Functional modeling for green biomass supply chains

Published version:

DOI:10.1016/j.compag.2016.01.014

This Accepted Author Manuscript (AAM) is copyrighted and published by Elsevier. It is posted here by agreement between Elsevier and the University of Turin. Changes resulting from the publishing process - such as editing, corrections, structural formatting, and other quality control mechanisms - may not be reflected in this version of the text. The definitive version of the text was subsequently published in COMPUTERS AND ELECTRONICS IN AGRICULTURE, 122, 2016, 10.1016/j.compag.2016.01.014.

You may download, copy and otherwise use the AAM for non-commercial purposes provided that your license is limited by the following restrictions:

(1) You may use this AAM for non-commercial purposes only under the terms of the CC-BY-NC-ND license.

(2) The integrity of the work and identification of the author, copyright owner, and publisher must be preserved in any copy.

(3) You must attribute this AAM in the following format: Creative Commons BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/deed.en), 10.1016/j.compag.2016.01.014

The publisher's version is available at:
http://linkinghub.elsevier.com/retrieve/pii/S0168169916000193

When citing, please refer to the published version.

Link to this full text:
http://hdl.handle.net/

This full text was downloaded from iris - AperTO: https://iris.unito.it/

Functional modeling of biomass supply chains

Dionysis Bochtis[1], Dimitris Pavlou[1], Anna Orfanou[1], Patrizia Busato[2], Remigio Berruto[2], and Claus Sørensen[1]

[1]Department of Engineering, Aarhus University, Inge Lehmanns Gade 10, DK-8000 Aarhus C, Denmark

[1] Department of Agricultural, Forest and Food Sciences (DISAFA), University of Turin, 10095 Grugliasco, Turin, Italy

Corresponding author: Dionysis.Bochtis@eng.au.dk

6 tables, 13 figures

Topic: Agricultural engineering

Abstract

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

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

1. INTRODUCTION

The biomass supply chain is a multiple-segment chain characterized by prominent complexity and uncertainty and as thus requiring increased managerial efforts as compared with the case of single operation management. In its full extent, biomass supply chain includes production of biomass, harvesting and in-field handling, transportation (occasionally, inter-mediate transportation, inter-mediate storage, and additional transportation), pre-treatment, storage, and conversion, while some times the storage and 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 decision making and planning approaches associated with the different segments of this specialized supply chain, including approaches for the initial network design (e.g. Zhang, F., et al., 2012; Mafakheri and Nasiri, 2014; Rentizelas et al., 2014; Grigoroudis et al., 2014), biomass storage planning (e.g., Rentizelas et al., 2009; Ebadian ET AL., 2013), and different planning levels such as operational (e.g., Zhang and Hu, 2013), tactical (e.g., Shabani et al., 2014), and strategic level (e.g., De Meyer et al., 2015).

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

In order to increase operational efficiency, improved methods and managements tools are required (Sørensen et al., 2010). This requirement is especially important in complicated production systems which involve large scale operations. During large scale harvesting, where biomass is used as a bioenergy resource, a number of sequential tasks are executed which are dependent on different factors, such as the type of biomass (plant residues, grass, and grain), the moisture content, and the final usage of the biomass (Sokhansanj, 2006). The 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 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.

This paper deals with the operations management within the supply chain of green (e.g. grass) and yellow (e.g. straw) biomass. Specifically, three different supply chain systems, in terms of machinery configuration, are analyzed and evaluated in terms of task times and cost 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 this modelling approach, three individual simulation models are built and implemented by the ExtendSim® simulation software. Finally, a sensitivity analysis is performed in order to assess the impact of the uncertainty of the yield and machinery productivity on the simulation models output.

2. METHODOLOGY

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.

2.2 MODELLING OF THE WORK PROCESS

For modeling the process of the tasks and operations in the previously described three systems, the IDEF0 (Integrated Computer Aided Manufacturing definition for Function Modeling) modelling scheme was implemented. IDEF0 is a function modeling technique for the analysis of manufacturing functions and the description of the workflows as an ordered sequence of events and involved objects. IDEF0 has been implemented to describe processes in supply chains of agricultural products, such as grain supply chains (Thakur and Hurburgh, 2009; Busato, 2015) and vegetable supply chains (Hu et al., 2012), and processes in agricultural production systems (van 't Ooster et al., 2013; Peres et al., 2011). The IDEF0 diagram follows a "box and arrow" structure representing functions as boxes and the interfaces between functions as arrows inputting or outputting a box. Functions operate either sequentially or simultaneously with other functions with the interface arrows "constraining" the various operations by triggering or controlling them. The basic syntax for an IDEF0 model is shown in Figure 2.

The architectures of the IDEF0 models for the three systems are presented in

Figure ***3***, Figure 4, and Figure 5, respectively, while the analytical descriptions of each model are given in Table 1, Table 2, and Table 3, respectively.

2.3 THE SIMULATION MODEL

2.3.1 SIMULATION ENVIRONMENT

The ExtendSim® programming environment (Imagine That Corporation, San Jose, CA, USA) has been used for creating the three simulation models that represent the three different systems of biomass harvesting operations. 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® software package.

2.3.2 INPUT PARAMETERS

The input parameters of the simulation include:

Field configuration:

- Area of the field
- Yield of the field
- Dry loses during physical drying
- Distance between the field entry/exit point and the container's location

Machinery inputs:

- Number of labor in each task
- The in-field travelling speed for machinery carrying biomass
- Capacity of machines
- The repair and maintenance factor for each tractor and for each implement
- Power of each tractor (or self-propelled machine)
- Time of loading and unloading processes involved in the chain
- The travelling speed of the truck from field to the storage facility
- Accumulated use of each machine

Cost inputs

- 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)
- The list price of each machine

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:

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

where, c_{Th} refers to the hourly tractor variable cost, c_f is the fuel cost, and c_{rm} is the 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):

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

where, c_{rm} is the accumulated repair and maintenance cost in typical field operating speeds (*€/h*), $RF1$ and $RF2$ refer to the repair and maintenance factors, P is the machine list price (*€*), and a is the accumulated use of machine (*h/y*).

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

$$c_{Ih} = c_{rm} \rightarrow € / h$$

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

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

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

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

2.3.4 PROCESSING

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

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 in-depth 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).

