A simulation model for a rice-harvesting chain

DOI:10.1016/j.biosystemseng.2014.09.012

A SIMULATION MODEL FOR A RICE-HARVESTING CHAIN

P. Busato*

University of Turin, Faculty of Agriculture, DISAFA Department Via Leonardo da Vinci 44, 10095, Grugliasco, Turin, Italy

*Corresponding author: patrizia.busato@unito.it

ABSTRACT

Management of rice harvesting presents a number of unique challenges that require development of dedicated tools. These include in-field trafficability constraints affecting the transport units, the increased number of combine unloading events due to low grain hopper capacity, and the transport cycle times for different fields. Furthermore, when a combine reaches the headland area, sequential decisions must be made whether to stop harvesting and proceed to the unloading location or to continue harvesting with a full or reduced operating width.

The objectives of this paper were to: 1) Develop a simulation model that incorporates operational features unique to rice harvesting, 2) use the model to provide performance evaluation measures, and 3) to demonstrate the capabilities of this model as a tool for operations management.

Experimental field operations were carried out to identify the necessary set of input parameters and to validate the simulation model. From measurements taken for validation, it was found that the error in operational parameter prediction was considerably low, ranging from 2.59% to 3.12%. In addition, using the simulation model, the practice of selectively harvesting at a reduced operating width was compared with the practice of harvesting a full operating width. It was found that harvesting at a reduced operating width significantly increases capacity (up to 7%) , particularly when the available transport unit capacity is a system performance limiting factor.

Keywords: Operations management, logistics, machinery management, discrete event simulation;

1. INTRODUCTION

Harvesting is the most complex operation among all field operations because it involves multiple units that must be coordinated to achieve the objective of the overall system's performance optimisation. These units include harvesters, transport units, and handling units. For this purpose, a number of system engineering approaches have been developed and applied to the operational management of individual tasks involved in the harvesting process. Previous work includes, area coverage planning (Ali et al., 2009), route planning methods for transport units (Jensen et al., 2012; Bochtis et al., 2010), the sequential scheduling of harvesting and handling operations (Orfanou et al., 2013; Bochtis et al., 2013), simulation models for harvesting cost prediction (de Toro et al., 2012), and performance evaluation and documentation systems (Amiama et al., 2008). However, the majority of the developed models cannot be applied to all cropping systems. In particular, the harvesting management of rice, although it is a grain crop, presents a number of specific challenges that require the development of dedicated tools.

Rice fields are covered by a water layer during the cropping period, and although water is removed before harvesting, the soil remains muddy, making the field area not trafficable for the transport units that are used for combine unloading since it is common for them to carry crop loads that are many times greater than the grain hopper capacity of the combine. Therefore, the process of unloading the harvested crop from the combine's grain hopper to a transport unit occurs with the combine at the headland area, while the transport unit is stationary on a road next to the field. Furthermore, because one of the two headlands in a rice field is next to an irrigation channel, one headland is available for the unloading process, a condition that adds further operational restrictions. In addition, because of trafficability conditions, the temporary grain hopper of the combine must have low capacity, resulting in an increase of the number of unloading occurrences and, depending on the operating width and the distance to the storage facilities, a higher number of transport units is typically required when compared to other grain-harvesting operations. It should also be noted that the structure of rice production systems usually includes a number of relatively small fields (in the range of 2-6 ha to manage field submersion) that are geographically dispersed at various distances from the storage facilities, resulting in considerably different transport cycle times among the fields and complicating the decision of the number and capacities of the transport units needed.

Furthermore, combines in rice harvesting generally use tracks in the front axis and thus cannot move fast within the field area both in cases of harvesting and when travelling towards the headland to the unloading location. Thus, the travelling speed is approximately the same as the harvesting speed (4-5 km h^{-1}). This speed results in highly non-productive times due to in-field travel, and frequently results is a decision to harvest in a reduced operating width while travelling back to the unloading location when there is still space in the grain hopper, but not enough to pass in the full operating width. Consequently, sequential decisions must be made each time that the combine reaches a headland area. Thus, general norms of field efficiency and productivity for grain harvesting cannot be applied in this complex system of sequential decisions.

The objective of this study is to develop a targeted simulation model for rice harvesting that incorporates all of the particular operational features mentioned above. To quantify input parameters and validate the simulation model, a number of experimental operations were carried out and monitored. The capabilities of the simulation model as an operations management tool were demonstrated, providing performance evaluation measures (e.g., harvester utilization and area capacity) as a function of the number of the transport units and the distance between the field and the storage facilities. Finally, the practice of implementing a reduced width is compared to the practice of harvesting solely in the full width to assess the best practice for farmers.

2. Simulation Model development

2.1 The decision-making process

As mentioned in the introduction, a number of sequential decisions must be made during harvesting. To develop the simulation process of rice harvesting, the logic behind the combine operator's decision making was analysed and modelled. The process of analysing and modelling was based on the on-site inspection of operators' practices and by interviewing a group of experts (combine operators and contractors) in an area of northern Italy. Because in-field travel speed is only slightly higher than the harvesting speed of the combine in paddy fields, the operator always tries to avoid in-field travel because this task is non-productive. Therefore, based on the remaining grain hopper capacity, the operator could decide to unload or harvest at full or reduced speed. This decision-making process occurs each time the operator reaches a headland. The logic of the decision is different if a turn occurs on headland next to or far from the unloading location, and if a transport unit is available at the unloading location. In-field travel only occurs when there is no sufficient space in the grain hopper to perform a harvesting pass while utilising at least 30% of the full cutting bar width. Otherwise, during the final harvesting pass before unloading, the combine will harvest at a reduced width ranging from 30 to 100% of the cutting bar width while moving towards the unloading location.

The logic of the operator's decision-making process is presented in Fig. 1. Each time the combine reaches a headland area, the operator considers the availability of a TU at the unloading location, whether the headland that is reached is next to the unloading location, and the current grain quantity in the grain hopper to determine whether to continue harvesting in the next pass at a full operating width or a reduced operating width or to proceed to the unloading location (involving in-field travel when the transport unit is located at the opposite headland and/or waiting for a transport unit to arrive).

Regarding the transport units, a standard cycle of activities is presented in Fig. 2. The model synchronises the work process of the combine and of the transport units through the unloading task of the combine to a transport unit.

