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A SIMULATION MODEL FOR A RICE-HARVESTING CHAIN

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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;

28

1. INTRODUCTION

29 Harvesting is the most complex operation among all field operations because it involves multiple units that must
30 be coordinated to achieve the objective of the overall system's performance optimisation. These units include
31 harvesters, transport units, and handling units. For this purpose, a number of system engineering approaches
32 have been developed and applied to the operational management of individual tasks involved in the harvesting
33 process. Previous work includes, area coverage planning (Ali et al., 2009), route planning methods for transport
34 units (Jensen et al., 2012; Bochtis et al., 2010), the sequential scheduling of harvesting and handling operations
35 (Orfanou et al., 2013; Bochtis et al., 2013), simulation models for harvesting cost prediction (de Toro et al.,
36 2012), and performance evaluation and documentation systems (Amiama et al., 2008). However, the majority of
37 the developed models cannot be applied to all cropping systems. In particular, the harvesting management of
38 rice, although it is a grain crop, presents a number of specific challenges that require the development of
39 dedicated tools.

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

55 Furthermore, combines in rice harvesting generally use tracks in the front axis and thus cannot move fast within
56 the field area both in cases of harvesting and when travelling towards the headland to the unloading location.
57 Thus, the travelling speed is approximately the same as the harvesting speed (4-5 km h⁻¹). This speed results in
58 highly non-productive times due to in-field travel, and frequently results in a decision to harvest in a reduced

59 operating width while travelling back to the unloading location when there is still space in the grain hopper, but
60 not enough to pass in the full operating width. Consequently, sequential decisions must be made each time that
61 the combine reaches a headland area. Thus, general norms of field efficiency and productivity for grain
62 harvesting cannot be applied in this complex system of sequential decisions.

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

70

71 **2. SIMULATION MODEL DEVELOPMENT**

72 **2.1 The decision-making process**

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

86 The logic of the operator's decision-making process is presented in Fig. 1. Each time the combine reaches a
87 headland area, the operator considers the availability of a TU at the unloading location, whether the headland
88 that is reached is next to the unloading location, and the current grain quantity in the grain hopper to determine

89 whether to continue harvesting in the next pass at a full operating width or a reduced operating width or to
90 proceed to the unloading location (involving in-field travel when the transport unit is located at the opposite
91 headland and/or waiting for a transport unit to arrive).

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

95

96 **2.2 Modelling of the work process**

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

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

112 The IDEF3 process diagram of the developed simulation model for the rice harvest operation is presented in Fig.
113 3. The activity 'Simulation commences' (UOB0) initiates the operation, while through junction J1, all of the
114 transport units move to the empty field (UOB6), and the combine begins to operate in the field (UOB1). Through
115 junction J2, all of the transport units (either coming from UOB0 or from UOB11 when a transport unit returns
116 from the storage facilities) travel to the empty field (UOB6) and wait to be loaded (UOB7) with transport units
117 that have already been partially loaded (UOB8) coming from the fan-out of junction J8. Transport units merge
118 together in junction J4 and enter the state 'TU is waiting to load' (UOB7). The priority in the queue is given to
119 the transport units that have been already partially loaded. The combine, after entering the field, begins to

120 operate (UOB1). After each pass, in junction J3, a decision is made concerning whether the combine should
121 continue to the next pass or move to the unloading location on the headland, where transport units are waiting for
122 the unloading process (UOB7). The decision-making process is based on the logic that is presented in **Error!**
123 **Reference source not found.** When there is adequate space in the combine's grain hopper to harvest the next
124 pass, the activity 'Combine is turning' (UOB2) takes place, and then, through junction J6, either the combine is
125 harvesting with reduced width (UOB3) or another decision-making process will take place after junction J9. If
126 there are still passes to harvest, the activity 'Combine is harvesting' (UOB1) is executed. Otherwise, the
127 simulation terminates (UOB13). If the combine's grain hopper becomes full (or there is not adequate space for a
128 pass with reduced width), the activity 'Combine is travelling to unload' (UOB4) will begin. Through the fan-in
129 asynchronous junction J5, which specifies that at least one TU and the combine should be available, the activity
130 'Combine is unloading' (UOB5) takes place. Following this activity and through junction J7, the combine is
131 passed to junction J9, where either it begins to harvest another pass (UOB1) or the simulation terminates
132 (UOB12). The latter takes place when the field is completely harvested. The cycle that is followed by the TU
133 after junction J8 includes either waiting for the next unloading (UOB8) or travelling fully loaded to the facilities
134 (UOB9), subsequently entering the queue for the weighing process (UOB10), entering the queue for the
135 unloading process (UOB11), and finally travelling empty back to the field (UOB6) through junction J2.

