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# MINIMISING MANPOWER IN RICE HARVESTING AND TRANSPORTATION OPERATIONS

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## ABSTRACT

Manpower is an important input parameter for both strategic and tactical management levels in agricultural production systems, connected to management tasks such as capacity planning, task times planning, and scheduling. In large scale field operations manpower surplus can lead to an unnecessary increase in operational cost, while, on the other hand, manpower shortages in the absence of appropriate planning can lead to reduced productivity with a high risk for timeliness costs. In this paper, the simulation model reported by Busato [Busato, 2015, A simulation model for a rice-harvesting chain. Biosystems Engineering, 129, 149-159] was extended to incorporate the functionality of the minimisation of manpower in large scale field operations, such as crop harvesting and transportation. Specifically, the model implements the practice where the number of transport units' operators is lower than the number of transport units. The simulation model was validated based on measurements in two harvesting and transport operations. The deviation of the predicted operation parameters as compared to the measured ones was relatively low. Specifically, for the case of area capacity the error in the prediction was 2.2% and 2%, respectively, compared to the measured area capacity in the two operations. Regarding the practice of the reduced number of operators, it was shown that there are significant reductions in required manpower use when fewer operators than the number of transport units are implemented in the operation. For the specific transport units-operators configurations examined, the reduction of manpower use ( $\text{h ha}^{-1}$ ) was in the range of 12% to 30%.

**Keywords:** Simulation modelling; agri-food logistics; operations management simulation;

## 1. INTRODUCTION

Manpower planning is an important task for both strategic and tactical management levels in agricultural production systems (Dionysis D. Bochtis, Sørensen, & Busato, 2014). The limited availability of human

29 resources in agricultural production and, especially, of human resources of high specialisation (e.g. operators of  
30 contemporary farm machinery), requires an effective decision making process for resource allocation to the  
31 various tasks involved in field operations (Guan, Nakamura, Shikanai, & Okazaki, 2009), as well as for the  
32 optimal execution of the field operations (Dionysis D. Bochtis, Sørensen, Busato, & Berruto, 2013; Zhou, Leck  
33 Jensen, Sørensen, Busato, & Bothtis, 2014). To that effect, manpower is a required input in decision support  
34 systems developed for various agricultural machinery management levels (Dionysis D. Bochtis et al., 2014)  
35 including, task times planning (Buckmaster & Hilton, 2005; Busato & Berruto, 2014; Sopegno et al., 2016;  
36 Sørensen, Halberg, Oudshoorn, Petersen, & Dalgaard, 2014) capacity planning (de Toro & Hansson, 2004;  
37 Gunnarsson, Spörndly, Rosenqvist, de Toro, & Hansson, 2009), and scheduling (D.D. Bochtis et al., 2013;  
38 Orfanou et al., 2013). In large scale operations, such as crop or biomass harvesting and transport operations,  
39 manpower surplus can lead to an unnecessary increase in operational cost, while, on the other hand, manpower  
40 shortages in the absence of appropriate planning can lead to reduced productivity with a high risk for timeliness  
41 cost occurrence.

42 The work presented here deals with the operational practice in crop harvesting and transport operations  
43 according which the operators are fewer in number than the number of the machines/vehicles involved in the  
44 operation, either due to operator unavailability or due to cost reduction measures. This paper is the continuation  
45 of the work presented in Busato (2015) where the development of a simulation tool targeted to rice-harvesting  
46 and transport operations was presented. Logistics operations for rice are more complex compared to other grain  
47 crops due to the trafficability constraints. The muddy soil during the harvesting period does not allow for in-field  
48 (on-the-go or stationary) unloading of the combine to the transport units and this process has to take place when  
49 the combine is (stationary) on the headland area. Furthermore, the irrigation system (irrigation channels) used in  
50 rice production does not allow the access of the transport unit to one of the two field headlands, thereby placing  
51 another operational restriction. The irrigation system also limits the size of the fields used for rice cultivation  
52 which is typically 2-6 ha. To that effect, rice farms include numerous small dispersed fields that require various  
53 cycle times for the transport units within the logistics system. Finally, the practice of harvesting with reduced  
54 width makes harvesting operation a complex process in terms of decision making. Harvesting with reduced  
55 width in a field-work track takes place when the remaining capacity of the grain hopper is not sufficient for the  
56 crop to be harvested if the entire width of the header is implemented. Busato (2015) found that the capacity of  
57 the harvesting system can be increased as much as 7% by the implementation of the above mentioned practice.  
58 The simulation model developed in Busato (2015) incorporates all the above mentioned operational features  
59 unique to rice harvesting. In this paper, this simulation model is extended to include different ways to manage  
60 the manpower operating the transport units. Specifically, the practice where the transport units are operated by