2.2 Modelling of the work process

For modelling the work process of the various tasks that are involved in rice harvest operation, the IDEF3 modelling formalism scheme was used. IDEF is a structured process modelling technique that is used to describe workflows as an ordered sequence of events and to describe the objects that are involved in these processes (Kusiak et al., 1994). IDEF has been recently implemented to describe various processes in the agricultural domain, e.g., in traceability systems in the grain supply chain (Thakur and Hurburgh, 2009) and in the vegetable supply chain (Hu et al., 2012), in harvesting in static rose cultivation systems (van 't Ooster et al., 2013), and in information management systems in viticulture (Peres et al., 2011).

An IDEF3 process flow diagram is composed of units of behaviour (UOBs), links, and junctions. The UOBs (e.g., the texted and numbered boxes in Fig. 3) refer to a process, action, decision, or any other procedure that is performed within a system. The UOBs are numbered progressively. In general, three types of links are used between UOBs, namely precedence, relational, and object flow links, depending on the relation between the various UOBs in the model. In the model that was developed in this study, only precedence links were used, which express a simple temporal precedence between UOBs. Junctions are used to describe the logic of branching within a process. The particular types of junctions that were implemented in the developed model and their meaning process paths are listed in **Error! Reference source not found.**.

The IDEF3 process diagram of the developed simulation model for the rice harvest operation is presented in Fig. 3. The activity ‘Simulation commences’ (UOB0) initiates the operation, while through junction J1, all of the transport units move to the empty field (UOB6), and the combine begins to operate in the field (UOB1). Through junction J2, all of the transport units (either coming from UOB0 or from UOB11 when a transport unit returns from the storage facilities) travel to the empty field (UOB6) and wait to be loaded (UOB7) with transport units that have already been partially loaded (UOB8) coming from the fan-out of junction J8. Transport units merge together in junction J4 and enter the state ‘TU is waiting to load’ (UOB7). The priority in the queue is given to the transport units that have been already partially loaded. The combine, after entering the field, begins to operate (UOB1). After each pass, in junction J3, a decision is made concerning whether the combine should continue to the next pass or move to the unloading location on the headland, where transport units are waiting for the unloading process (UOB7). The decision-making process is based on the logic that is presented in **Error! Reference source not found.**. When there is adequate space in the combine's grain hopper to harvest the next pass, the activity 'Combine is turning' (UOB2) takes place, and then, through junction J6, either the combine is harvesting with reduced width (UOB3) or another decision-making process will take place after junction J9. If there are still passes to harvest, the activity 'Combine is harvesting' (UOB1) is executed. Otherwise, the simulation terminates (UOB13). If the combine's grain hopper becomes full (or there is not adequate space for a pass with reduced width), the activity 'Combine is travelling to unload' (UOB4) will begin. Through the fan-in asynchronous junction J5, which specifies that at least one TU and the combine should be available, the activity 'Combine is unloading' (UOB5) takes place. Following this activity and through junction J7, the combine is passed to junction J9, where either it begins to harvest another pass (UOB1) or the simulation terminates (UOB12). The latter takes place when the field is completely harvested. The cycle that is followed by the TU after junction J8 includes either waiting for the next unloading (UOB8) or travelling fully loaded to the facilities (UOB9), subsequently entering the queue for the weighing process (UOB10), entering the queue for the unloading process (UOB11), and finally travelling empty back to the field (UOB6) through junction J2.

The detailed actions that were carried out during the simulation, which are synthetically represented in the IDEF3 diagram, are presented in Table 2. The activities described below occurred for each run that was made with the model.

2.3 The simulation model

The simulation of in-field grain-handling systems must be dynamic because of the importance of time evolution while considering the position of the combine and transport units, the interaction between them, and being discrete because of the start-stop of the vehicles and start-ending of the activities. The discrete event simulation model should provide a way to analyse the entire harvesting-transportation chain together as part of one system.

The simulation model was developed using the ExtendSim® programming environment (Imagine That Corporation, San Jose, CA, USA). ExtendSim® is a general-purpose package suitable for modelling discrete, continuous and mixed systems. The basic ExtendSim® software package contains 90 pre-built blocks. Users can also build their own library blocks, including hierarchical blocks. Standard blocks and custom blocks were used to build the model used to simulate the harvesting-transportation process and the decision-making process. To improve the model representation of the fieldwork pattern, the field was represented as a series of linear segments. Conceptually, any path can be modelled as a series of linear segments. The segment approach reduces motion from 2-D motion through the field to 1-D motion along a straight path, simplifying the simulation and significantly increasing the accuracy of the working pattern for every field shape and size. Each segment has several properties (e.g., width, yield, length, direction of harvest). A number of properties are generated within the simulation process (e.g., the width of a pass when deciding to harvest at a reduced operating width), while other properties must be defined by the user, such as the capacity of the transport units, the harvest system (e.g., combine working width). To carry all of the action that is represented in the IDEF3 diagram, including reading/writing data into the database both internally and externally, the model requires 588 blocks from the discrete event library, the value library and the tools library.

A detailed list of the input parameters is presented in the following section. All input parameters and results are created and stored in an MS ACCESS® database. The results are global indices, such as the total working time per hectare but also the combine and transport unit utilisation for different tasks (e.g., unloading, harvesting, and turning), allowing for in-depth and detailed work to be carried out by each single machine and less time spent on each single task. In addition, the waiting times in different locations are computed for the combine and transport units. Furthermore, the total use of manpower is estimated. The results allow for the further evaluation of the detailed inefficiency in the operations.

3. MATERIALS AND METHODS

3.1 Quantification of the input data

To quantify the input parameters of the simulation model, a number of field trials were carried out at the Venaria Farm in Vercelli Province, Piedmont, Italy. The field trials were carried out on a paddy rice farm cultivating the "Vialone Nano" rice cultivar (in a total area of 540 ha). The harvest and transportation operations were monitored in four fields (F1, F2, F3, and F4 in Fig. 4). The area of these fields and the distance from the storage facilities are listed in Table 2. The average yield was 7 t ha^{-1}, with a 13% average moisture content (5.9 t ha^{-1} dry matter).

The following parameters were measured during the field trials:

- The length of each individual pass and the corresponding time to harvest it (to estimate the working speed of the combine)
- The time that the combine requires to execute a 90° turn

- The time that the combine requires to execute a 180° turn
- Any distance that is travelled by the combine within the field area without harvesting to reach the unloading location and the corresponding time (to estimate the travelling speed within the field area)
- The unloading time (for a full load) of the harvester to a transport unit
- Any distance that is travelled by a transport unit with a full load and the corresponding time (to estimate the travelling speed with full load)
- Any distance that is travelled by a transport unit empty and the corresponding time (to estimate the travelling speed while empty)
- The weighing time for a transport unit at the storage facility
- The time for a transport unit to move from the weighing station to the elevator at the storage facility
- The unloading time of the transport units at the storage facilities

3.2 Model validation

The model was validated based on the global performance indicators, namely the area capacity, the combine utilisation, and the transport unit utilisation. In addition, it was considered important to compare the actual field area and the digitalised area that was implemented by the simulation. The difference between these two values (actual and simulated) originated from the fact that the field-work passes in the simulation model are considered rectangular, which is not true in reality unless the field is perfectly rectangular. Excluding the case of rectangular field shapes, a number of triangular areas are neglected in the simulation model in all other field shape types.

