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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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12

13 6 tables, 13 figures

14 **Topic:** Agricultural engineering

15

## 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.

30

31 **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  
37 includes production of biomass, harvesting and in-field handling, transportation  
38 (occasionally, inter-mediate transportation, inter-mediate storage, 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  
41 al., 2011). To that effect, numerous studies have been dedicated to analyze and elaborate  
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  
60 required (Sørensen et al., 2010). This requirement is especially important in complicated  
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  
66 capacity, agronomical factors, etc. Advanced management models are required, such as fleet  
67 management tools for operations of multiple machines in multiple fields (Sørensen and

68 Bochtis, 2010; Orfanou et al., 2011), in order to analyze the process and understand the inner  
69 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  
74 the systems in terms of activities, actions, processes, and operations are generated. Based on  
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

82 The three examined systems of biomass supply chain are shown in Figure 1. Systems 1  
83 and 2 regard chains where the cut biomass is physically dried prior to its transportation to the  
84 process facility (bio-energy generation plant or any intermediate storage facility). System 3  
85 regards a supply chain system of wet biomass where the biomass is cut and transported  
86 directly to the designated location with high moisture content without any prior physical  
87 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 IDEF0  
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

- 133 - The unit fuel cost (in the case where the fuel consumption is estimated within the
- 134 simulation model) or the hourly fuel cost for each task in the case where these values
- 135 are available (form experimental or historical data)
- 136 - The list price of each machine

137

### 138 2.3.3 PRE-PROCESSING

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

$$146 \quad c_{Th} = c_f + c_{rm} \rightarrow \text{€} / h$$

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.

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

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

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

158 where,  $c_{rm}$  is the accumulated repair and maintenance cost in typical field operating speeds  
 159 (€/h),  $RF1$  and  $RF2$  refer to the repair and maintenance factors,  $P$  is the machine list  
 160 price (€), 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:

$$163 \quad c_{Ih} = c_{rm} \rightarrow \text{€} / h$$

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:

$$168 \quad c_h = c_{Th} + c_{Ih} + c_{Lh} \rightarrow \text{€} / h$$

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>  
173 simulation programming environment was used. ExtendSim<sup>®</sup> is a simulation software for  
174 modeling discrete, continuous 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

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

192

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

#### 194 3.1 CASE STUDY DESCRIPTION

195 For the demonstration of the simulation model, data from a real biomass production  
196 system located in Piedmont region, North Western Italy, was used. These data refers to the  
197 machinery features for each system, yield related data, and operational times data. The crop

198 cultivated in the considered production system is grass (2<sup>nd</sup> cut) with an average yield of  
199 10.2 t/ha. Based on experimental results in the system, yield losses, during the harvesting  
200 and handling operations, of an average value of 22% have to be considered. Furthermore, for  
201 systems 1 and 2, a mass loss of 75% has been considered (water) as an outcome of the field  
202 drying process from 80% to 18% MC w.b. This value corresponds to an average period of  
203 drying in the specific region. The machinery implemented for each system is provided in  
204 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  
212 system that executes the task of the out-of-field removal of biomass (that is in System 1 the  
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.

223 These bottlenecks are the result of the matching between different features of the  
224 system, for example the productivity of the biomass collection process and the capacity (or  
225 the number) of the available containers. In order to highlight the effect of the differentiation  
226 of the results in terms of the bottlenecks occurrence and duration a number of scenarios have  
227 been run implementing different containers number and capacities for the case of system 1  
228 for a field of 5 ha and for two distances between the field and the processing facility (a short  
229 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

232 in parallel, two underestimates and overestimates ( $\pm 20\%$  and  $\pm 40\%$ ) of the capacity basis  
233 value have been examined. The goal was to find an optimal combination between the  
234 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  
241 time and cost is 8,300kg - 2 containers. In the case of long distances, the best combination  
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.

246 Another functionality of the simulation model is the estimation of the distribution of  
247 cost elements. For example, Figure 10 presents the distribution in terms of cost of the  
248 different operations involved in the examined systems for fields located at short distance (5  
249 km) with the area of 5 ha. In the presented distributions, the cost of each operation regards  
250 the set of all tasks making up a complete operation, for example the cost of the collector in  
251 Figure 10a regards the laying biomass collection task, the in-field transport to and from the  
252 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  
283 data, can be done. Machinery performance, on the other hand, is affected by factors such as  
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.

293 The varying yield estimates sensitivity analysis is presented in Figure 12. For the case of  
294 the operating time, in general, the system is more sensitive to underestimations compared to  
295 overestimations. This trend is not followed in the case of the cost where there is a balance  
296 between both cases. For both of output parameters (operating time and cost), the most  
297 sensitive system on the yield estimation is system 3, followed by system 1, while the less  
298 sensitive system is system 2. The separate response of system 2 to yield variations compared

299 to systems 1 and 3 can be attributed on the main differentiation of system 2 where the  
300 biomass is handled as a condense material (i.e. bales) without the presence of containers that  
301 discretize the material flow while in systems 1 and 3 the biomass is handled as a voluminous  
302 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:

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

332 - The inclusion of models for in-field area coverage (for example the model presented  
333 in Zhou et al., 2014). This will provide an in-depth analysis of the effect of different  
334 operational features (e.g., field shape, coverage pattern, in-field obstacles, and  
335 variation of yield) on the total time and cost of the operation.  
336

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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

<b>Function</b>	<b>Description</b>
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 container becomes an output of the function. In case that there are not available 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.

