However, the model in its current form cannot represent the actual increase 273 in field efficiency since it is not take into account the detailed operational features (e.g. field 274 shape, number of individual headland turnings, etc.) but in contrast it uses average norms 275 and standards (e.g. provided by ASABE). The inclusion of the detailed execution of the field 276 tasks is a matter of future research and improvement of the presented model.

277

### 278 **4. Sensitivity analysis**

279 The input parameters of the simulation model which are known with a level of 280 uncertainty are the expected yield and the expected machinery performance. Yield is 281 affected by biological, soil, and weather parameters and also by losses during harvesting and 282 consequently, only average estimations of the expected yield, mainly based on historical data, can be done. Machinery performance, on the other hand, is affected by factors such as 283 284 the operator's experience, the field shape and topography, and various machinery features 285 such as operating functionalities and embedded technologies (e.g. operator's aiding 286 systems). To that effect, a sensitivity analysis has been carried out to evaluate how sensitive 287 are the outputs of the simulation model to under- or over-estimates of yield and machinery 288 performance. Specifically, for both parameters, underestimates and overestimates of 10% 289 and 20% have been examined in terms of the deviation of the outputs (total operating time 290 and total cost) from their real values. These scenarios have been run for all of the three 291 supply chain systems and for the cases of a long (26 km) and of a short (5 km) transportation 292 distance for a field of 5 ha area.

The varying yield estimates sensitivity analysis is presented in Figure 12. For the case of the operating time, in general, the system is more sensitive to underestimations compared to overestimations. This trend is not followed in the case of the cost where there is a balance between both cases. For both of output parameters (operating time and cost), the most sensitive system on the yield estimation is system 3, followed by system 1, while the less sensitive system is system 2. The separate response of system 2 to yield variations compared to systems 1 and 3 can be attributed on the main differentiation of system 2 where the biomass is handled as a condense material (i.e. bales) without the presence of containers that discretize the material flow while in systems 1 and 3 the biomass is handled as a voluminous material.

303 The varying machinery performance sensitivity analysis is presented in Figure 13. In all 304 three systems for both output parameters, the system is less sensitive in terms of machinery 305 performance in case where the transport distance is increased. This is an outcome of the fact 306 that the machinery performance refers mainly to in-field activities and by increasing the 307 transport distances the share of the (out-field) transportation on the total operating time and 308 cost is increased and thus the systems are less sensitive to parameters affecting the share of 309 the in-field activities in the operating time and cost. Regarding the cost output (Figure 13b), 310 it appears to be more sensitive to the machinery performance values for the case of system 1, 311 followed by the system 2, and be less sensitive in the case of system 3. Regarding the 312 operating time output (Figure 13a), the same trend is observed for the short transportation 313 distance, while in the case of the long transportation distance the most sensitive system is 314 system 2, followed by system 1, and the less sensitive system is again system 3.

### 315 **5.** CONCLUSIONS

316 Three individual simulation models were built in order to analyze and evaluate different 317 biomass harvesting and handling chains in terms of machinery configuration. The models 318 provide the structural representations of the systems in terms of activities, actions, processes, 319 and operations. It was shown that the models can identify the bottlenecks of the systems and 320 can be further used as a decision support system by testing various alternatives, in terms of 321 resources used and their dimensioning. This allows for configure the right system based on 322 the criteria of total operation cost and/or total operation time. Finally, the models were 323 evaluated against their sensitivity on input parameters which are known with a level of 324 uncertainty, i.e. the expected yield and the expected machinery performance.

- 325 Future work elements include:
- The inclusion of continues models for physical (in-field) drying process of biomass
   (for example, the model presented in Bartzanas, et al. 2010). This will provide insight
   for the scheduling task for collecting biomass from multiple-fields.
- The expansion of the chain under question to include also the technical biomass
   drying process (when necessary). This will allow a direct comparison between total
   costs and performance of the different systems.