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

139

140 **2.3 The simulation model**

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

145 The simulation model was developed using the ExtendSim[®] programming environment (Imagine That
146 Corporation, San Jose, CA, USA). ExtendSim[®] is a general-purpose package suitable for modelling discrete,
147 continuous and mixed systems. The basic ExtendSim[®] software package contains 90 pre-built blocks. Users can
148 also build their own library blocks, including hierarchical blocks. Standard blocks and custom blocks were used
149 to build the model used to simulate the harvesting-transportation process and the decision-making process. To
150 improve the model representation of the fieldwork pattern, the field was represented as a series of linear

151 segments. Conceptually, any path can be modelled as a series of linear segments. The segment approach reduces
152 motion from 2-D motion through the field to 1-D motion along a straight path, simplifying the simulation and
153 significantly increasing the accuracy of the working pattern for every field shape and size. Each segment has
154 several properties (e.g., width, yield, length, direction of harvest). A number of properties are generated within
155 the simulation process (e.g., the width of a pass when deciding to harvest at a reduced operating width), while
156 other properties must be defined by the user, such as the capacity of the transport units, the harvest system (e.g.,
157 combine working width). To carry all of the action that is represented in the IDEF3 diagram, including
158 reading/writing data into the database both internally and externally, the model requires 588 blocks from the
159 discrete event library, the value library and the tools library.

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

167

168 **3. MATERIALS AND METHODS**

169 **3.1 Quantification of the input data**

170 To quantify the input parameters of the simulation model, a number of field trials were carried out at the Venaria
171 Farm in Vercelli Province, Piedmont, Italy. The field trials were carried out on a paddy rice farm cultivating the
172 “Vialone Nano” rice cultivar (in a total area of 540 ha). The harvest and transportation operations were
173 monitored in four fields (F1, F2, F3, and F4 in Fig. 4). The area of these fields and the distance from the storage
174 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}
175 dry matter).

176 The following parameters were measured during the field trials:

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

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

191

192 **3.2 Model validation**

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

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

201 **3.3 Simulated scenarios for system assessment**

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

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

210 The selected dependent values were investigated:

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

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

226

227 **4. RESULTS**

228 **4.1 Input parameter quantification**

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

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4.2 Model Validation

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4.3 Simulated scenarios for system assessment

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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.

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 ($3.3 \text{ man-hours ha}^{-1}$) 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 ($1.33 \text{ man-hours ha}^{-1}$) 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

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

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276 **4.4 Evaluation of harvesting at a reduced width**

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

282 The reason for the greater increase in the case of a single available transport unit is that for a standard yield
283 value, the number of passes that the combine operates at a reduced operating width (and the level of this
284 reduction) increases when the frequency of a transport unit not being available at the field site increases.
285 Consequently, fewer transport units or greater distances between the field and the storage facilities increased the
286 number of passes at a reduced width. For example, Fig. 8 presents the effect of the limited transport capacity on
287 the number of the passes at a reduced operating width and on the level of reduction. As in the case of a single
288 transport unit, the number of passes at a reduced width (5 passes) is considerably higher than the case of three
289 transport units (3 passes). Furthermore, in the case of a single transport unit, the reduction was at the limit
290 (70%), while in the case of three transport units, the reduction was below 25%.