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

<b>Library</b>	<b>Block</b>	<b>Description</b>
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. a field).
	Activity	Each operation (mowing, baling, collecting, etc.) is represented by an activity block which holds one or more items and passes them out based on the process time and arrival time of each one.
	Transport	It transports items from one physical point to the other, e.g. from the field to container or from the field to the storage facility.
	Queue	It holds items (e.g., container, trailer, etc.) when the corresponding activity is occupied and releases them when it is available.
	Gate	It limits the passing of items, for example when a container is not available at the field side the gate closes not allowing any material flow between the two 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 statistics 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 final destination, i.e. amount of biomass at storage facility. The simulation terminates when the desire number of items is absorbed by this block.
	Cost Stats	It is used for exporting the cost data.
	Value	Constant
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. They permit a gate to open or not, allowing the flow of material and items. It is also used with activity blocks in order to stop the activity, if it is necessary.

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**Table 5.** Machinery data for the three examined systems

System	Machine	RF1	RF2	Market Price (€)	Fuel cost (€/h)	Accum. Use (h/y)	Productivity (min/ha)	Capacity	Travel speed (km/h)
S1,S2,S3	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	

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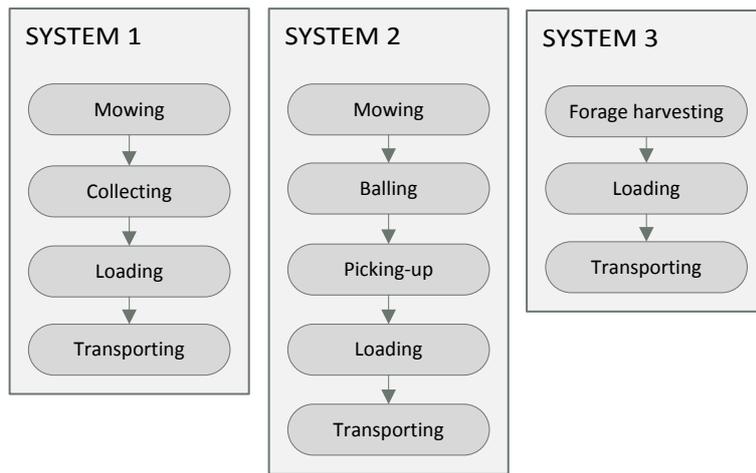
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408 **Table 6.** Operation time and cost elements for different capacity and number of available  
 409 containers

No. of containers	Capacity of container (kg)	Idle time for forage harvester (min)	Idle time for truck (min)	Total operation time (min)	Total cost (€)
<b>Short Distance</b>					
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
<b>Long Distance</b>					
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

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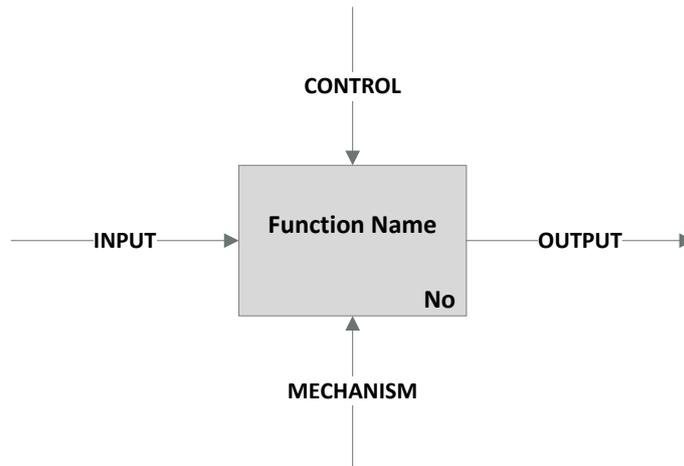


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414 **Figure 1.** The three examined biomass supply chain systems and the involved operations