3. MODEL IMPLEMENTATION

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 (2nd 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.

3.2 MODELS' FUNCTIONALITY

The simulation model provides the in-depth status of the material flow as a function of time for the different operations. When two operations interacts bottlenecks phenomena (imbalance of resources allocated in two or more interacting operations) might occur which are the main causes for increasing the operating time and consequently, the total cost of the 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 collector, in System 2 the pick-up machine, and in System 3 the forage harvester), and in the transportation of the biomass to the processing facility.

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

Starting from the basis scenario (two containers of 6,900 kg capacity) the number of the containers was increased until the idle-time of the forage harvester was reached zero and in parallel, two underestimates and overestimates (±20% and ±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.

Based on the results listed in Table 6, less idle time does not result to less total operating time and/ or less total cost. In general, idle time is reduced in the case of higher number of containers with higher capacity. However, the truck travels more times from the field to the storage facility and back, getting as a result a more time and cost consuming system. In the case of short distance, the best combination between capacity and number of 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 between capacity and number of containers in terms of idle time is 6,900kg – 3 containers and 5,500 kg - 4 containers, while in terms of time and cost is 8,300 kg – 3 containers. This means that when the distance between the field and the storage facility is long, containers 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.

3.3 SYSTEMS COMPARISON

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

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

4. SENSITIVITY ANALYSIS

The input parameters of the simulation model which are known with a level of uncertainty are the expected yield and the expected machinery performance. Yield is affected by biological, soil, and weather parameters and also by losses during harvesting and 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 the operator’s experience, the field shape and topography, and various machinery features such as operating functionalities and embedded technologies (e.g. operator’s aiding systems). To that effect, a sensitivity analysis has been carried out to evaluate how sensitive are the outputs of the simulation model to under- or over-estimates of yield and machinery performance. Specifically, for both parameters, underestimates and overestimates of 10% and 20% have been examined in terms of the deviation of the outputs (total operating time and total cost) from their real values. These scenarios have been run for all of the three supply chain systems and for the cases of a long (26 km) and of a short (5 km) transportation 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.

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

5. CONCLUSIONS

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

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.

References

An H, Wilhelm W E, Searcy S W, 2011. Biofuel and petroleum-based fuel supply chain research: A literature review. Biomass Bioenerg 35: 3763-3774.

ASAE D497.6., 2009. Agricultural machinery management data. In ASABE STANDARD 2009. (Ed.), ASABE, Vol. I (pp. 360-367). St. Joseph, MI, USA.

ASAE EP496.3. (2009). Agricultural machinery management. In ASABE STANDARD 2009. (Ed.), ASABE, Vol. I (pp. 354e357). St. Joseph, MI, USA.

Balaman S Y, Selim H, 2014. A network design model for biomass to energy supply chains with anaerobic digestion systems. Applied Energy 130: 289-304.

Bartzanas T, Bochtis D D, Sørensen C G, Sapounas A A, Green O, 2015. A numerical modelling approach for biomass field drying. Biomass Bioenerg 106: 458-469.

Busato P, 2015. A simulation model for a rice-harvesting chain. Biomass Bioenerg 129: 149-159.

De Meyer A, Cattrysse D, Orshoven J V, 2015. A generic mathematical model to optimise strategic and tactical decisions in biomass-based supply chains (OPTIMASS). European Journal of Operational Research. Available online 27 February 2015, http://dx.doi.org/10.1016/j.ejor.2015.02.045

Ebadian M, Sowlati T, Sokhansanj S, Townley-Smith L, Stumborg M, 2013. Modeling and analysing storage systems in agricultural biomass supply chain for cellulosic ethanol production. Applied Energy 102: 840-849.

Iakovou E, Karagiannidis A, Vlachos D, Toka A, Malamakis A, 2010. Waste biomass to-energy supply chain management: a critical synthesis. Waste Management 30: 1860–1870.

Hu J, Zhang X, Moga L M, Neculita M, 2012. Modeling and implementation of the vegetable supply chain traceability system. Food Control 30: 341-353.

Grigoroudis E, Petridis K, Arabatzis G, 2014. RDEA: A recursive DEA based algorithm for the optimal design of biomass supply chain networks. Renewable Energy 71: 113-122.

Lin T, Rodríguez L F, Shastri Y N, Hansen, A C, Ting K C, 2014. Integrated strategic and tactical biomass–biofuel supply chain optimization. Bioresource Technology 156: 256-266.

Kim J, Realff M J, Lee J H, 2011. Optimal design and global sensitivity analysis of biomass supply chain networks for biofuels under uncertainty. Comput Chem Eng 35: 1738-1751.

Mafakheri F, Nasiri F, 2014. Modeling of biomass-to-energy supply chain operations: Applications, challenges and research directions. Energy Policy 67: 116-126.

Orfanou A, Busato P, Bochtis D D, Edwards G, Pavlou D, Sørensen C G, Berruto R, (2013). Scheduling for machinery fleets in biomass multiple-field operations. Comput Electron Agric 94: 12-19.

Rentizelas A A, Tolis A J, Tatsiopoulos I P, 2009. Logistics issues of biomass: The storage problem and the multi-biomass supply chain. Renew Sustainable Energy Rev 13: 887-894.

Rentizelas A A, Tolis A J, Tatsiopoulos I P, 2014. Optimisation and investment analysis of two biomass-to-heat supply chain structures. Biomass Bioenerg 120: 81-91.

Shabani N, Sowlati T, Ouhimmou M, Rönnqvist M, 2014. Tactical supply chain planning for a forest biomass power plant under supply uncertainty, Energy, Volume 78, 346-355.

Sørensen C G, Bochtis D D, 2010. Conceptual model of fleet management in agriculture. Biomass Bioenerg 105, 41-50.

Thakur M, Hurburgh C R, 2009. Framework for implementing traceability system in the bulk grain supply chain. J Food Eng 95: 617-626.

Zhang F, Johnson D M, Johnson, M.A. (2012). Development of a simulation model of biomass supply chain for biofuel production. Renewable Energy 44: 380-391.

Zhang L, Hu G, 2013. Supply chain design and operational planning models for biomass to drop-in fuel production. Biomass Bioenerg 58: 238-250.