291

292 **5. CONCLUSIONS**

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

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

300 Using the simulation model, the practice of implementing a reduced width in rice harvesting while moving
301 toward the unloading location was compared with the practice of harvesting solely at full width to assess their
302 effectiveness. It was shown that harvesting at reduced width can increase the area capacity significantly, (up to
303 7%) especially when the available transport unit capacity is a system's performance limiting factor .

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

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

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

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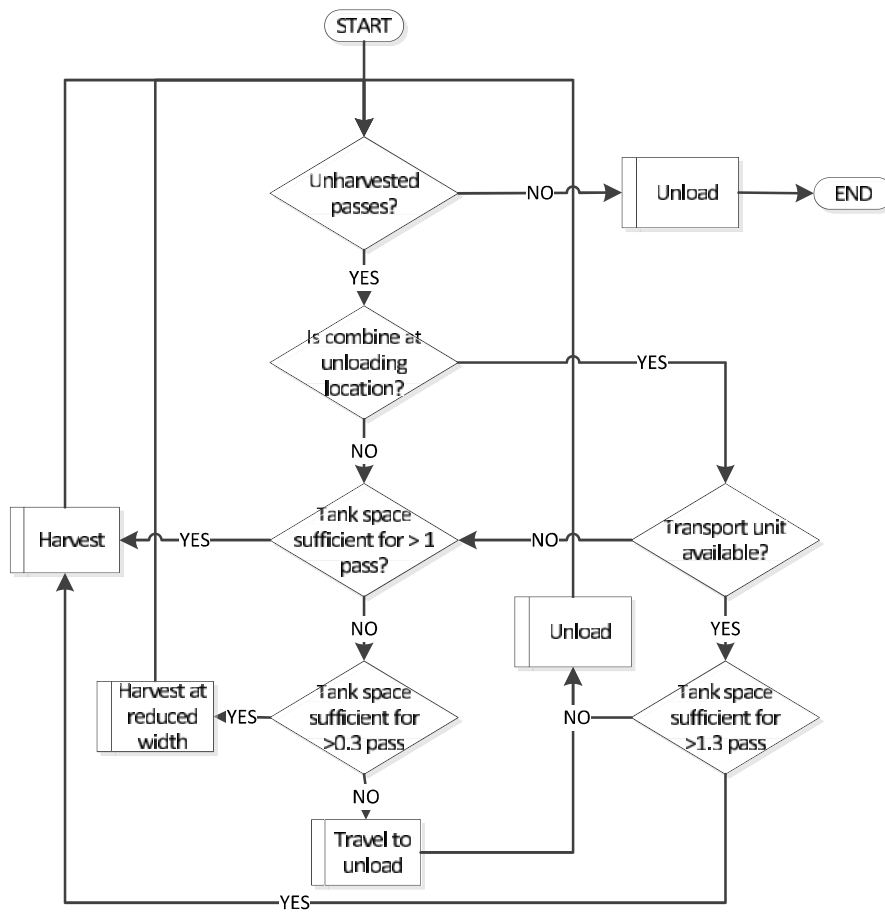


Figure 1 - Flow diagram of the decision-making process that drives the combine-working process.



Figure 2 – The activities cycle of the transport units.