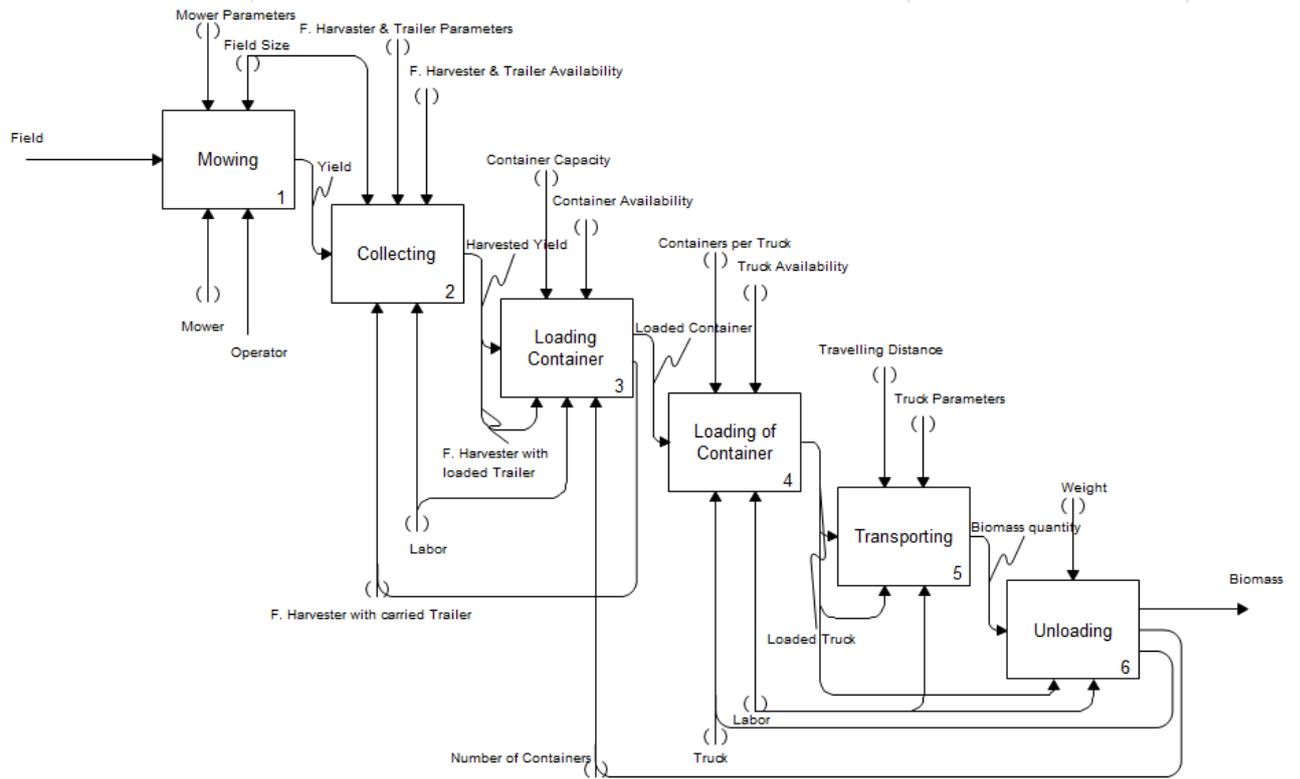
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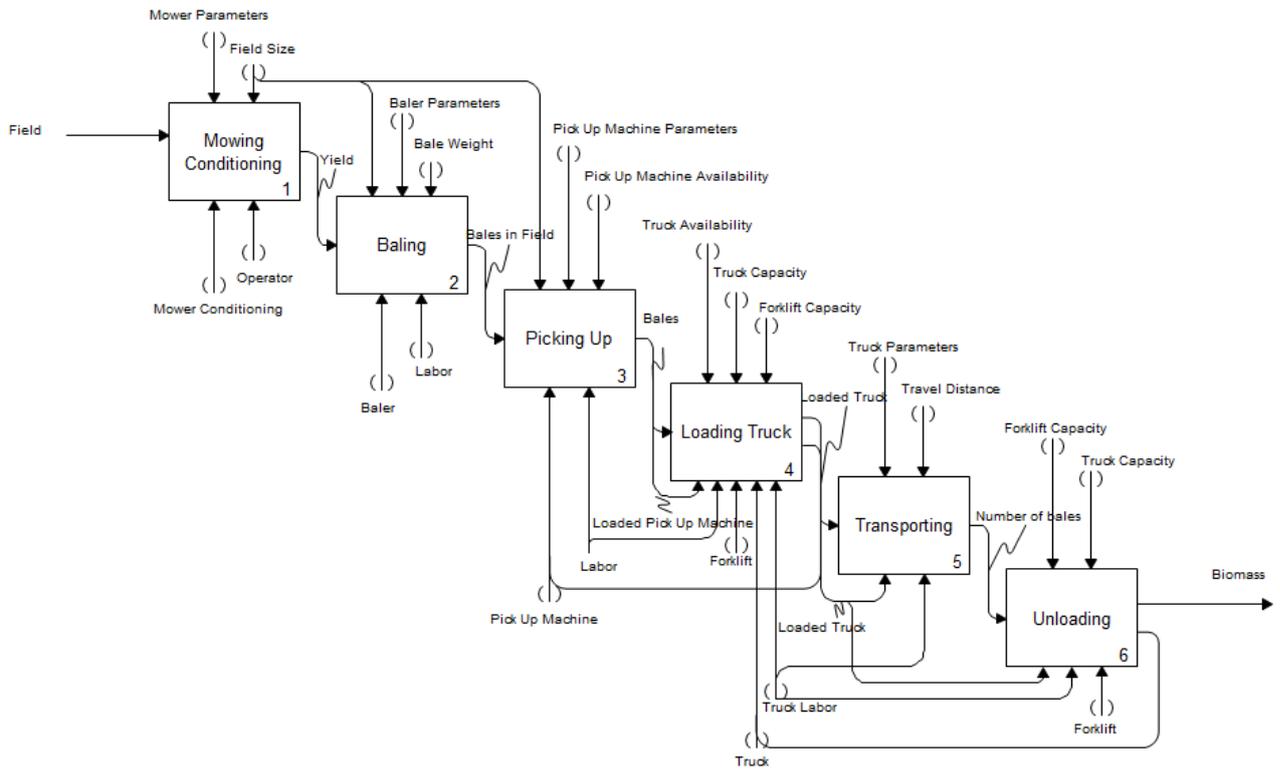
417 **Figure 2.** The basic syntax of an IDEF0 model