Zhou K, Jensen A L, Sørensen C G, Busato P, Bochtis D D, 2015. Agricultural operations planning in fields with multiple obstacle areas. Comput Electron Agric 109: 12–22.

van't Ooster A, Bontsema J, van Henten E J, Hemming S, 2013. Simulation of harvest operations in a static rose cultivation system. Biomass Bioenerg 120: 34-46.

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 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

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. 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	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. 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.

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	

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

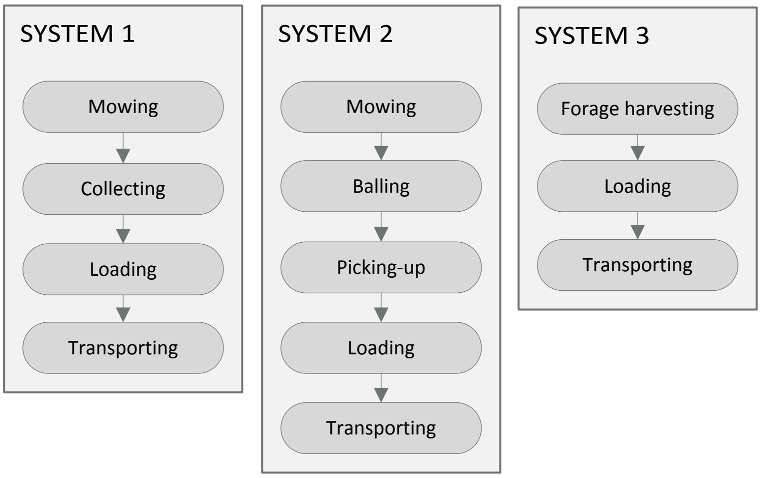


Figure 1. The three examined biomass supply chain systems and the involved operations