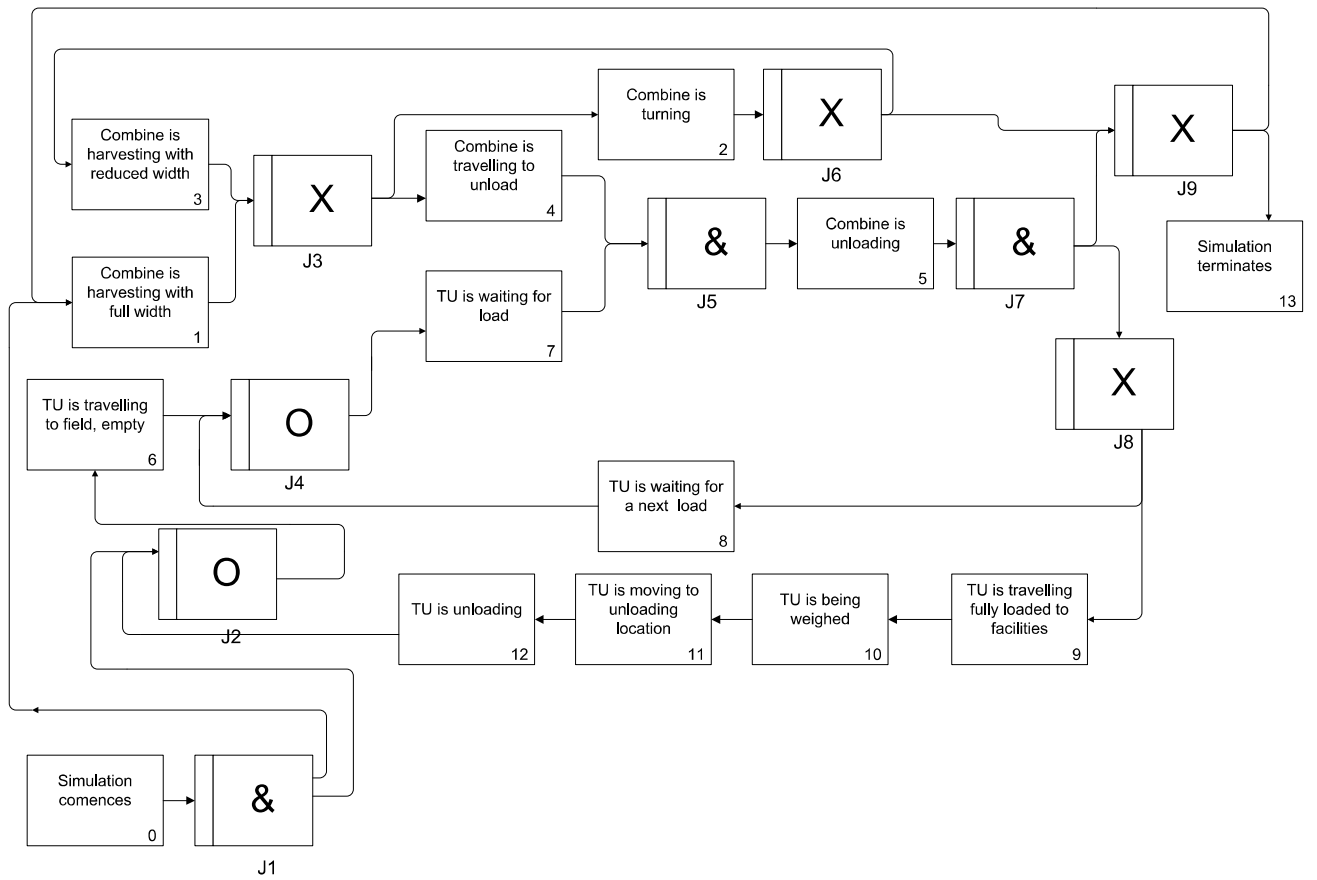


Figure 3 - IDEF process diagram of the rice harvest model (TU: transport unit)