61 one less operator is implemented. During this type of process an operator leaves a transport unit at the designated  
 62 unloading location and drives back to the delivery location a full transport unit left by another operator (or the  
 63 same in the case that only one operator is used for the transportation task). The objectives of this paper were 1)  
 64 define the logistics system's components and their interaction, 2) extend the simulation model presented in  
 65 Busato (2015) to describe the practice by adding functional modules to the existing simulation model, 3) conduct  
 66 an evaluation of the various configurations of the system in terms of defined performance measures, and 4)  
 67 evaluate manpower required for crops harvesting and transport operations taking account also the timeliness  
 68 factor.

69 **2. DEVELOPMENT OF THE MODEL**

70 **2.1 Work process modelling**

71 The simulation model was built on the previous version of the model developed in Busato (2015). Therefore, the  
 72 model simulates the occasionally applied reduced working width practice previously described. Each time the  
 73 combine reaches a headland area, it is considered whether there is an unloading location in the particular  
 74 headland area, the availability of a transport unit in the field boundary, and the quantity carried currently in the  
 75 harvester's temporary grain hopper. Based on this considerations it is determined whether harvesting will be  
 76 continued in the subsequent field-work track at a full or at a reduced working width that ranges between 30%  
 77 and 100% of the full header width), or the combine will interrupt harvesting and move to the unloading location.

78 Figure 1 presents the IDEF3 diagram that describes the functionality of the simulation model. The explanation of  
 79 the various activities and junctions is presented in Table 1.

80

81

**Table 1 – The list of the activities and junctions of the IDEF3 diagram**

UOB0	Simulation commences	It initiates the operation. In terms of the simulation process, the internal database is updated with the configuration parameters. This configuration regards the combine features (e.g. grain hopper capacity, full operating width, etc.), operational parameters (e.g. the sequence under which the passes will be harvested, working and in-field travelling speed, etc.), transport unit features (e.g. number of units available and corresponding

		capacities), and field features (e.g. yield, geometrical features of each pass, and distance from the storage facilities)
UOB1	First TU is travelling to the field	The first TU travels to the field with empty wagon.
UOB2	Operator available for the combine	The driver of the TU will be the operator of the combine.
UOB3	Combine is harvesting at full operating width	After the completion of the unloading process (UOB8 through J8 and J9) or after a headland turning (UOB6 through J6) (or in the beginning of the operation – UOB2) the combine re-starts the (or starts) the harvesting operation.
UOB4	Combine is harvesting with a reduced operating width	After a headland turning (UOB6) if the remaining grain hopper capacity does not allow for a full width harvesting, the combine proceeds in harvesting with reduced width
UOB5	Combine is travelling to unload	When the combine completes a pass harvested by reduced width (end of activity UOB4) it travels to the unloading location.
UOB6	Combine is turning	After a pass the combine performs a headland turn (unless the grain hopper is full)
UOB7	TU is waiting for load	The TU is waiting idle at the unloading location to receive the grain from the combine.
UOB8	Combine is unloading	The TU and the combine are batched (as simulation items) for the unloading process
UOB9	TU is travelling fully loaded to facilities	If the TU is full (UOB9) and if an operator is available (UOB17 through junction J12) it is travelling to the storage facilities.
UOB10	TU is being weighted	The TU after its arrival at the storage facilities is being weighted according to an arrival priority queue.