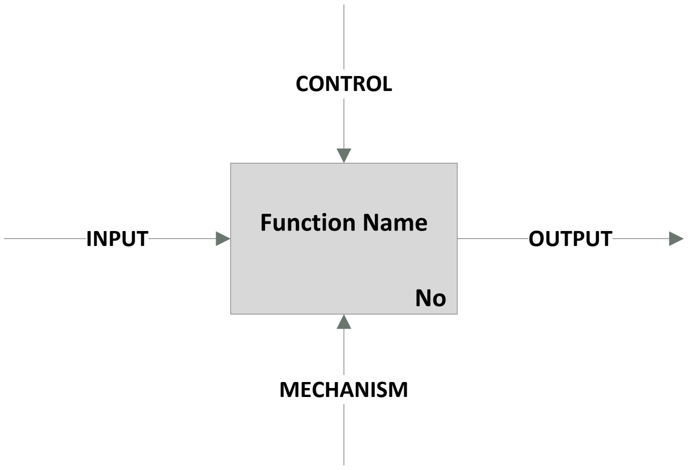


Figure 2. The basic syntax of an IDEF0 model

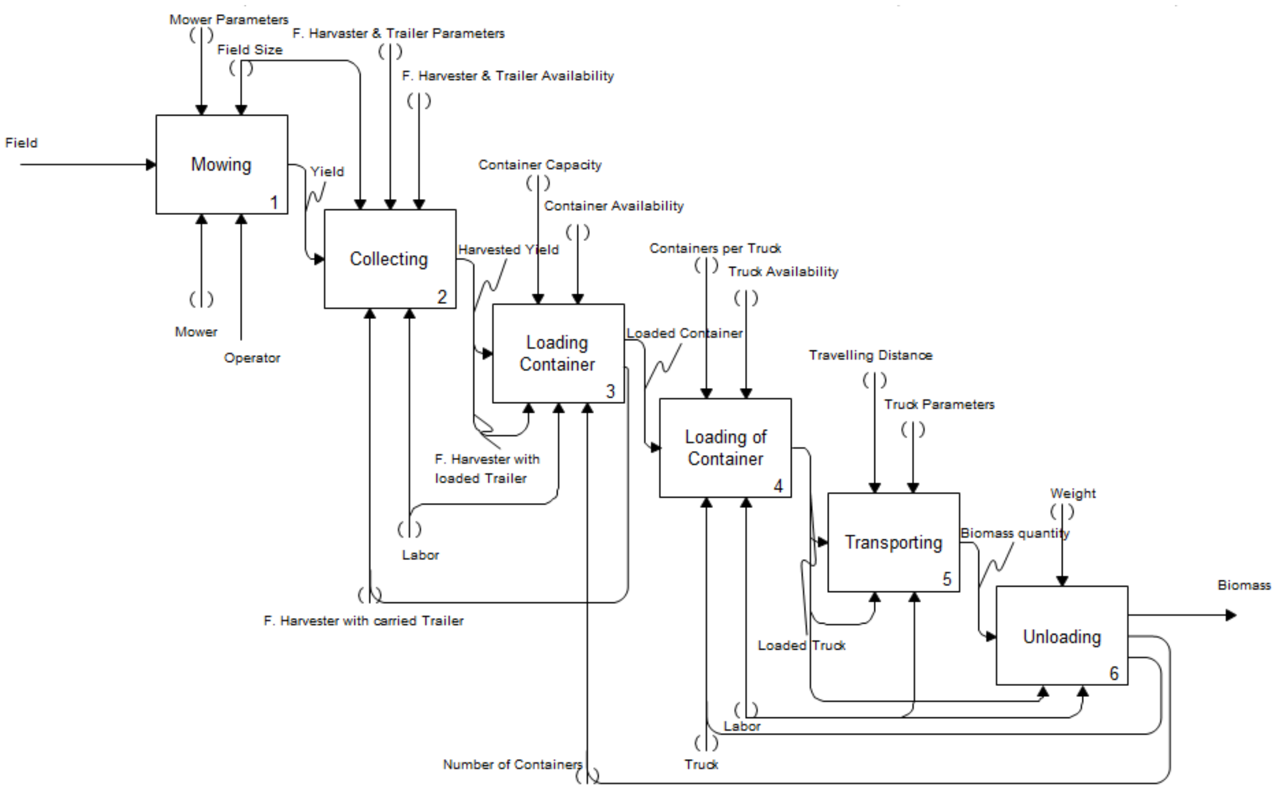


Figure 3. The IDEF0 architecture of a system 1

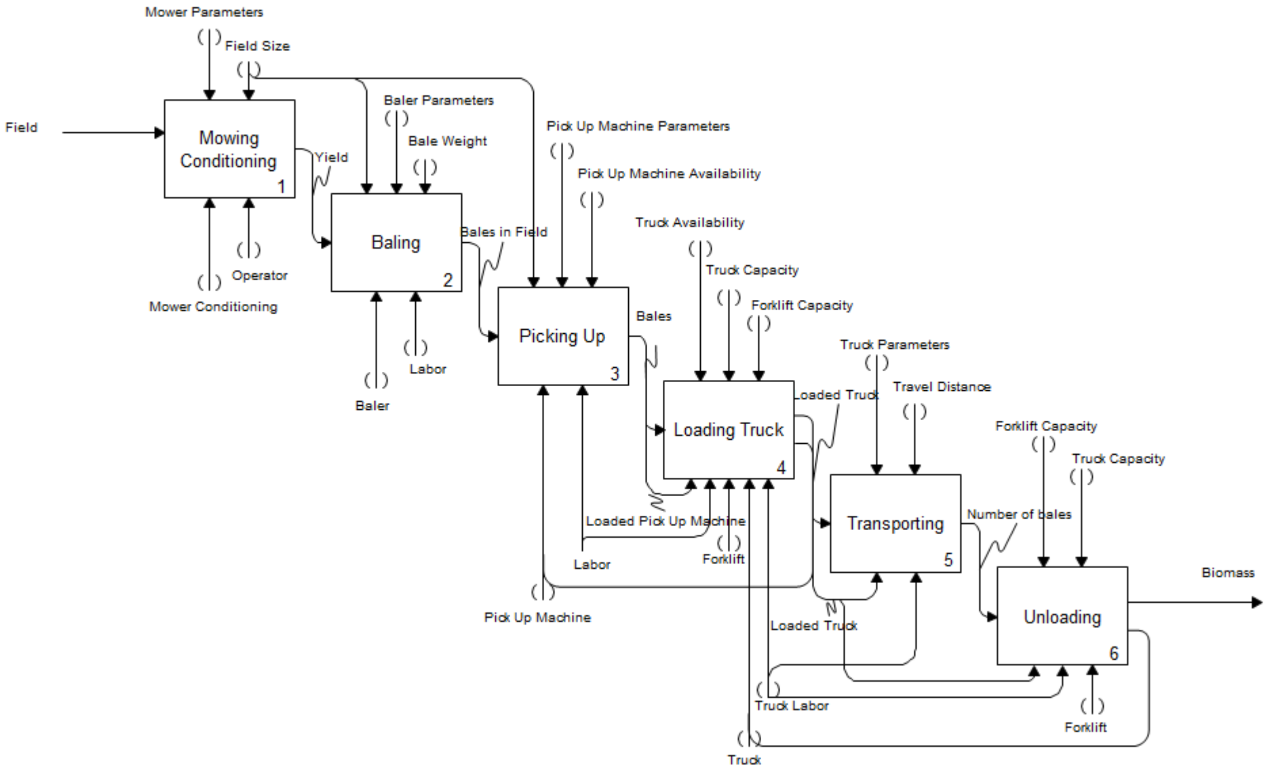