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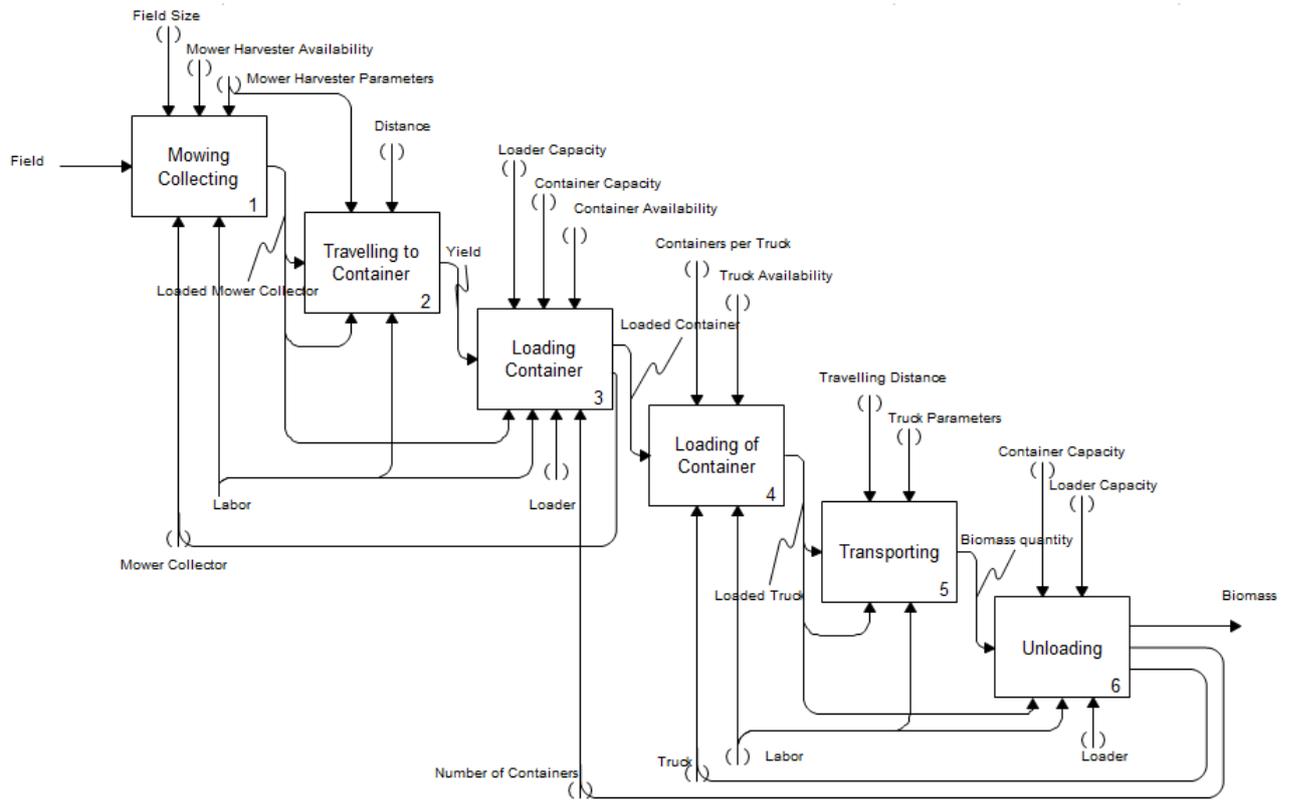
**Figure 3.** The IDEF0 architecture of a system 1



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

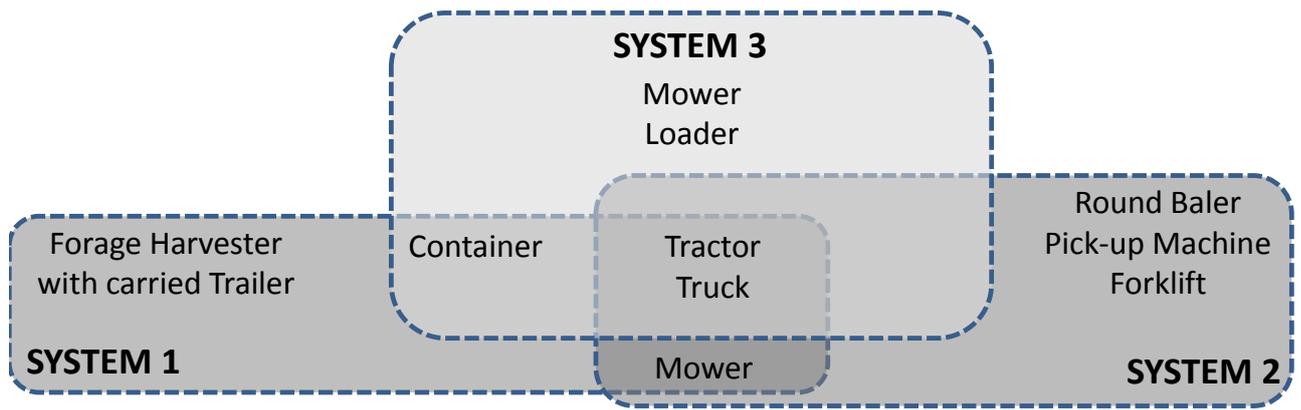
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428 **Figure 5.** The IDEF0 architecture of a system 3

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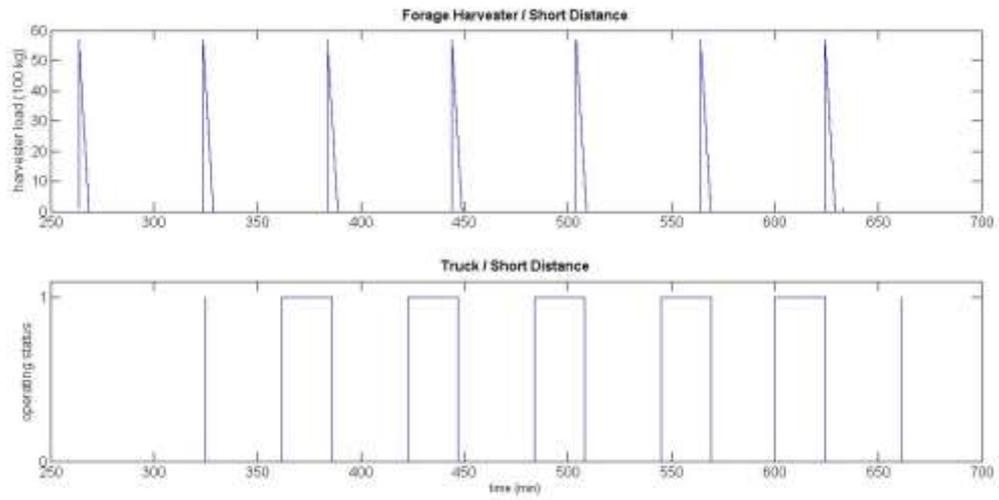