For validation, the actual output parameters from the operations that were carried out in fields 5 and 6 (F5 and F6, respectively, in Fig. 4) were compared with the resulting parameters from the simulation model.

3.3 Simulated scenarios for system assessment

A number of simulated experiments have been carried out on the four fields that were used to quantify the data (a total harvested area of app. 20 ha). The same operational features of the machinery were used, i.e., the harvester's full operating width, the grain hopper payload, and the transport unit payload (8 t). The task time elements and speed elements that were used as input resulted from the quantification of the model. An average yield of 7 t ha^{-1} at a harvest moisture of 22% was assumed.

The scenarios that were simulated have as independent variables the distance between the field and the storage facilities, with values from 1 km to 15 km at increments of 1 km, and the number of the implemented identical transport units, specifically for one, two, and three transport units.

The selected dependent values were investigated:

- The area capacity (ha h^{-1}), which is the field area in which the crop can be harvested and transported in the unit time
- The transport unit utilisation coefficient, which is the ratio of the active working time versus the total operation time. The non-working time of the transport unit includes the following time elements: waiting on the headland unloading point for the combine, waiting in a queue for weighing in the storage facilities, and waiting in a queue at the elevator for unloading
- The combine utilisation coefficient, which is the ratio of the active working time of the combine versus the total operation time. It has to be noted that the combine utilisation time is not equivalent to the term "field efficiency" because the former considers as non-productive time only the time that the harvester remains idle waiting for the arrival of the transport unit, while the latter includes all of the accessory time (e.g., headland turnings, unloading)
- The required man-hours per unit area.

The model was run in a stochastic mode, and each scenario was repeated 100 times. Totally, considering one yield (7 t), three transport units, 15 distances from the storage location (1 to 15 km), and two strategies (reduced pass yes-no), 90 experiments were carried out with a total of 9000 runs.

4. RESULTS

4.1 Input parameter quantification

The data that were collected in the field trials on the four fields are presented in Tables 4 and 5 for the parameters related to the combine or to the transport units, respectively. To extract the statistical distribution and the related statistical parameters, the BestFit software package, which is included in the ExtendSim® software, was implemented.

4.2 Model Validation

For the simulation, the internal parameters of the model that are listed in Tables 4 and 5 were used. However, the external parameters (field shape, size, yield, and distances) that were used in the simulation were the actual ones of fields 5 and 6. The number of transport units that were available for the operation were 2 with an 8-t capacity, and the effective combine working width (6,5 m) was used in this validation process. The area of the fields was 2.52 ha for field 5 and 3.16 ha for field 6. The yield was 7.1 t/ha and 6.8 t/ha for fields 5 and 6, respectively. The distance from the storage facilities was 2.15 km and 6.81 km for fields 5 and 6, respectively. The validation was based on 100 runs of the simulated model for each field. The validation results are summarised in Table 6.

4.3 Simulated scenarios for system assessment

Figure 5 presents the area capacity of the harvesting system for the use of one, two, and three transport units for distances ranging from 1 km to 15 km between the field and the storage facility. For the simulated case, the maximum chain capacity (1.63 ha h^{-1}) corresponds to when there is no idle time for the combine and can be achieved by implementing two transport units for transport distances of up to 3 km and by the implementation of three transport units for distances of up to 8 km. For a single transport unit, even for the marginal scenario instance of the transport distance of 1 km, this maximum capacity cannot be achieved because of the idle times that occurred for the combine (the area capacity equals 1.50 ha h^{-1}).

Figure 6 presents the required manpower (man-hours ha^{-1}) for various numbers of available transport units and various distances between the field and the storage facilities. Manpower includes the combine operator and the transport unit(s) operator(s), considering also the idle time for each individual. It should be noted that a greater value of the required manpower (3.3 man-hours ha^{-1}) corresponds to the case of the implementation of a single transport unit at a 15 km field–to-storage-facilities distance, while a lower required manpower (1.33 man-hours ha^{-1}) corresponds again to the case of a single transport unit and for a lower simulated field-to-storage-facilities distance, i.e., 1 km. For distances of up to 4 km, the implementation of a single transport unit results in lower values of the required manpower, while for distances greater than 4 km, the implementation of two transport units results in lower values of the required manpower. In the case of three transport units, the constant trend in the required manpower for distances of up to 12 km is explained by the fact that the combine is utilised at its maximum efficiency, meaning that there are no idle times for the combine and that the total operation time is consequently the same for every case.

Among the results, the utilisation coefficient of the machines (combine and transport units) allows for quantifying the contribution of each individual machine to the productivity of the harvesting chain and indicating bottlenecks in the system. During harvesting, the most expensive resource is the combine, which should be fully utilised. As observed in Fig. 7a, the full utilisation of the combine occurs for distances of up to 5 km in the case of two transport units and for distances of up to 9 km in the case of three transport units. In the case of single transport unit, even in the case of a 1-km distance, there is no full utilisation of the combine, resulting in system bottlenecks. A greater capacity (minimisation of the bottlenecks of the combine) can be achieved by implementing more transport units, which could incur a reduced utilisation of the transport units (Fig. 7b). However, it cannot be determined whether this implementation results in a higher operational cost, as detailed economical estimations must be made. Seeking the maximum utilisation of the combine is the case in which the timeliness of rice harvesting and delivery to the storage facility is the sole factor considered.

4.4 Evaluation of harvesting at a reduced width

Figure 9 presents the increase in the area capacity under the practice of harvesting passes at a reduced width. Excluding the case of a single available transport unit in the distance of 1 km between the field and the storage facilities, the field capacity increases. The average increase for all of the examined distances was 4.2%, 2.7%, and 1.7% for the cases of one, two, and three, transport units, respectively. The area capacity significantly increases when the transport units are a limiting factor of the combine performance.

The reason for the greater increase in the case of a single available transport unit is that for a standard yield value, the number of passes that the combine operates at a reduced operating width (and the level of this reduction) increases when the frequency of a transport unit not being available at the field site increases. Consequently, fewer transport units or greater distances between the field and the storage facilities increased the number of passes at a reduced width. For example, Fig. 8 presents the effect of the limited transport capacity on the number of the passes at a reduced operating width and on the level of reduction. As in the case of a single transport unit, the number of passes at a reduced width (5 passes) is considerably higher than the case of three transport units (3 passes). Furthermore, in the case of a single transport unit, the reduction was at the limit (70%), while in the case of three transport units, the reduction was below 25%.