Figure 4. The IDEF0 architecture of a system 2

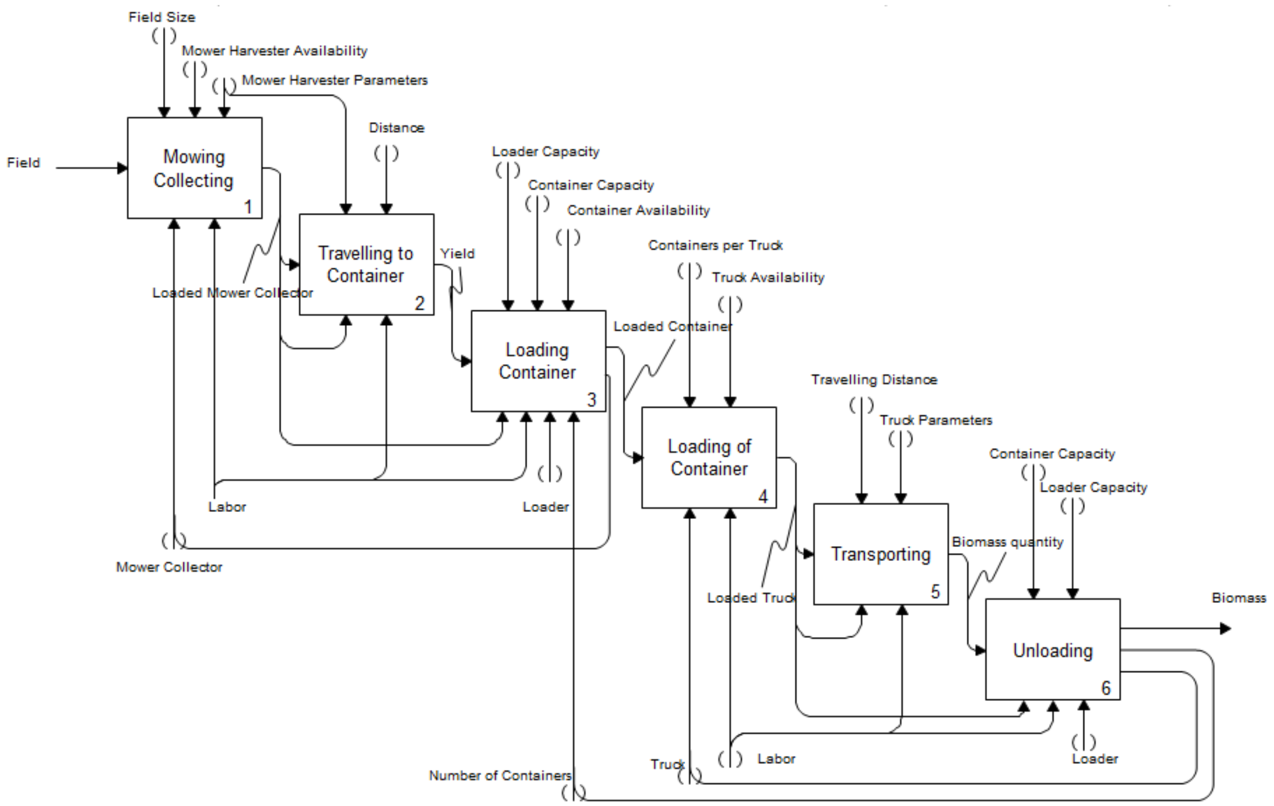


Figure 5. The IDEF0 architecture of a system 3

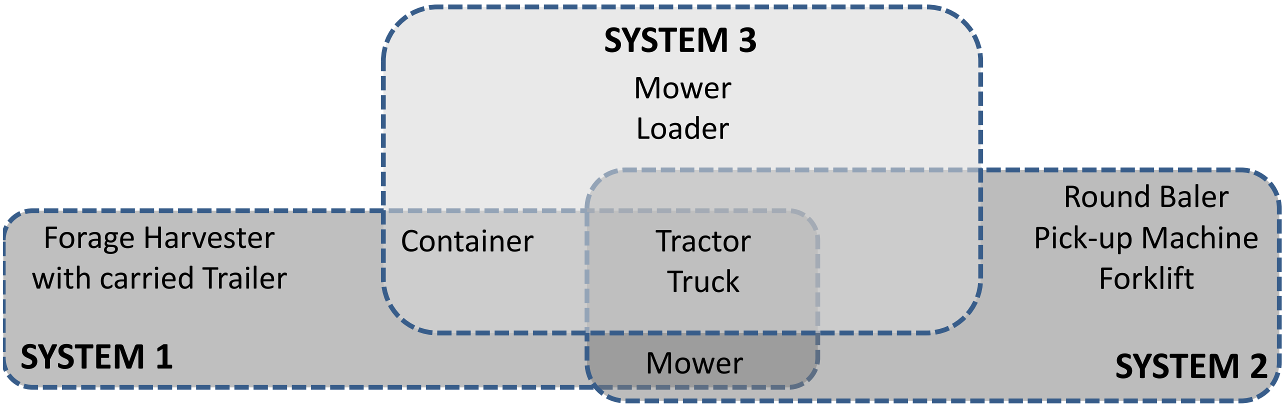
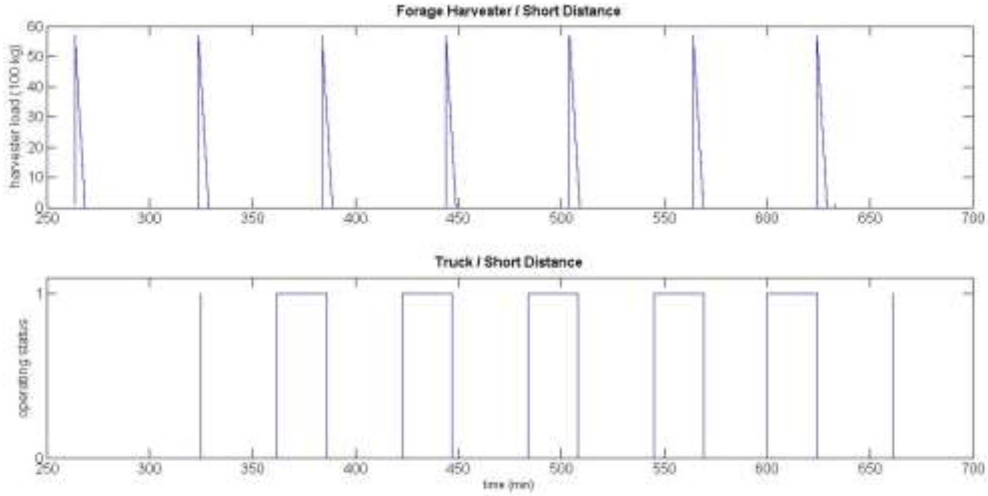
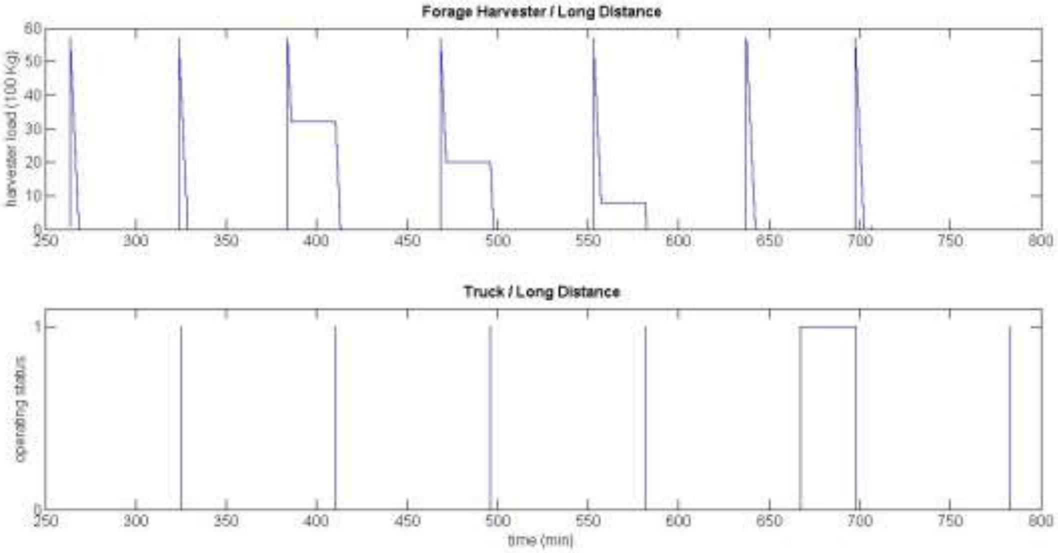