UOB11	TU is moving to the unloading location	After the weighting process in the storage facilities the TU is moving to the elevator for the unloading process.
UOB12	TU is unloading	The TU enters the unloading process at the storage facilities.
UOB13	TU is waiting for the next load	The TU is partially loaded at the unloading locations (e.g. in the headland area) and remains there for the next combine unloading process.
UOB14	Operators available for driving TUs to the field	The process that determines the availability of an operator at the storage facilities for driving a TU to the field.
UOB15	TUs available	The process that determines the availability of a TU at the storage facilities.
UOB16	TU is travelling to the field empty	In the case that a TU and an operator are available, the two items are batched and the TU is travelling to the field for servicing the combine.
UOB17	Operator is waiting for full wagon	When the TU arrives empty at the field, the TU and the operator items are un-batched (J4) and the operator is waiting for the first available TU with a full wagon.
UOB18	Simulation terminates	This activity terminates the entire simulation process.
J1		The simulation items “operator” and “TU” are un-batched.
J2		Through this junction, any remaining TU available (UOB15) is matched with any operator available (UOB14)
J3		Through J3, after each pass (either in the main field area or in the headland area), a decision making takes place that determines if the combine has to turn (UOB6) and continue to harvest at a subsequent pass or should move to the unloading

		location (UOB5) for the unloading process (UOB8).
J4		The TU and the operator items are un-batched.
J5		A transport unit (according to the priority queue rule) is prepared for the combine unloading (UOB5).
J6		Through this junction, after a headland turning the combine either starts to harvest a new pass with reduced width (UOB4) or a new decision-making process takes place after junction J9
J7		Within UOB5 the combine travels the unloading location for the unloading process through J7. As soon as the transport unit is available at UOB7, both the combine and the transport unit are sent to J7. Through the junction J7, the activity ‘Combine is unloading’ (UOB8) takes place since the condition of at least one TU and the combine be available is fulfilled.
J8		The combine and the TU items are un-batched after the unloading process.
J9		This junction verify if there is still remaining passes to be harvested (then the combine has to start harvesting a new pass - UOB3) or not (then the simulation terminates – UOB18).
J10		This junction represents the condition for an empty wagon and an operator available for a TU to travel to the field.
J11		This junction determines if the TU should wait for a next unloading process (UOB13) or should travel back to the storage facilities (UOB12).
J12		Through this junction an available operator (UOB17) and a full loaded TU (through J11) are batched to travel back to the farm (UOB9).





99 (each time that the parameter is acquired) based on the statistical measures of the parameter. All modified  
100 parameters (e.g. current grain hopper space, harvested passes) were continuously updated and a time stamp  
101 assigned in each update. All time elements of the different tasks during the activity are allocated to the  
102 corresponding object (combine, operator, transport unit). After the completion of the activity all locked  
103 objectives are released.

104

### 105 **3. MATERIALS AND METHODS**

106 The data quantification and the simulation model validation were based on a series of field trials carried out at a  
107 paddy rice farm at Veneria Farm in Vercelli Province, Piedmont, Italy, where the “Vialone Nano” rice cultivar  
108 was cultivated. The average yield was 7 t ha<sup>-1</sup> (~ 5 t ha<sup>-1</sup> dry matter). All logistics tasks were monitored in four  
109 fields of various areas and distances from the storage facilities (Table 2). For all of the four fields for the  
110 logistics operations two transport units were implemented operated by one operator (Figure 2).

111

112 **Table 2 – The field area and the distance from the storage facilities of the four fields were field trials were carried**  
113 **out.**

<b>Field ID</b>	<b>Area (ha)</b>	<b>Distance (km)</b>
F 1	2.52	4.3
F 2	3.11	5.4
F 3	2.82	6.7
F 4	3.89	4.8

114

#### 115 **3.1 Data quantification**

116 For the input data quantification the measured data from F1 and F2 were used (the data from the other two fields  
117 were used for the model validation). During the field trials the following parameters were measured (measuring  
118 of speed elements regards the measurement of the travelled distance and the corresponding time):

- 119 - The working speed of the combine (in each individual segment)
- 120 - The turning time of the combine (for executing 90° turns and 180° turns)
- 121 - The in-field non-working travelling speed of the combine for reaching the unloading location

- 122 - The unloading time of the grain from the combine to the transport unit
- 123 - The travelling speed of the transport units for both cases of full and empty load
- 124 - The time for weighing the transport unit at the storage facilities
- 125 - The time required for the move of the transport unit from the weighing location to the elevator
- 126 - The time required for the unloading of the transport unit
- 127 - The time that the operators needed to move from one transport unit with empty trailer to the other one
- 128 with the full trailer

129

130



131

132

**Figure 2 – The machinery systems surveyed in the field trials**

133

### **3.2 Model validation**

134 The validation of the simulation model was based on the comparison of the simulated and measured output  
135 parameters on fields F3 and F4 using as input the quantified data from fields F1 and F2. The output parameters  
136 used for the validation were four selected performance indicators, namely the area capacity, the combine  
137 utilisation coefficient, the transport unit utilisation coefficient, and the manpower. It is worth noting that the real  
138 field area and the simulated one were not identical due the digitalisation of the latter. So, in addition the  
139 measured and the simulated field areas were compared.