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431 **Figure 6.** The implemented machinery in the examined supply chain systems

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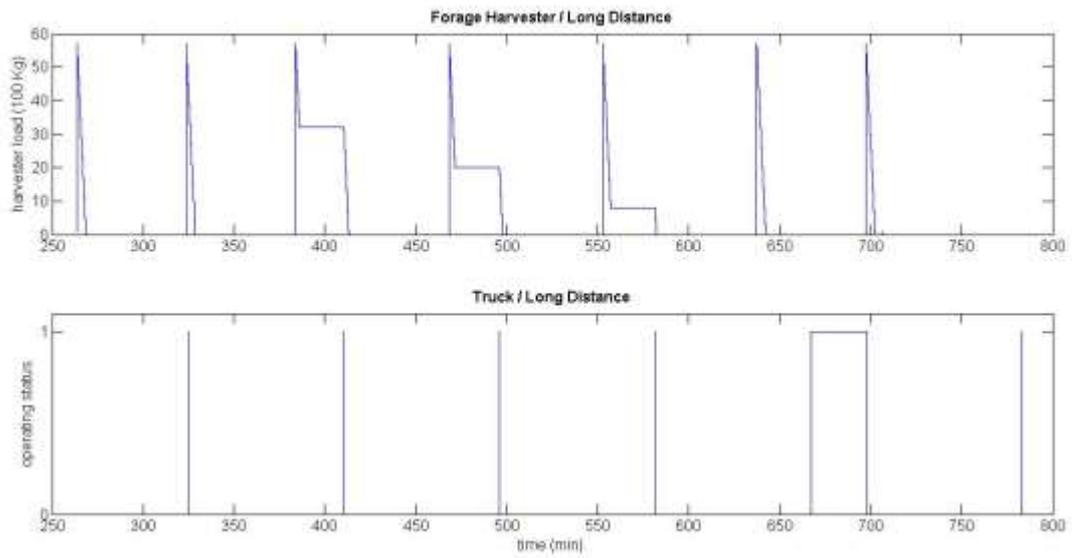
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(a)



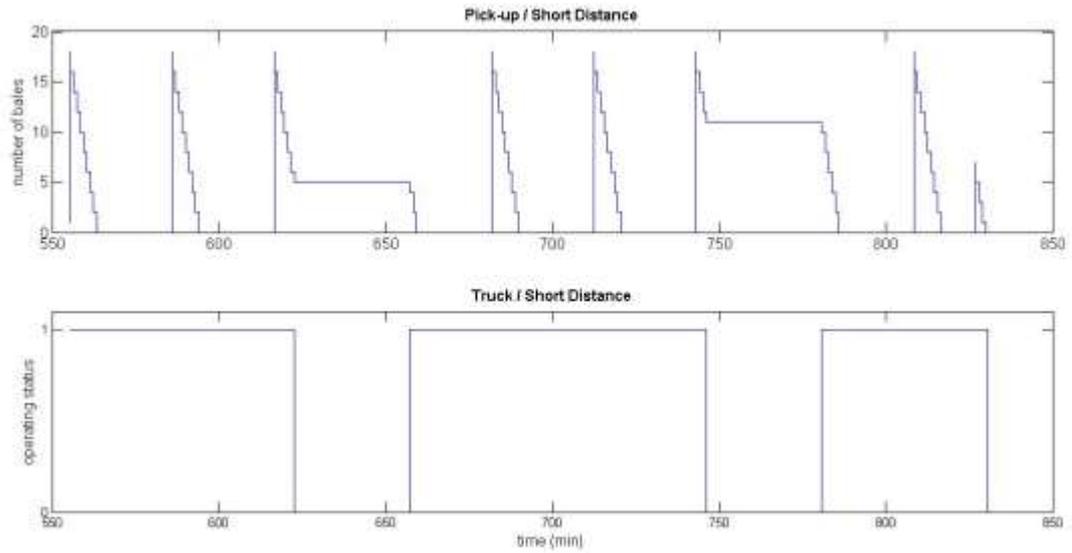
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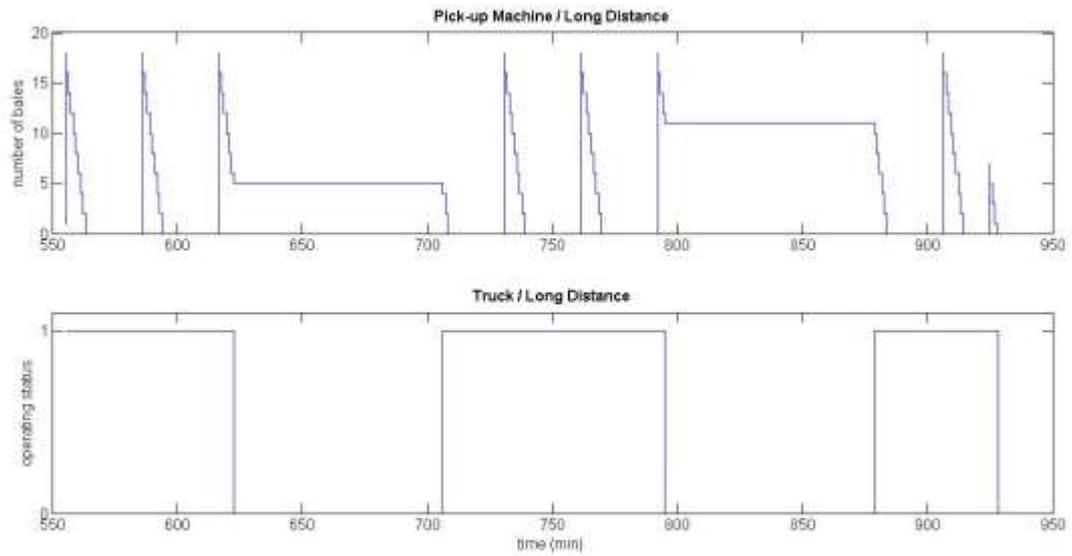
(b)