Figure 6. The implemented machinery in the examined supply chain systems

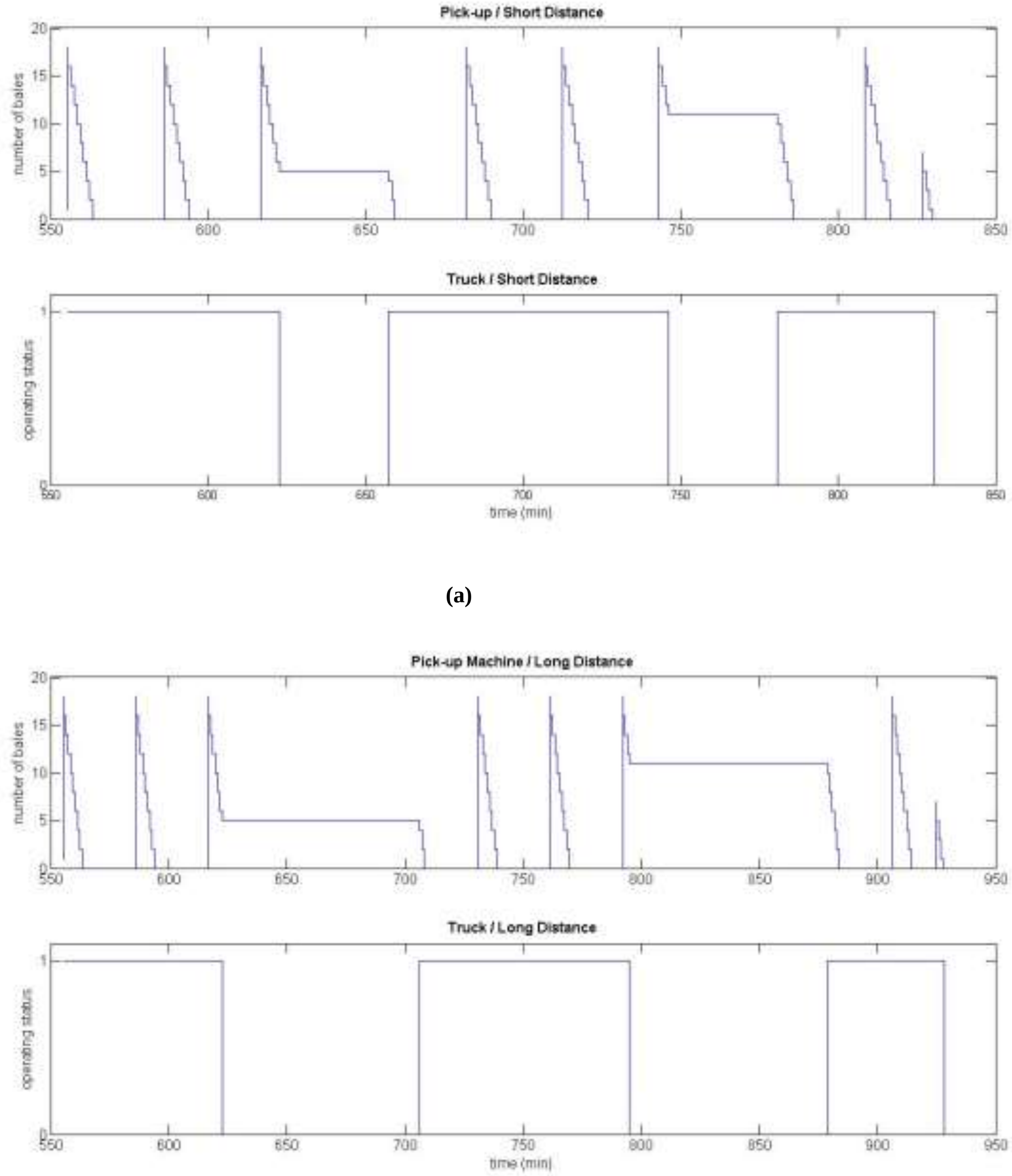


(a)



(b)

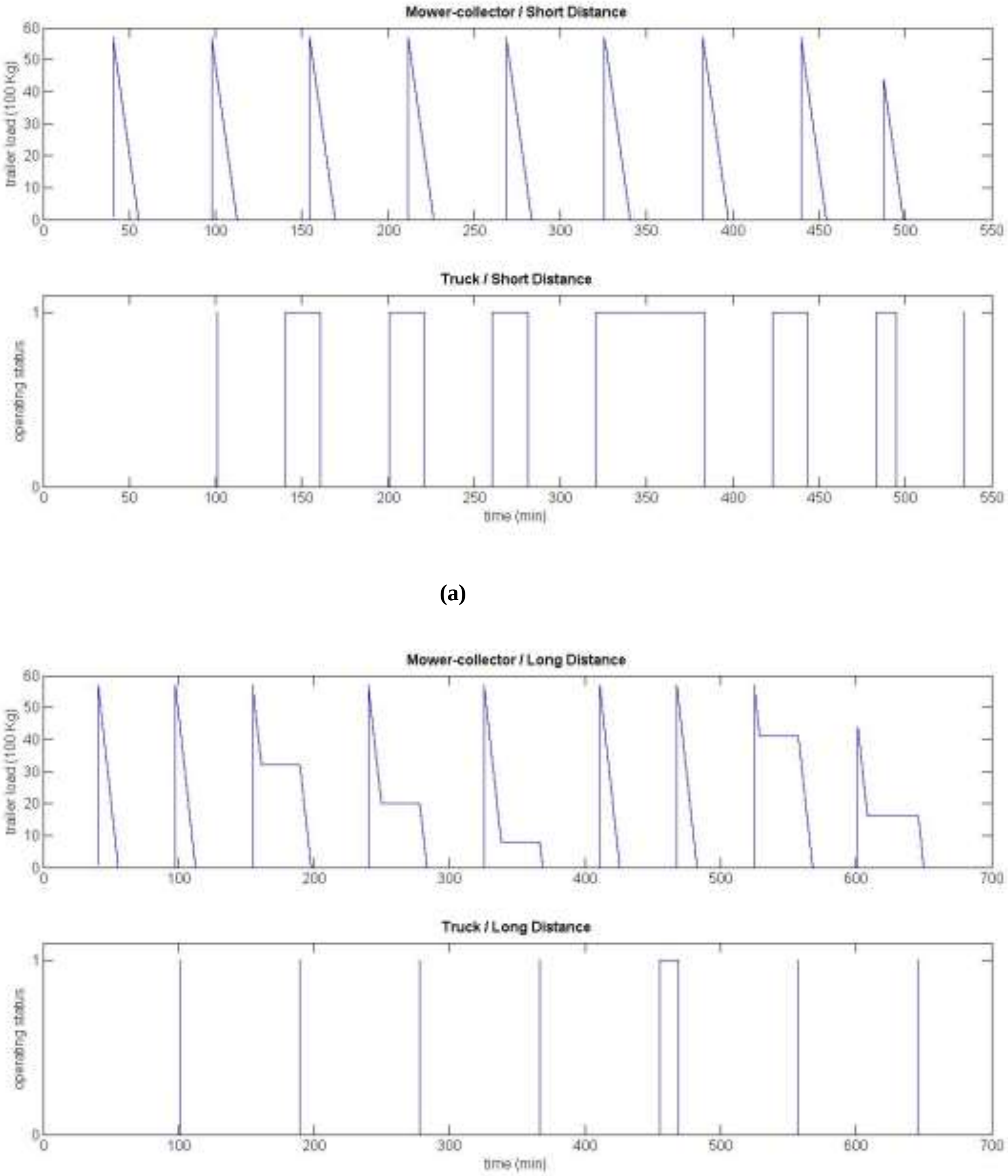
Figure 7. Bottlenecks in System 1, (a) for a short transport distance and (b) for a long transport distance.