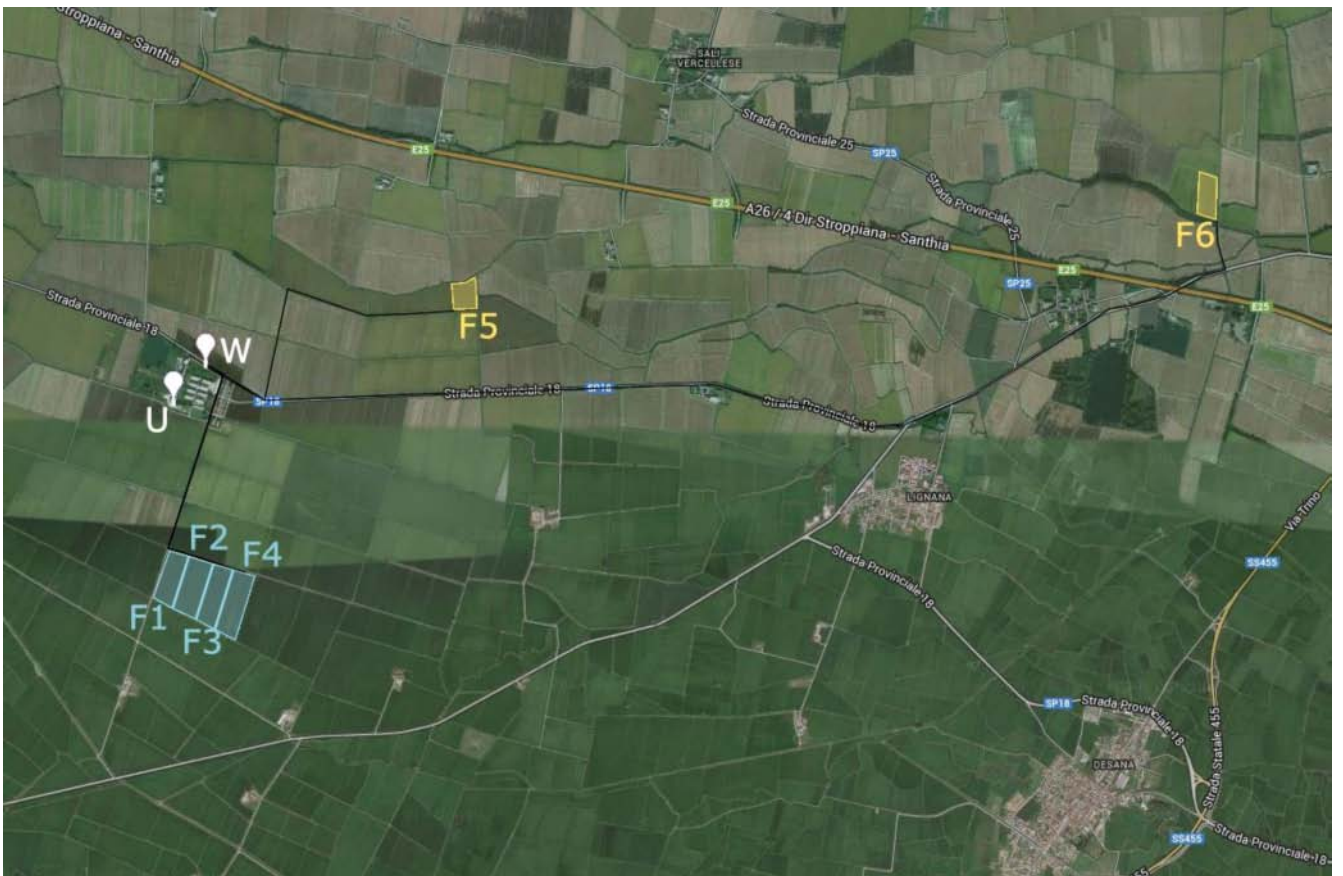


Figure 4 – The locations of experimental fields F1, F2, F3, and F4, which were used to quantify the model, and F5 and F6, which were to validate the model; W: weighing location, U: unloading location