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

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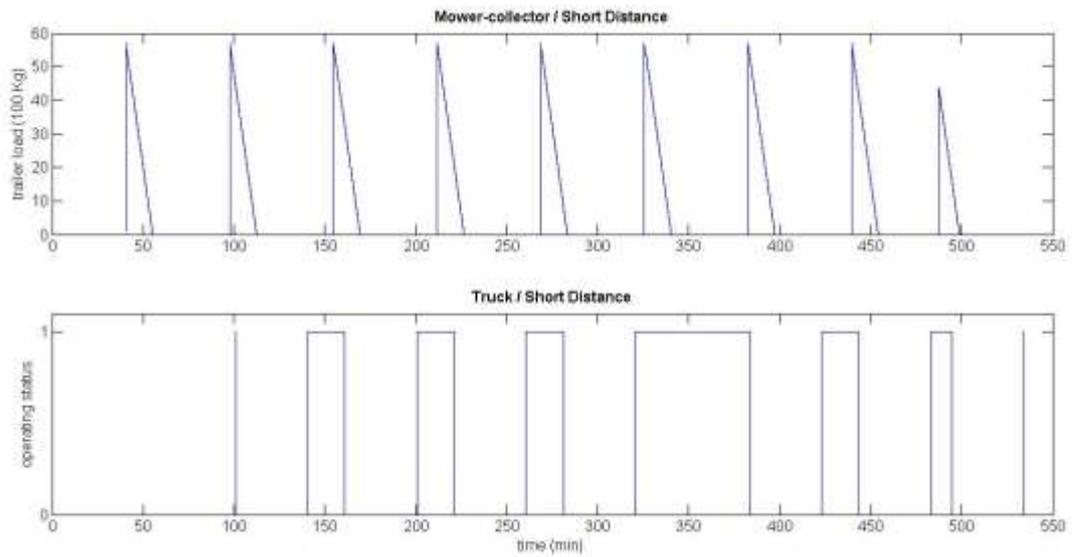
(a)



(b)

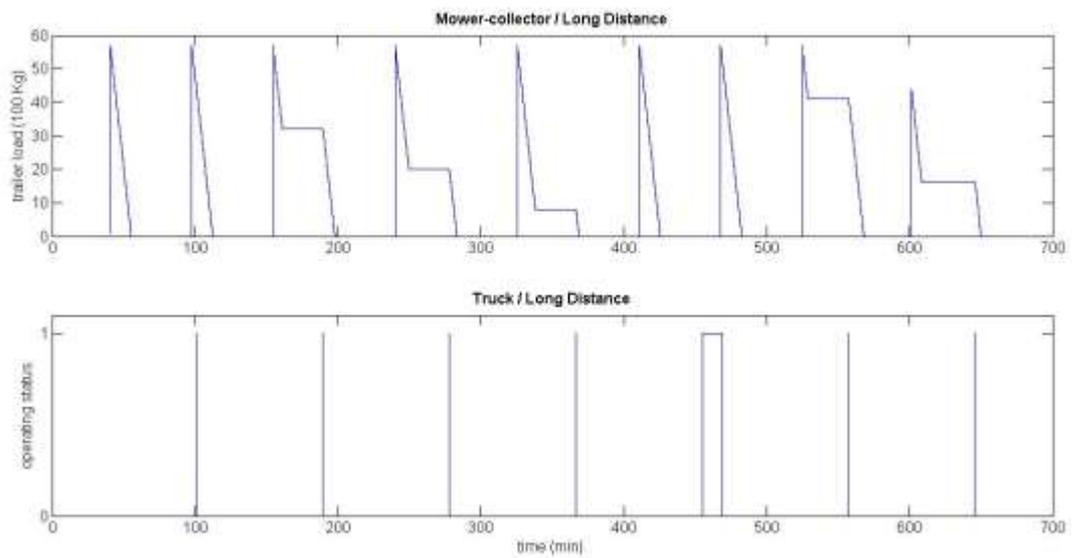
**Figure 8.** Bottlenecks in System 2, (a) for a short transport distance and (b) for a long transport distance.