- The inclusion of models for in-field area coverage (for example the model presented
   in Zhou et al., 2014). This will provide an in-depth analysis of the effect of different
   operational features (e.g., field shape, coverage pattern, in-field obstacles, and
   variation of yield) on the total time and cost of the operation.
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   static rose cultivation system. Biomass Bioenerg 120: 34-46.
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# Table 1. System 1 IDEF0 model description

Function	Description
Mowing (#1)	The first function regards the activity of transforming the standing biomass to cut biomass laying on the ground. For a given field (input) the mowing activity is controlled by the field size and the parameters of the mower. The mechanisms of the activity are the mower and the operator. The function terminates when the whole field has been mowed. The output of the activity is the certain amount of the biomass (yield) laying on the field surface.
Collecting (#2)	This function starts when the previous one is completed. It receives as input the yield generated in function #1 (this yield corresponds to the cut biomass laying on the field area). The function is constrained by the parameters of the forage harvester that is used to collect the biomass and the carried trailer (e.g. trailer's capacity), its availability, and the field size. If the forage harvester is occupied at the subsequent activity (function #3), function #2 is interrupted until the forage harvester is available again. The mechanisms of the function #2 are the forage harvester with the carried trailer and the labor. The output of the activity is a full load of the carried trailer. If the trailer is not completely full at the last cycle of the activity and there is not any yield left in the field, the activity terminates and the machine proceeds to the next activity.
Loading Container (#3)	In this function the load of the trailer (carried by the forage harvester) is unloaded to containers located at the boarder of the field. The controls of this function are the capacity of the containers and its availability. If there is no container available (in case, for example, they could be occupied within functions #4, #5, or #6), function #3 is interrupted. The mechanisms of the function are the forage harvester and the carried trailer, the labor, and the number of the containers. There are two outputs in this function. The first output is the empty trailer of the forage harvester which returns to the previous activity (function #2). The second output is a fully loaded container. The process is repeated until the whole yield is loaded into containers. If the last container is not completely full (in the case where there is no yield left) it continues to the next function (#4) and the current function terminates.
Loading of Container (#4)	When a container (input) is full and the truck is available, the container is loaded onto the truck. This function is controlled by the capacity of the truck (containers per truck) and the availability of the truck. If the truck is not present at the loading location the function is interrupted. The mechanisms are the truck and the labor. The output of the activity is a loaded truck which travels to the storage facility (e.g. a biogas plant). The function terminates when the last loaded container is loaded onto the truck.
Transporting (#5)	When the designated number of containers has been loaded onto the truck, the truck drives to the storage facility. The travelling distance and the truck parameters are the constraints of this function. The mechanisms are the truck and labor. The output is the biomass quantity that is delivered to the facility.
Unloading (#6)	This function describes the unloading process of the container at the storage facility. The capacity of the container affects the activity, which uses the same mechanisms as in the previous two functions. There are three outputs. The biomass which is unloaded at the processing facility and the truck with the empty container, which returns to the field. When the truck is back to the field, the container is unloaded and it is available for function #3. Then the truck is available to function #4. When all of the biomass is delivered to the processing facility all functions terminate.

# Table 2.- System 2 IDEF0 model description

Function	Description
Mowing – Conditioning (#1)	Same function as in System 1 with the difference that the machine is both cutting and condition the biomass (generates rows)
Baling (#2)	When function #1 terminates, function #2 is initiated. As input is used the output of function #1. The function's constrains are the field size, machine's parameters (e.g. time/bale), and the weight of a bale. The baler and labor are the mechanisms of this function.
Picking-up (#3)	The produced bales from function #2 are used as input. The function is controlled by the field size, the parameters (e.g. number of bales that it can be carried), and the availability of the pick-up machine. The mechanisms of the function are the pick-up machine and labor. Every time that the pick-up machine is full with bales, the function is interrupted providing as output a full load with bales. The function resumes again when the pick-up machine is available. In the case that there not enough bales to fill up the machine (last cycle), the machine proceeds to the subsequent function and function #3 terminates.
Loading Truck (#4)	The input of this function is the bales which are unloaded from the pick-up machine and loaded to the truck. The function uses the pick-up and the labor from function #3, a forklift, a truck, and the related labor. Constrains of this activity are the capacity of the truck, its availability, and the capacity of the forklift (number of bales that can be moved simultaneously). When the pick-up machine is unloaded, it is an output of the function and it returns to function #3. This loop continues until the truck is full. The second output is a full truck. In the case that the truck is full but the pickup machine is not empty yet, the truck leaves and the pickup machine waits until the truck is available again. This means that both functions (#3 and #4) are interrupted. Function #4 resumes again when the truck returns from the processing facility. The function terminates when there are no more bales to be loaded to the truck.
Transporting (#5)	A full truck is used as an input and as a mechanism in this function, which is controlled by the truck parameters and the travel distance. The output is the number of bales which are delivered to the processing facility.
Unloading (#6)	This function starts when the truck arrives to the processing facility. The capacity of the forklift and the truck controls the function. The physical aspects are the truck and labor from functions #4 and #5, and the forklift. The output is the biomass and the truck that returns back to the field. When all of the bales are delivered to the facility the whole process terminates.