5. CONCLUSIONS

A targeted simulation model for rice harvesting was developed, validated, and used to compare rice harvesting practices. The model was validated based on field trials, ascertaining a low error in the prediction of the operational parameters. The error ranged from 2.59% to 3.12% in the area capacity prediction.

The simulation model's operations management capabilities to provide performance evaluation measures were demonstrated. The model provided useful insights into the interaction between the harvesting system machines their interaction with the operational environment, such as field dimensions and distances and with the transport units.

Using the simulation model, the practice of implementing a reduced width in rice harvesting while moving toward the unloading location was compared with the practice of harvesting solely at full width to assess their effectiveness. It was shown that harvesting at reduced width can increase the area capacity significantly, (up to 7%) especially when the available transport unit capacity is a system's performance limiting factor .

Future research will focus on expanding the simulation model to include:

a) The use of a number of operators lower than the number of transport units. This will address the case of an operator leaving a transport unit at the unloading location and driving back a full unit that was left behind by the same or another operator.

b) The inclusion of economic aspects throughout harvesting. In particular, include the timeliness of grain delivery to the storage facility and its associated cost in the decision-making process of machinery system selection.

REFERENCES

Ali, O., Verlinden, B., van Oudheusden, D. (2009). Infield logistics planning for crop-harvesting operations. Engineering Optimization, 41(2), 183–197.

Amiama, C., Bueno, J., Alvarez, C. J., Pereira, J. M. (2008). Design and field test of an automatic data acquisition system in a self-propelled forage harvester. Computers and Electronics in Agriculture, 61, 192-200.

Berruto, R. and P. Busato (2006). EnergyFarm: Web Application to Compare Crop Systems Under Technical, Economic and Energetic Aspects. 4th World Congress on Computers in Agriculture and Natural Resources. J. X. F. S. Zazueta, S. Ninomiya, G. Schiefer. Orlando, Florida USA, American Society of Agricultural and Biological Engineers. I: 481-487.

Bochtis, D., Sørensen, C., Vougioukas, S. (2010). Path planning for in-field navigation-aiding of service units. Computers and Electronics in Agriculture, 74, 80–90.

Bochtis, D.D, Dogoulis, P., Busato, P., Sørensen, C.G., Berruto, R, Gemtos, T. (2013). A flow-shop problem formulation of biomass handling operations scheduling. Computers and Electronics in Agriculture, 91, 49–56.

de Toro, A., Gunnarsson, C., Lundin, G., Jonsson, N. (2012). Cereal harvesting - strategies and costs under variable weather conditions. Boisystems Engineering, 111, 429-439

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.

Jensen, M. A., Bochtis, D., Sørensen, C. G., Blas, M. R., Lykkegaard, K. L. (2012). In-field and inter-field path planning for agricultural transport units. Computers & Industrial Engineering, 63(4), 1054-1061.

Kusiak, A., Zakarian, A. (1996). Risk assessment of process models. Computers & Industrial Engineering, 30(4). 599-610.

Orfanou, A.; P. Busato; D.D. Bochtis; G. Edwards; D. Pavlou; C.G. Sørensen; R. Berruto; Scheduling for machinery fleets in biomass multiple-field operations, Computers and Electronics in Agriculture, 94, 12-19.

Peres, E., Fernandes, M.A., Morais, R., Cunha, C.R., López, J.A., Matos, S.R., Ferreira, P.J.S.G., Reis, M.J.C.S. (2011). An autonomous intelligent gateway infrastructure for in-field processing in precision viticulture. Computers and Electronics in Agriculture, 78, 176-187.

Thakur, M., Hurburgh, C.R. (2009). Framework for implementing traceability system in the bulk grain supply chain. Journal of Food Engineering, 95, 617-626.

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

Figure

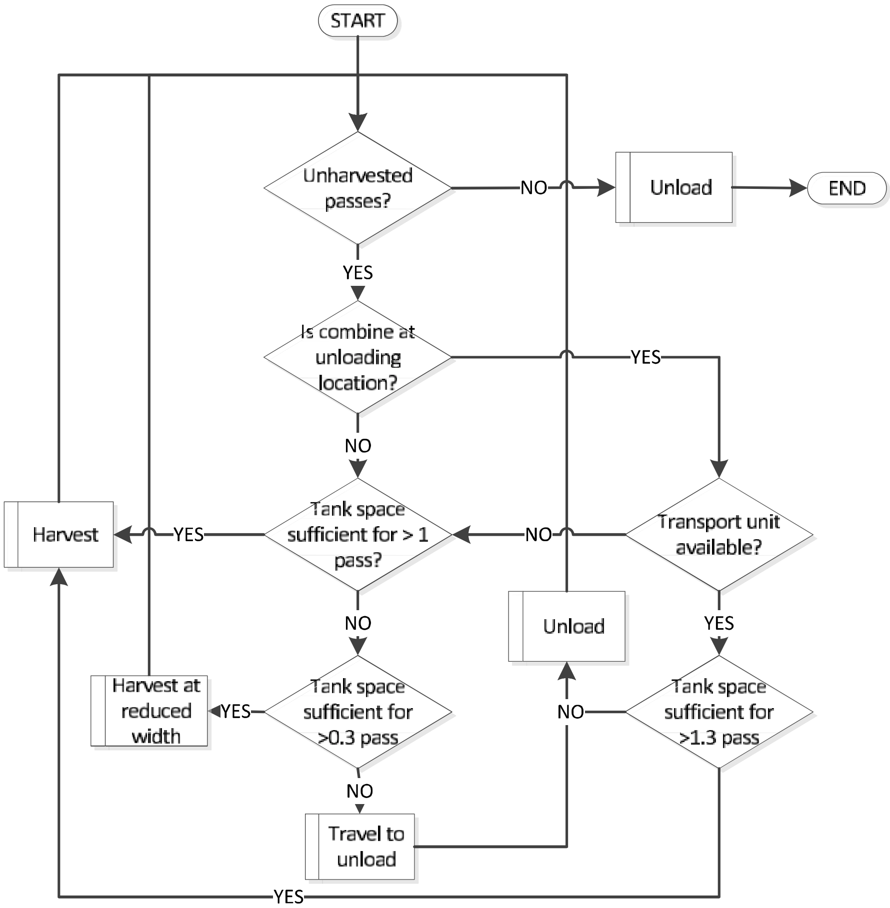


Figure 1 - Flow diagram of the decision-making process that drives the combine-working process.