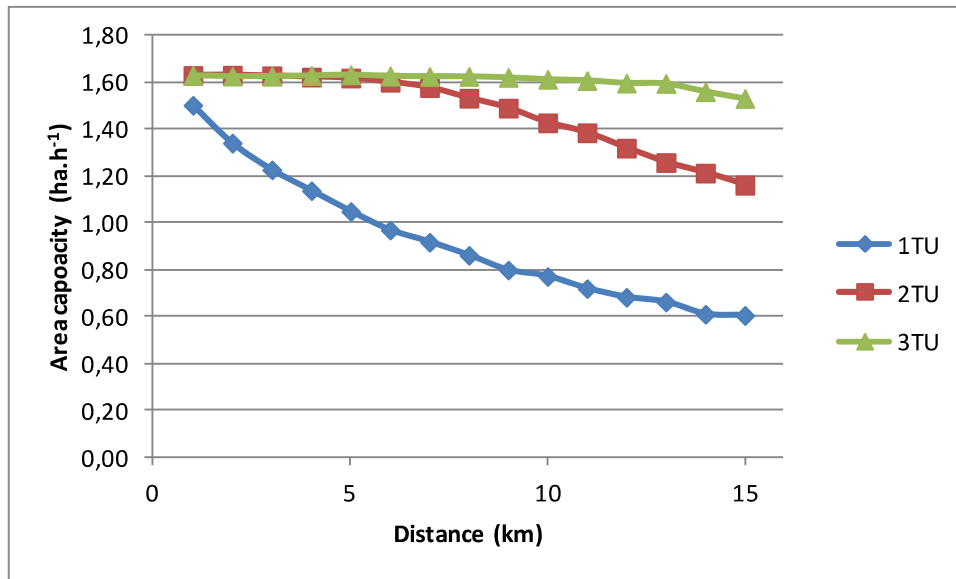


Figure 5 - Area capacity for various distances between the field and the storage facilities and different numbers of available transport units