# Table 3. System 1 IDEF0 model description

Function	Description			
Mowing-collecting (#1)	The input in this function is the field. The controls of this function are the field size, the parameters of the machine and its availability. In case that the machine is not available this function is interrupted. The mechanisms of the function are the mower-collector machine and the labor. Every time that the machine is full, it proceeds to the subsequent function (function #2) representing the output of the function. When the whole field has been processed and there is no yield to be harvested, the function terminates.			
Travelling to container (#2)	Every time that the mower-collector machine must unload it enters as an input in this function. This function is controlled by the parameters of the machine and the distance to container(s). The same labor and mower-collector from function #1 are the mechanisms of this function. The output of the function is the machine with the yield positioning alongside the container. The functions ends when there is no yield to be transported.			
Loading Container (#3)	The input in this function is the yield, which has been collected in function #1. The mower-collector, which carries the cut and collected biomass, its labor, a loader, and the number of the containers, are the mechanisms of the function. Constrains that control the function are the capacity of the loader and of the container, and the availability of a container. If there is not available container due to they are full or they have proceeded to one of the following functions (functions #4, #5, #6), the function is interrupted. The output of the function is the mower-collector, which has to be empty and be available to continue its operation in function #1. The loop of the mower-collector in functions #1, #2, and #3 continues until the container is full with yield. Then the loaded containers the mower-collector waits until an empty container enters the function. When the entire yield has been loaded to container, both mower-collector and the container exit the function as outputs and the function is terminated.			
Loading Container onto truck (#4)	Same as in System 1			
Transporting (#5)	Same as in System 1			
Unloading (#6)	This function describes the unloading process of the container at the storage facility. The capacity of the container and the loader affects the activity, which uses the same mechanisms as in the previous two functions and a loader. There are three outputs. The biomass which is unloaded at the processing facility and the truck with the empty container, which returns to the field. When the truck is back to the field, the container is unloaded and it is available for function #3. Then the truck is available to function #4. When all of the biomass is delivered to the processing facility all functions terminate.			

Library	Block	Description					
Item	Executive	This block provides simulation control in a discrete event simulation. It terminates the simulation when specific number of biomass arrives to the final destination.					
-	Create	It creates items that are going to be processed during the simulation (e.g. field).					
-	Activity	Each operation (mowing, baling, collecting, etc.) is represented by an activit block which holds one or more items and passes them out based on the proces time and arrival time of each one.					
-	Transport	It transports items from one physical point to the other, e.g. from the field t container or from the field to the storage facility.					
-	Queue	It holds items (e.g., container, trailer, etc.) when the corresponding activity i occupied and releases them when it is available.					
-	Gate	It limits the passing of items, for example when a container is not available a the field side the gate closes not allowing any material flow between the tw resource items (i.e. trailer-container).					
-	Batch	It is used for synchronizing resources and joining items. For instance the truck is batched with a full container and they are considered as one item for a certain time period during the simulation.					
-	Unbatch	It is used for separating items. For instance, when the truck returns to the field, it is un-batched from the empty container.					
-	Recourse Item	It provides items, e.g. machines and labor.					
-	Select Item In	It selects items from one input based on a decision to be made.					
-	Select Item Out	It selects which output gets items from the input, based on a decision.					
-	Information	Throughout the simulation, these blocks are used in order to report statistic about the items that pass through it, such as amounts of biomass, containers etc.					
-	Exit	In each simulation model this block provides the number of items at the fina destination, i.e. amount of biomass at storage facility. The simulatio terminates when the desire number of items is absorbed by this block.					
-	Cost Stats	It is used for exporting the cost data.					
Value	Constant	It is used for determining the inputs of the simulation model.					
-	Read	It is used for determining the inputs of the simulation model in the case of multiple runs (e.g. different travelling distances).					
	Equation	All the equations in the simulation models are executed through Equation blocks. The inputs are imported from blocks such as, Constant, Information etc. and the output is exported to blocks such as Activity, Batch, and Decision					
-	Decision	Decision blocks are used mostly in combination with Gate blocks. The permit a gate to open or not, allowing the flow of material and items. It is als used with activity blocks in order to stop the activity, if it is necessary.					