Figure

Figure 2 – The activities cycle of the transport units.

Figure

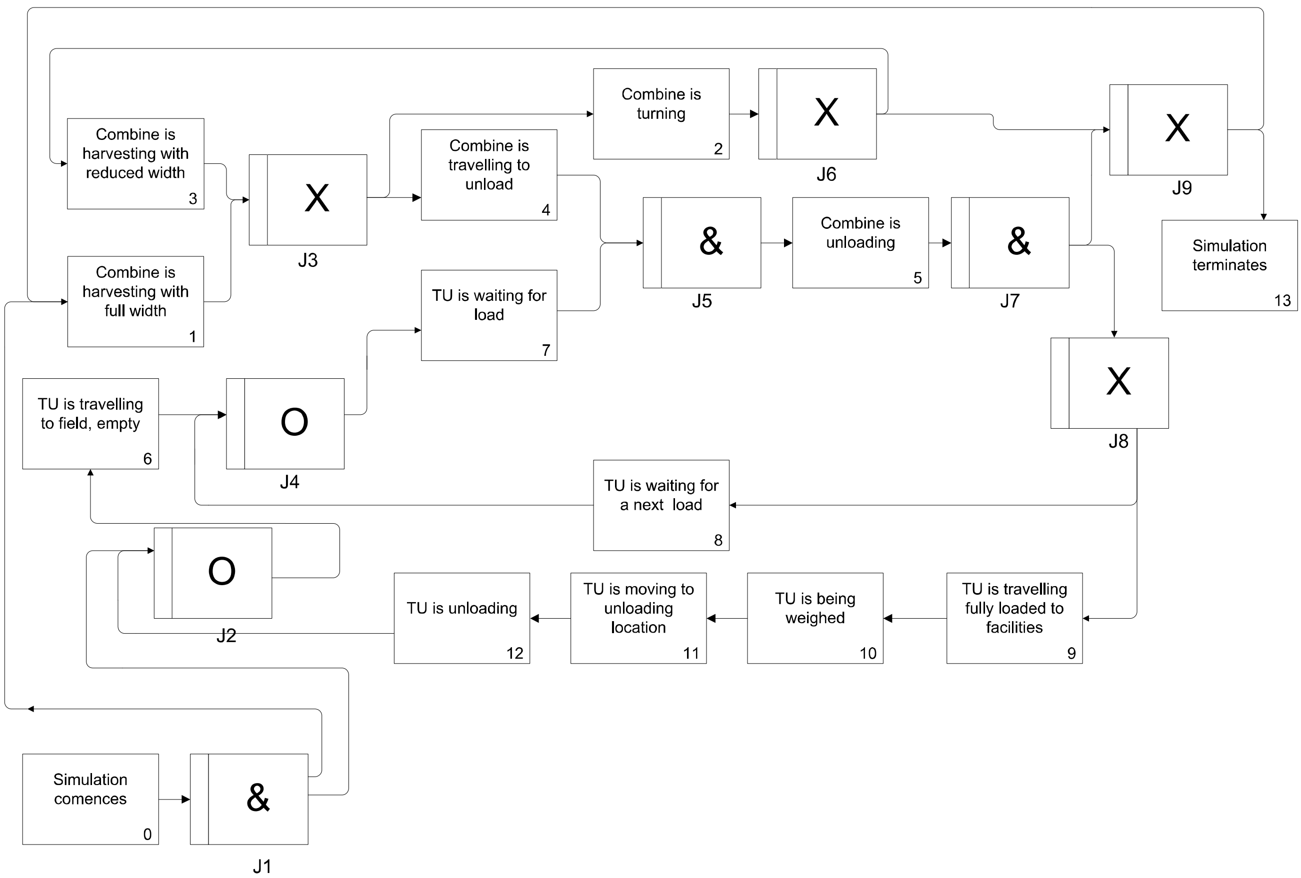


Figure 3 - IDEF process diagram of the rice harvest model (TU: transport unit)

Figure

Figure 4 – The locations of experimental fields F1, F2, F3, and F4, which were used to quantify the model, and F5 and F6, which were to validate the model; W: weighing location, U: unloading location

Figure

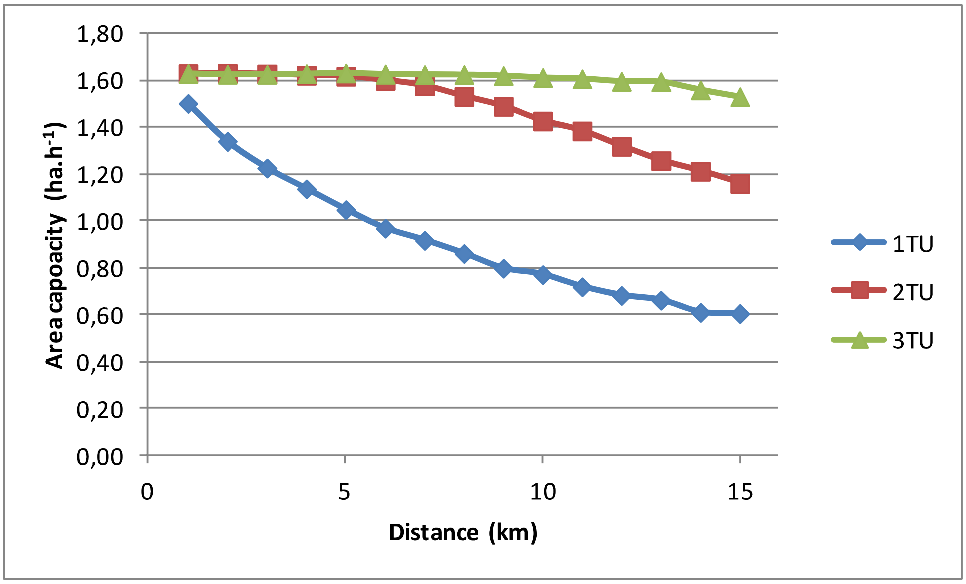


Figure 5 - Area capacity for various distances between the field and the storage facilities and different numbers of available transport units