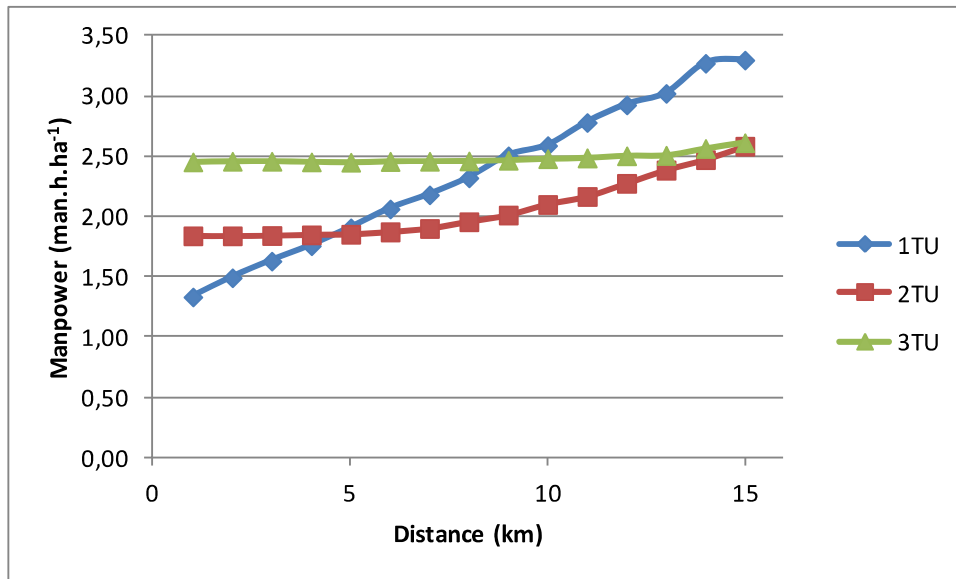
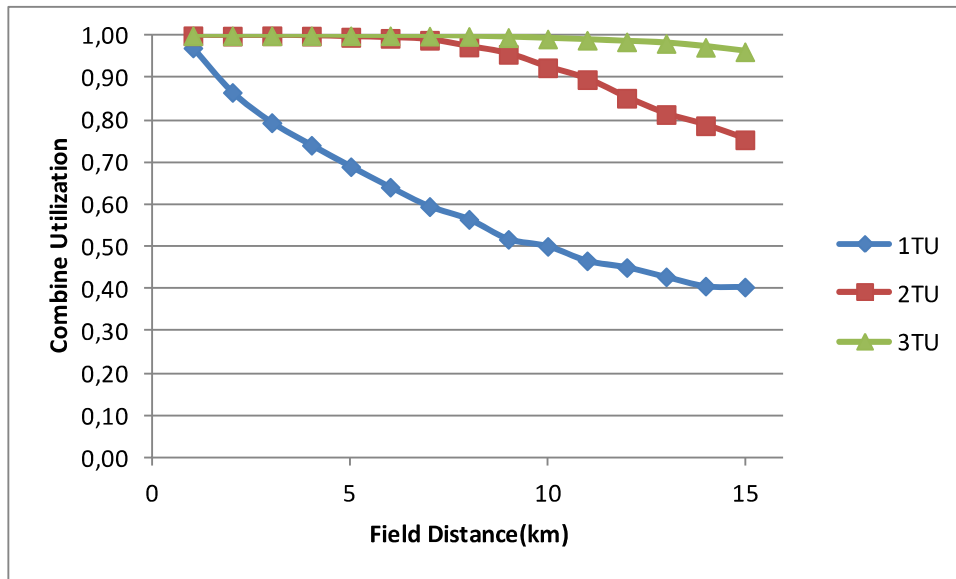
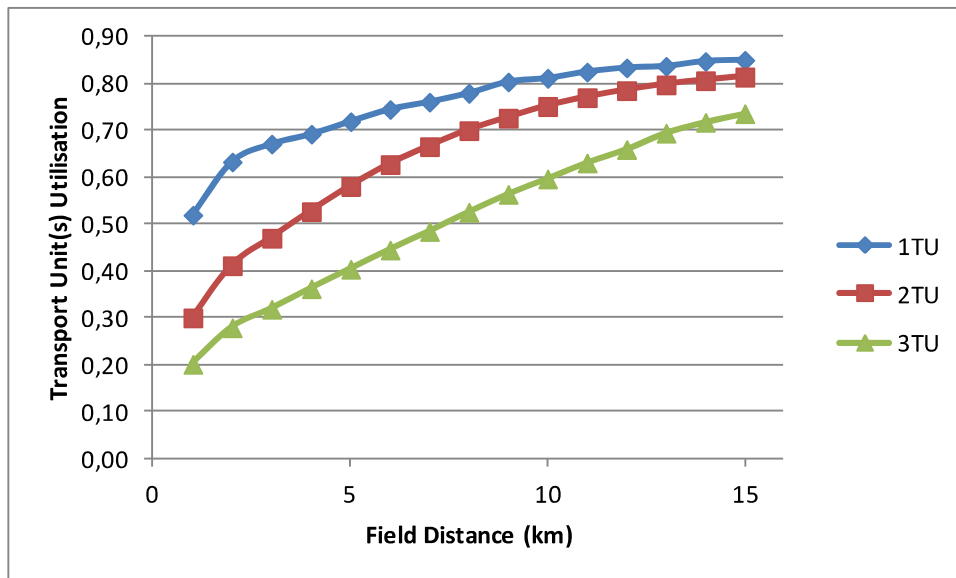


Figure 6 - Required manpower (man-hours ha⁻¹) for various distances between the field and the storage facilities and different numbers of available transport units.



(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.