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450  
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(a)



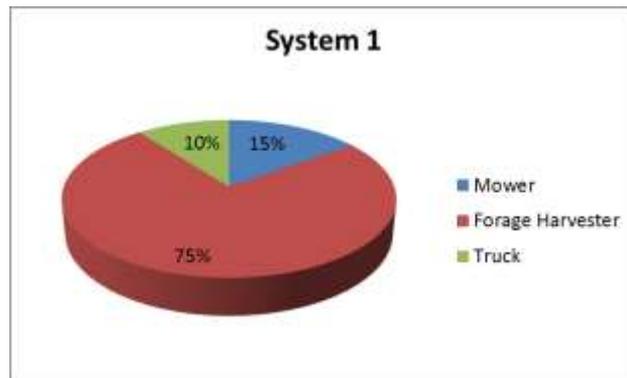
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(b)

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

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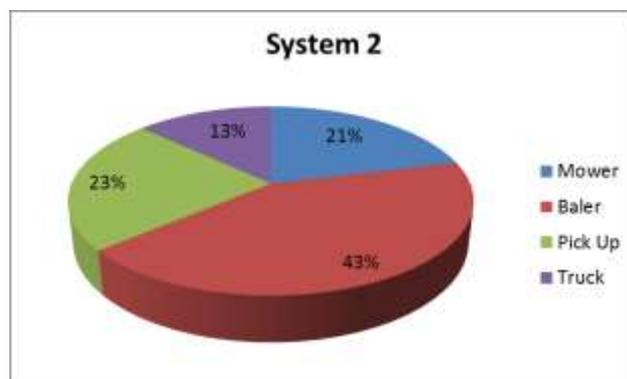
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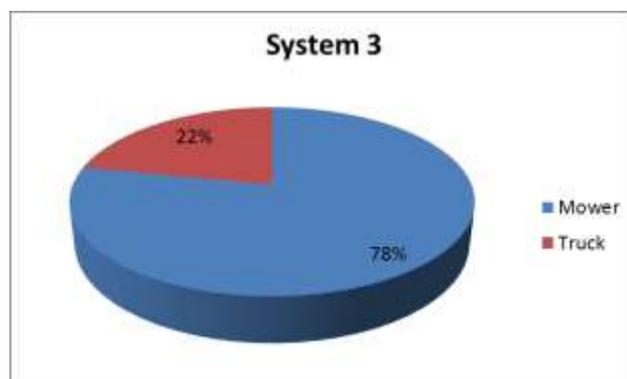
(a)



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(b)



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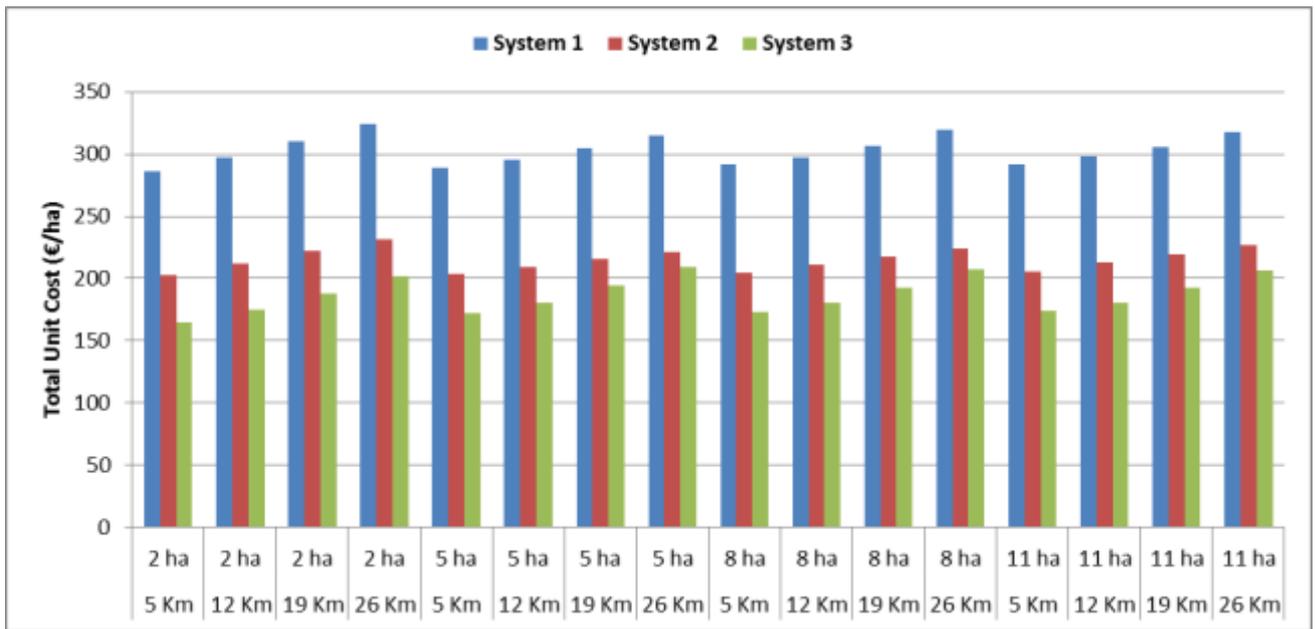
(c)

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**Figure 10.** Total cost distribution in different operations.