Figure

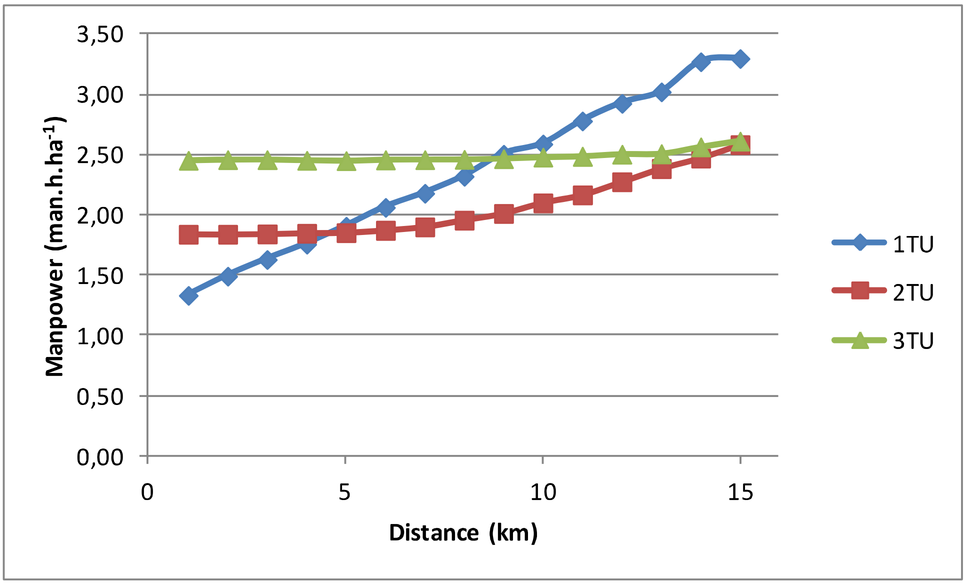
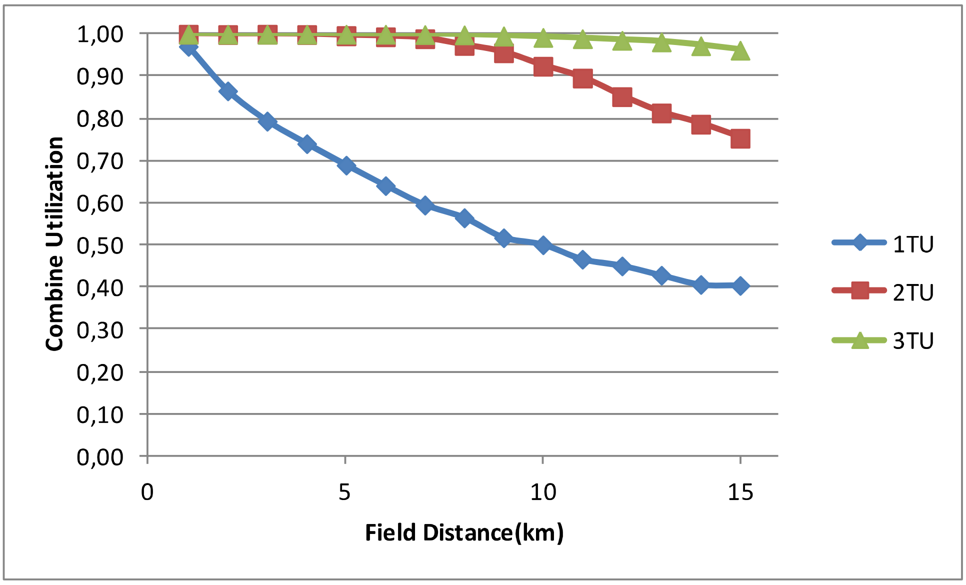
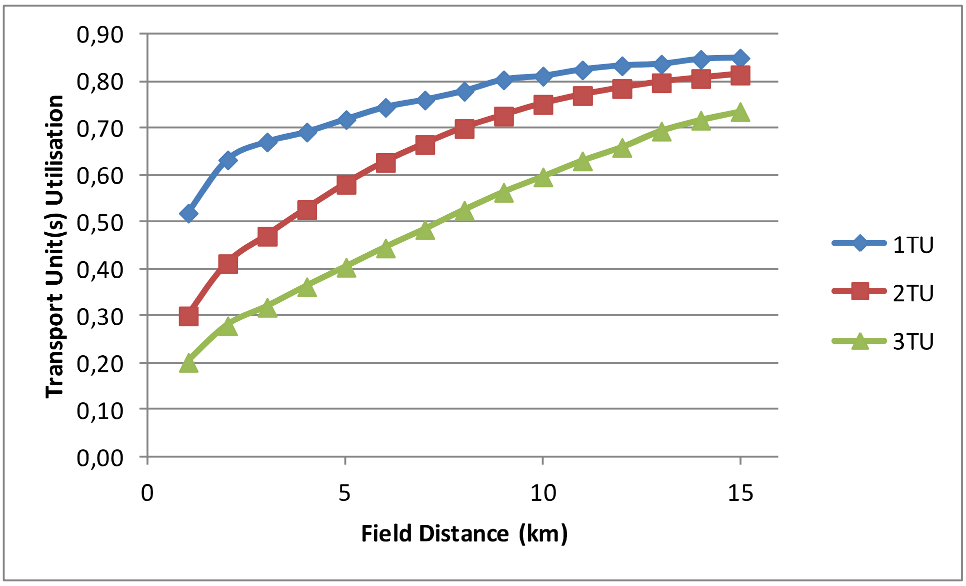


Figure 6 - Required manpower (man-hours ha^{-1}) for various distances between the field and the storage facilities and different numbers of available transport units.

Figure



(a)



(b)

Figure 7 – The utilisation of the combine (a) and the transport units (TU) (per TU in the case of 2 TUs and 3 TUs) (b) for different field-to-farm distances.