(a)

(b)

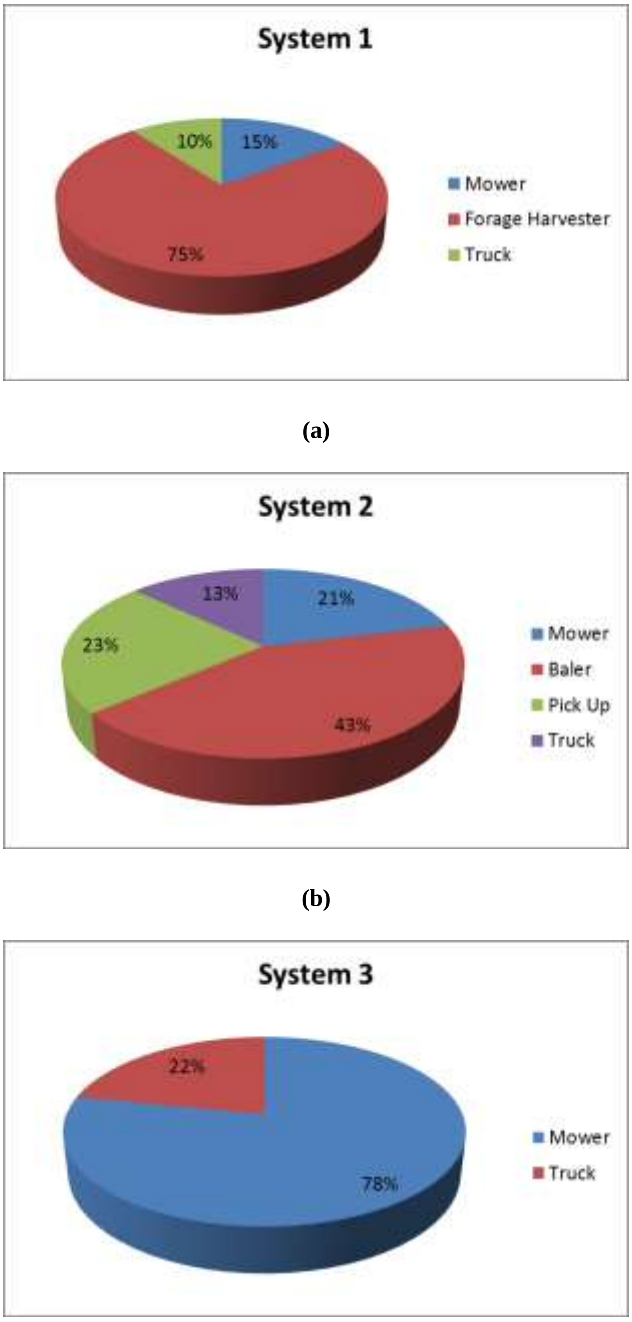
Figure 8. Bottlenecks in System 2, (a) for a short transport distance and (b) for a long transport distance.



(a)

(b)