**Table 4.** The block types used for the main simulation part

System	Machine	RF1	RF2	Market Price (€)	Fuel cost (€/h)	Accum. Use (h/y)	Productivity (min/ha)	Capacity	Travel speed (km/h)
\$1,\$2,\$3	Tractor (150 hp)	0.003	2.0	60,000	-	1,000			
	Truck	0.003	2.0	110,000	Full: 17.92 Empty: 12.46	1,750		1 container (S1,S3) 48 bales (S2)	51.5 (out-field)
	Mower	0.44	2.0	15,000	11.89	400	42		
S1,S3	Container							6,918 kg	
S1	Forage harvester	0.03	3.0	3,000	67.52	800	92	5,681 Kg	15.0
	Trailer	0.40	1.7	40,000		800			
S2	Round baler	0.43	1.8	32,000	14.18	400	65		
	Pick-up	0.16	1.6	34,000	13.03	400	62	18 bales	15.0
	Fork-lift	0.4	1.7	9,000	8.46	400	17.86	2 bales	

 Table 5. Machinery data for the three examined systems

## **Table 6.** Operation time and cost elements for different capacity and number of available

409 containers

No. of containers	Capacity of container (kg)	Idle time for forage harvester (min)	Idle time for truck (min)	Total operation time (min)	Total cost (€)				
	Short Distance								
2	6900	0.00	153.10	697.84	1447.25				
2	5500	0.00	139.60	701.35	1473.71				
2	4100	66.11	132.09	765.88	1515.75				
3	4100	0.00	77.17	710.95	1489.52				
2	8300	0.00	160.44	669.76	1434.15				
2	9700	0.00	191.07	701.61	1440.80				
		Lon	g Distance						
2	6900	73.47	30.58	868.91	1577.32				
3	6900	0.00	0.00	838.33	1554.80				
3	5500	68.64	0.00	953.17	1645.94				
4	5500	0.00	0.00	953.17	1631.10				
4	4100	154.49	0.00	1123.11	1740.84				
5	4100	68.73	0.00	1123.11	1722.27				
2	8300	46.41	31.81	785.78	1533.57				
3	8300	0.00	8.69	762.67	1518.52				
2	9700	21.98	66.25	821.45	1535.76				
3	9700	0.00	66.25	821.45	1531.01				



**Figure 1.** The three examined biomass supply chain systems and the involved operations



**Figure 2.** The basic syntax of an IDEF0 model



**Figure 3.** The IDEF0 architecture of a system 1



**Figure 4.** The IDEF0 architecture of a system 2



**Figure 5.** The IDEF0 architecture of a system 3

		SYSTEM 3 Mower Loader	
Forage Harvester with carried Trailer	Container	Tractor Truck	Round Baler Pick-up Machine Forklift
SYSTEM 1	`	Mower	 SYSTEM 2

**Figure 6.** The implemented machinery in the examined supply chain systems



438 Figure 7. Bottlenecks in System 1, (a) for a short transport distance and (b) for a long
439 transport distance.



445 Figure 8. Bottlenecks in System 2, (a) for a short transport distance and (b) for a long
446 transport distance.





454 Figure 9. Bottlenecks in System 3, (a) for a short transport distance and (b) for a long
455 transport distance.





469

150

100

50

0

2 ha

2 ha

2 ha

2 ha

5 ha

470

471 Figure 11. Total cost (a) and total operating time (b) for the three systems for different 472 combinations of field area and transport distance.

5 ha

5 ha

**(b)** 

5 ha

8 ha

5 Km 12 Km 19 Km 26 Km 5 Km 12 Km 19 Km 26 Km

8 ha

8 ha

8 ha

11 ha 🛛 11 ha

11 ha 11 ha





**Figure 13**. Operating time (a) and cost (b) changes due to machinery performance variation