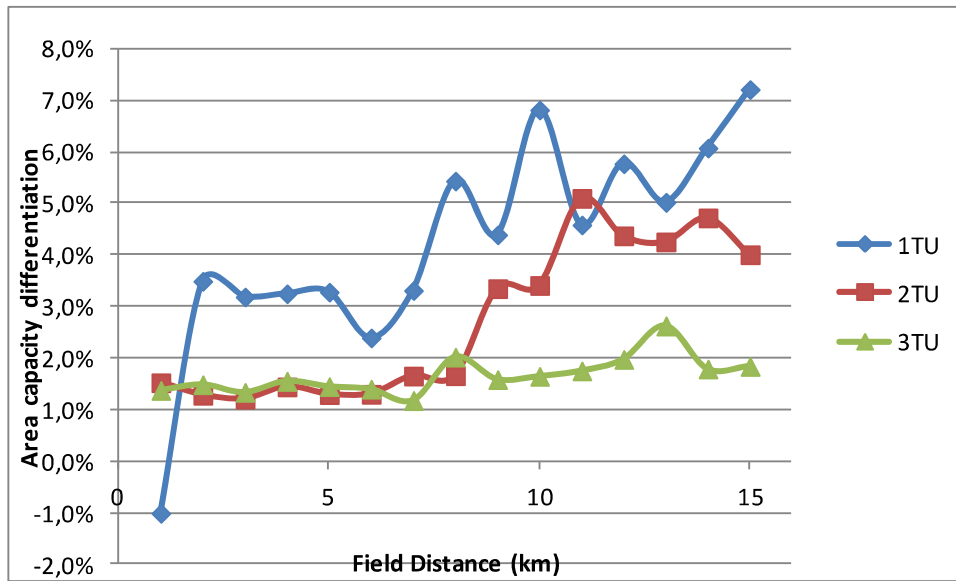
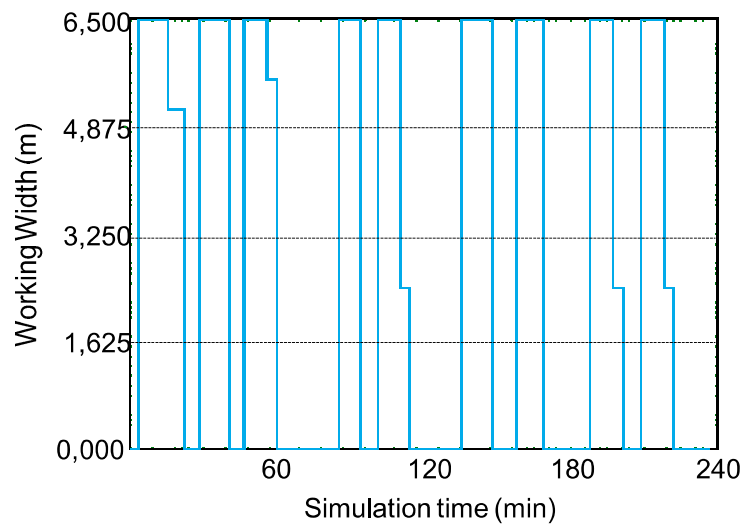
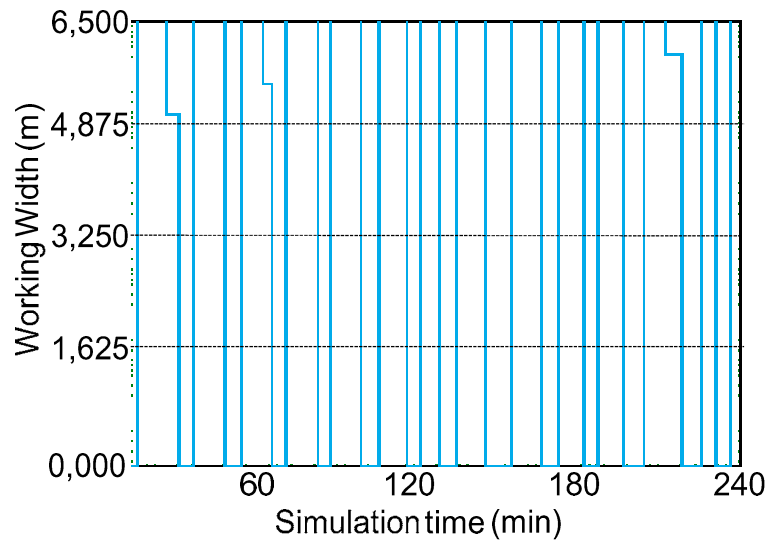


Figure 8 – Percent increase in the field capacity of the combine due to the use of reduced passes vs. the traditional way of operation



(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 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 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	<p>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:</p> <p>a) overall results: total time spent to harvest the fields, total working time for combine, and total working times for the transport units;</p> <p>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</p> <p>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).</p> <p>The simulation process is shut down.</p>

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 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 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 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

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