Figure

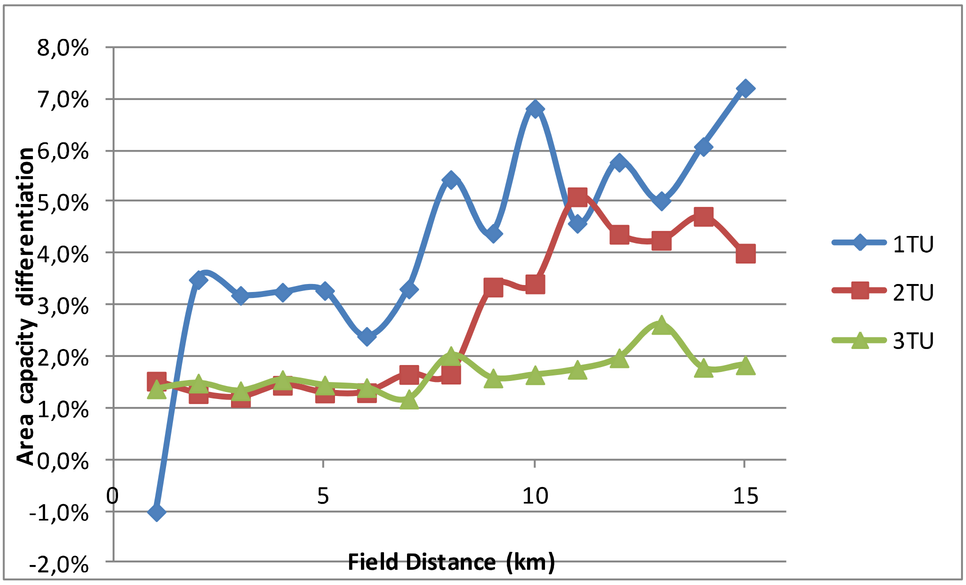
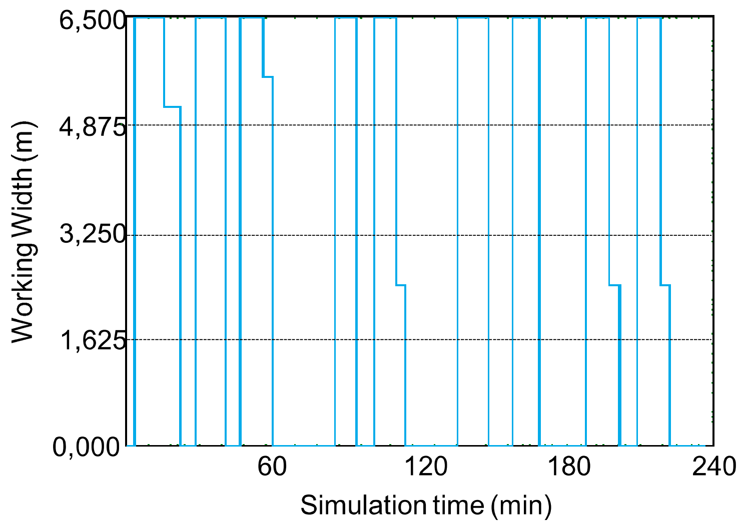
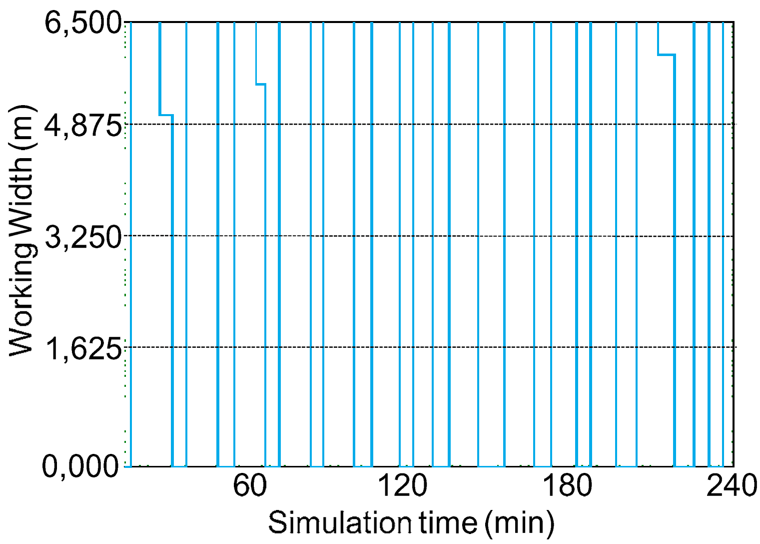


Figure 8 – Percent increase in the field capacity of the combine due to the use of reduced passes vs. the traditional way of operation

Figure



(a)

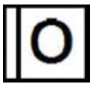


(b)

Figure 9 – The implemented working width in a time frame of four hours of operational time for the case of (a) a single transport unit and (b) three transport units (the depicted results regard the simulated operation for a 4-km distance between the field and the storage facilities).

Table

Table 1. The specific junctions of the IDEF3 schema that were used in the rice harvesting process diagram and their meanings (adapted from Mayer et al., 1995).

Junction icon	Name	Use in convergence flow	Use in divergence flow
	Asynchronous AND	All of the preceding activities must be completed.	All of the following activities must begin.
	Asynchronous OR	One or more of the preceding activities must be completed.	One or more of the following activities must begin.
	XOR (Exclusive OR)	Exactly one preceding activity is completed.	Exactly one following activity begins.

Table

Table 2 - Detailed description of the UOBs and junctions of the IDEF3 diagram that were presented in Fig. 3.

ID	Activity	Description
UOB0	Simulation commences	The configuration parameters for the current run are updated as follows: combine parameters (effective working width, grain hopper capacity, current hopper load set to zero, and selection of first segment to be harvested), transport unit parameters (capacity and number of transport units available), and field main parameters (initial number of single passes to complete the work, yield, and distance from the facilities). All of the field passes with their own features are uploaded from the database (e.g., length, coordinates next to unloading headland, type of pass – headland pass, main pass). The configuration parameters are written in the internal database. The combine object is created. Transport unit(s) object(s) are created. Field(s) object(s) are created. The combine is sent to UOB1. The transport unit(s) is (are) sent to J2.
UOB1	Combine is harvesting at a full width	The next field pass to be harvested and its features are acquired. The combine is locked. The combine working speed (taken from random distribution; see Table 4) is acquired. The activity duration using the pass length and harvesting speed is computed. The internal clock is updated. The current grain quantity is updated by adding the current grain harvested. The current pass being harvested is updated. The total time spent in this activity by the combine is updated. The combine is released. The remaining space in the grain hopper of the combine is computed. The grain to be harvested in the next pass is computed. The combine is sent to J3.
J3		The parameters to choose the next operation (UOB2 and UOB4) are set based on the decision-making process that is presented in Fig. 1 (position of the combine, availability of transport units at the unloading location, and space left in the grain hopper).
UOB2	Combine is turning	The time to turn a combine (taken from random distribution, see table 4) is acquired. The combine is locked. The internal clock is updated. The total time spent in this activity type by the combine is updated. The combine is released. The combine is sent to J6.
J6		The decision is made to send the combine to either J9 or to send the combine to harvest at a reduced working width (UOB3). The decision-making process follows Figure 1.
J9		The decision is made to send the combine to harvest at full width (UOB1) if there are still passes to be harvested or to terminate the simulation (UOB13).
UOB3	Combine is harvesting at a reduced width	The next field pass to be harvested (length) is acquired. The reduced working width as a function of the space left in the grain hopper is computed. The combine is locked. A process analogous to UOB1 takes place. The remaining passes are updated to include the remaining width not being harvested. The total time spent in this activity by the combine is updated. The combine is released. The combine is sent to J3.