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

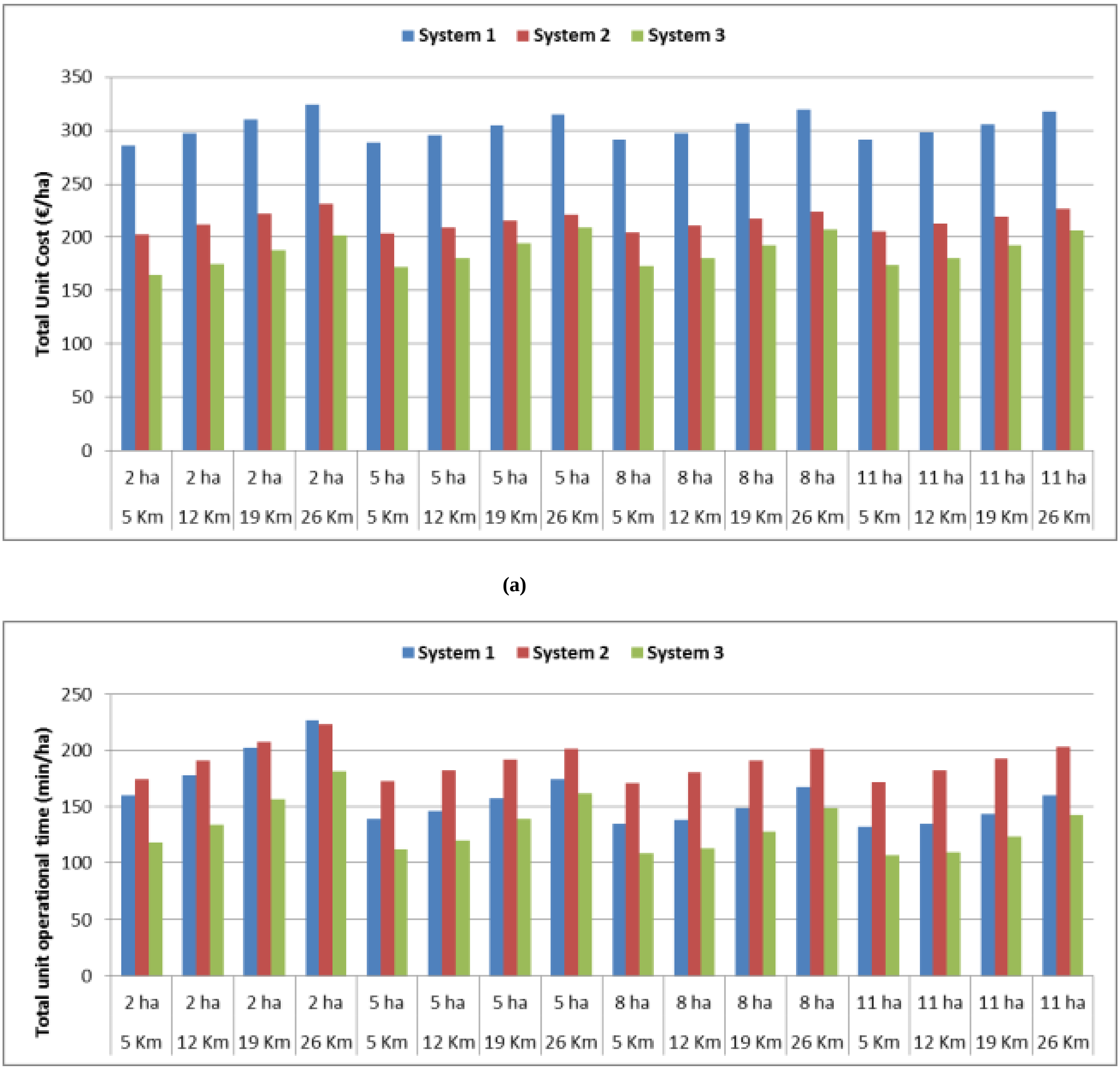


(a)

(b)

(c)

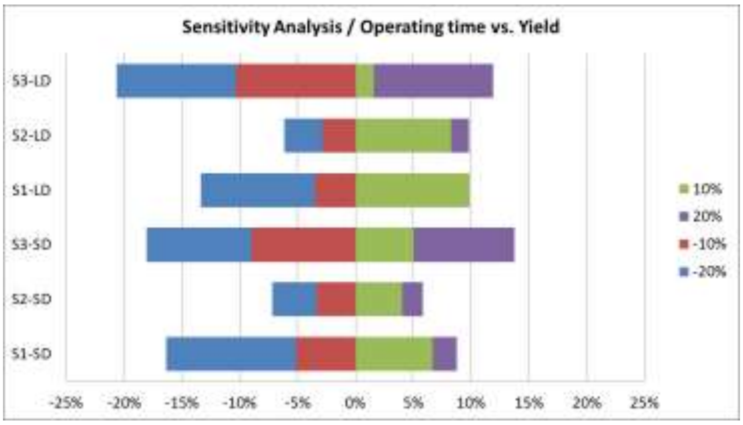
Figure 10. Total cost distribution in different operations.



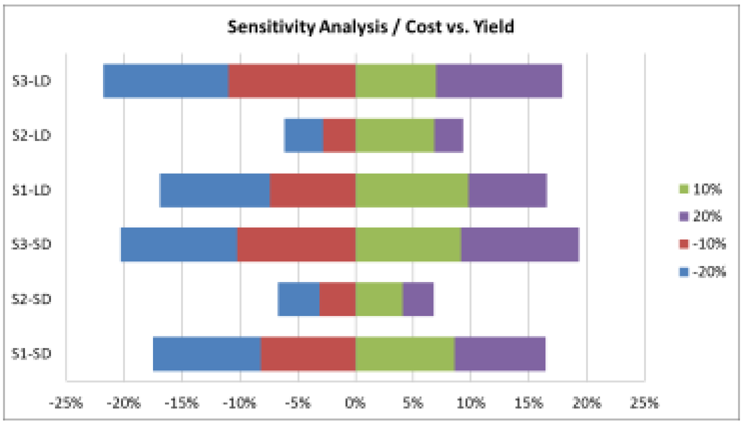
(a)

(b)

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

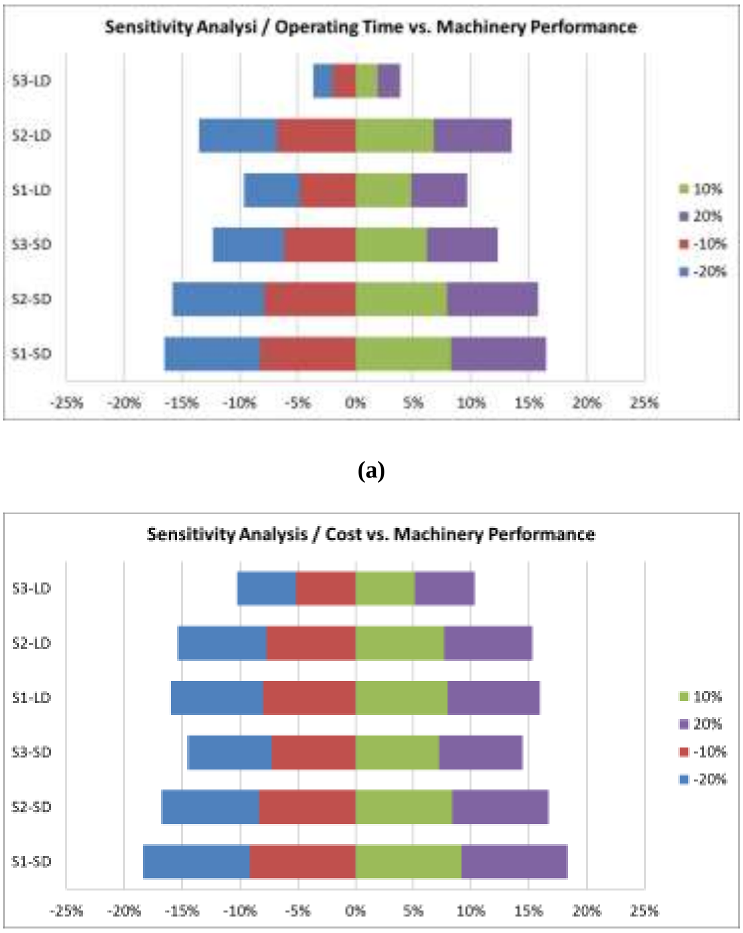


(a)



(b)

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



(a)

(b)

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