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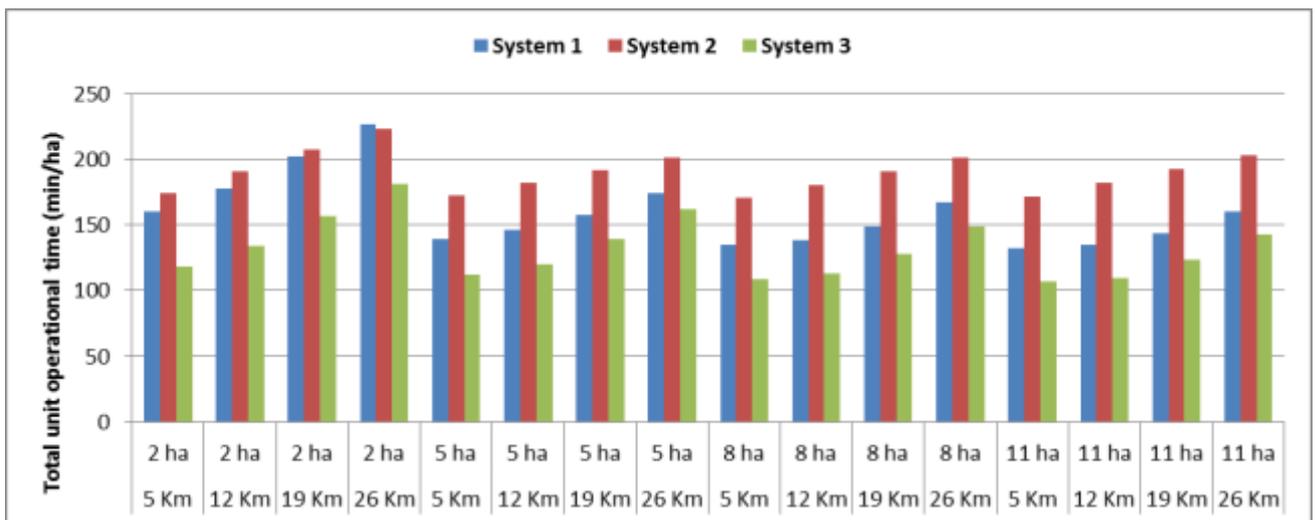
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(a)



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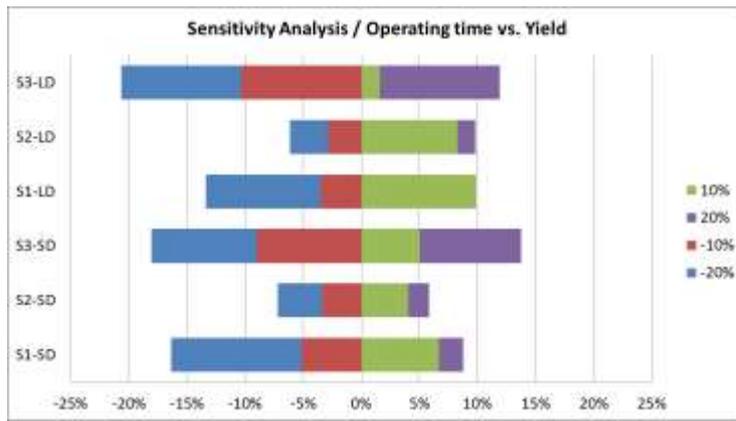
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(b)

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.

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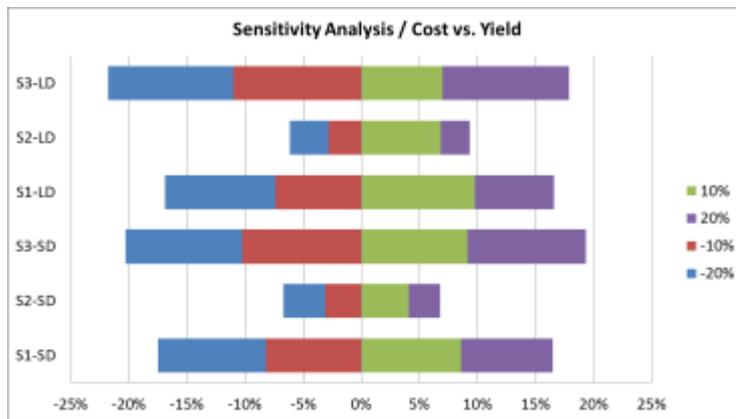
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(a)



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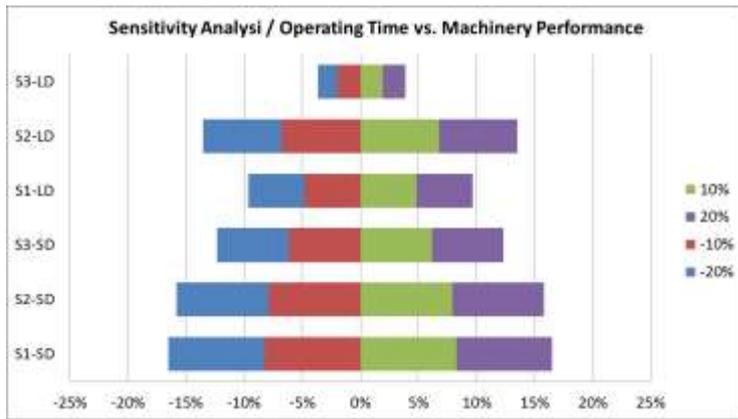
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(b)

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**Figure 12.** Operating time (a) and cost (b) changes due to yield variation

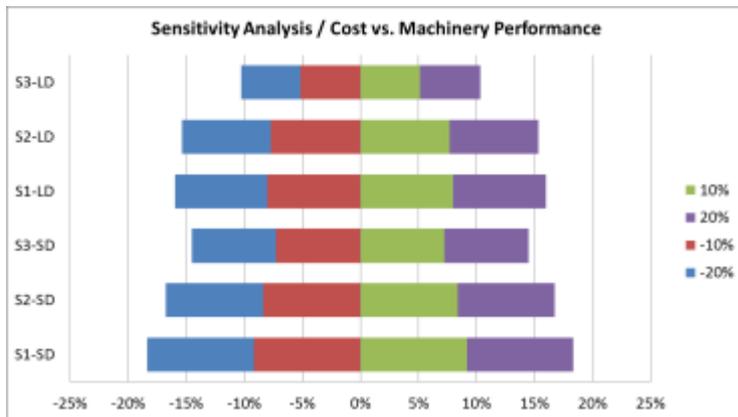
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481

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(a)



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(b)

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

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