UOB4	Combine is travelling to unload	The speed for travelling to unload (taken from random distribution, see Table 4) is computed. The distance to be travelled (from current combine position vs. the unloading position) is acquired. The time to complete the activity is computed. The internal clock is updated. The total time spent in this activity by the combine is updated. The combine is released. The combine is sent to an internal queue at UOB4. The combine is waiting in the queue to engage with a transport unit for unloading. The idle time of the combine is computed. The average waiting time and average queue length are updated. As soon as the transport unit is available at UOB7, both the combine and transport are sent to J5.
J5		The combine and the first available transport unit are sent for combine unloading (UOB5).
UOB5	Combine is unloading	Both the combine and the first transport unit in the queue are locked. The time to unload the combine into the transport unit (taken from random distribution; see Table 4) is updated. The internal clock of the simulation is updated. The grain hopper quantity is added to the current transport unit current weight. The current grain in the combine hopper is set to 0. The total time spent in this activity by the transport unit is updated. The total time spent in this activity by the combine is updated. The transport unit is released. The combine is released. Both the transport unit and the combine are sent to J7.
J7		The combine is sent to J9, while the transport unit is sent to J8.
J8		If the transport unit is full, it is sent to UOB9. If the transport unit can receive another load, it is sent to UOB8.
UOB6	TU is travelling to an empty field	The speed for travelling empty of the transport unit (taken from random distribution, see Table 5) is computed. The activity duration using the distance from the facilities as set in UOB0 is computed. The transport unit is locked. The internal clock is updated. The total time spent in this activity by the transport unit is updated. The transport unit is released. The transport unit is sent to J4.
UOB7	TU is waiting for the load	The transport unit is placed in a priority queue for loading. The first in the queue will be the transport units that have already received one load from the combine. The waiting time is recorded. The number of waiting transport units is recorded. The average waiting time and average queue length are updated. When the combine completes UOB4, the first transport unit in the queue is sent to J5 to prepare to receive the grain from the combine in UOB5.
UOB8	TU is waiting for the next load	The transport unit is placed in a priority queue, waiting for next load. This transport unit will be the first that is served by the combine since previously receiving one load from the combine. The waiting time is recorded. The number of waiting transport units is recorded. The average waiting time and average queue length are updated. The transport unit is sent to J4.
J4		Both of the transport units coming from UOB6 and UOB8 are sent to UOB7.

UOB9	TU is travelling fully loaded to the facilities	The speed for travelling full of the transport unit (Table 5) is acquired. The activity duration using the distance from the facilities as set in UOB0 is computed. The transport unit is locked. The internal clock is updated. The total time spent in this activity by the transport unit is updated. The transport unit is released.
UOB10	TU is being weighed	The time to unload a single transport unit (Table 5) is acquired. The transport unit is locked. The internal clock is updated. The total time spent in this activity by the transport unit is updated. The transport unit is released.
UOB11	TU is moving to the unloading location	The time to unload a single transport unit (Table 5) is acquired. The transport unit is locked. The internal clock is updated. The total time spent in this activity by the transport unit is updated. The transport unit is released.
UOB12	TU is unloading	The time to unload a single transport unit (Table 5) is acquired. The transport unit is locked. The internal clock of the simulation is updated with the activity duration. The total time spent in this activity by the transport unit is updated. The total quantity that was unloaded by the transport unit is updated. The current quantity in the transport unit=0 is updated. The transport unit is released.
J2		Transport units are received from UOB0 and UOB12 and passed to UOB6.
UOB13	Simulation terminates	The external MS ACCESS database is update with all of the internal configuration parameters that are cited in UOB0 and all of the cumulated results of the simulation: a) overall results: total time spent to harvest the fields, total working time for combine, and total working times for the transport units; b) combine parameters: time spent in harvest at a full width (from UOB1), time spend in harvest at a reduced working width (from UOB3), turning time (from UOB2), travelling to unloading (from UOB4), unloading time (UOB5), and waiting time before unloading (from J5); and c) Transport unit parameters: time spent travelling empty to the field (from UOB6), time spent waiting for the 2nd load (from UOB8), time spent waiting for the 1st load (from UOB7), time spent travelling full to the storage facilities (from UOB9), time spent weighing (from UOB10), time spent to moving to the unloading location (from UOB11), and time spent unloading (from UOB12). The simulation process is shut down.

Table 3 – The area and the field-to-farm distance of the four fields that were selected to quantify the model.

Field ID	Area (ha)	Distance (km)
Field 1	4.25	1.29
Field 2	5.42	1.44
Field 3	4.61	1.57
Field 4	5.79	1.71

Table

Table 4 – Measured parameters for the combine harvester

Parameter	Number of observations	Best fit statistical distribution	Mean	Standard deviation
Working speed on passes (km h^{-1})	117	Normal	3.92	0.86
Working speed on headlands (km h^{-1})	22	Lognormal	2.11	1.19
Manoeuvring time for a 90° turn (min per turn)	47	Lognormal	0.252	0.11
Manoeuvring time for a 180° turn (min per turn)	70	Lognormal	0.329	0.15
Travelling time to the unloading location (min)	55	Lognormal	0.642	1.64
Unloading time (min)	28	Lognormal	1.76	0.803

Table

Table 5 – Measured parameters for the transport units

Parameter	Number of observations	Best fit statistical distribution	Mean	Standard deviation
Travelling speed with empty wagon (km h^{-1})	9	Normal	26.6	2.06
Travelling speed with full wagon (km h^{-1})	11	Normal	26.7	2.55
Weighting time at farm (min)	23	Lognormal	1.25	0.821
Time to move from the weighing station to the unloading location (including positioning) (min)	19	Lognormal	4.1	3.85
Unloading time (min)	15	Lognormal	0.798	1.14

Table

Table 6 - Comparison between actual and simulated results

Parameter		Field 5	Field 6
Area capacity	Actual (ha h^{-1})	1.60	1.54
	Simulated (ha h^{-1})	1.65	1.58
	Error (%)[&]	**3.12**	**2.59**
Combine utilisation	Actual	1	0.98
	Simulated	1	0.95
	Error (%)	**0**	**3.06**
Transport unit(s) utilisation	Actual	0.43	0,63
	Simulated	0.41	0,67
	Error (%)	**4.65**	**6.35**
Area[*]	Actual (m^2)	25,258	31,160
	Simulated (m^2)	25,093	30,820
	Error (%)	**0.65**	**1.09**

[&] $$Error = \frac{|Actual\ Value - Simulated\ Value|}{Actual\ Value} \cdot 100\%$$