### 140 3.3 Simulated experiments scenarios

141 A series of simulation experiments were carried out for the total area of the four fields (12.34 ha in total) using  
142 the task times and speed elements obtained from field trials and the operational features (operating width,  
143 combine's grain hopper capacity, and transport unit payload) of the machinery system used in the monitored  
144 physical operations.

145 Five transport unit – operator configurations were examined in all of the simulation experiments including:

146 1 transport unit – 1 operator (1TU-1O);

147 2 transport units – 1 operator (2TU-1O);

148 2 transport units – 2 operators (2TU-2O);

149 3 transport units – 2 operators (3TU-2O); and

150 3 transport units – 3 operators (3TU-3O).

151 In the first set of simulated experiments the five transport units – operators configurations and the field-to-  
152 storage facilities for values ranged between 1- 15 km with a step of 1 km) were used as independent values. The  
153 dependent values included:

154 a) the area capacity, which denotes the rate (area per time unit) that an agricultural machine performs its primary  
155 function,

156 b) the manpower requirements,

157 c) the utilisation coefficient of the combine, and

158 d) the utilisation coefficient of transport units.

159 The area capacity ( $\text{ha h}^{-1}$ ) represents the performance of the entire operational system. The manpower measure  
160 considered the man-hours required for an area unit ( $\text{h ha}^{-1}$ ) and expressed the average of the summation of the  
161 hours of each individual operator committed to the operation for the completion of the work in a one hectare  
162 area. The utilisation coefficient of the combine expressed the ratio between the active working time and the total  
163 operation time of the combine. Analogously, the transport unit utilisation coefficient expressed the ratio between  
164 the average active working time per transport unit and the total operation time. Both ratios were always less than  
165 1 since the total operating time includes non-working time elements of the combine that are: potential waiting  
166 times to be serviced by a transport unit, unloading times, headland turnings times, and other accessory times, and

167 non-working time elements for the transport units which potentially include the waiting times for the combine  
168 unloading and the queue times at the weighing location and the elevator availability at the storage location.

169 For all of the above mentioned simulation experiments the yield was assumed to be  $7 \text{ t ha}^{-1}$ .

170 The second set of the simulated experiments introduces as a third independent parameter the yield including  
171 values in the typical range of rice yield production in the specific area (from  $6 \text{ t ha}^{-1}$  up to  $9 \text{ t ha}^{-1}$  with a step of  $1$   
172  $\text{t ha}^{-1}$ ). The output parameters examined in this case were the area capacity and the material throughput capacity  
173 ( $\text{t ha}^{-1}$ ) as productivity measures.

174 The first set of simulated experiments included 75 scenarios (15 distances, 5 configurations) while the second  
175 group included 300 scenarios (15 distances, 5 configurations, 4 yield values). Each one of the scenarios in the  
176 simulation experiments was run for 100 repetitions where in each repetition the simulation model generates  
177 values for each one of the measured parameters randomly based on its mean value, the standard deviation value,  
178 and the distribution type, in order to cope with the stochastic nature of the measured parameters.

179 The last set of simulation experiments considered the effect of the reduced manpower to the timeliness of the  
180 operations. In field operations timeliness is defined as “*the ability to perform an activity at such a time that crop*  
181 *return is optimised considering quantity and quality of product*” (ASAE S495.1, 2005). The reduced manpower  
182 available could reduce the operating cost, but on the other hand it might increase the operating time (e.g. in the  
183 case where long field-to-storage distances are inherited resulting in higher bottlenecks). To that effect, it is  
184 reasonable to examine in the farm level if the proposed practice (for reduced manpower available) is feasible in  
185 terms of the timeliness restrictions.

186 The time available for harvesting a specific area  $A$  (ha) is a function of the harvesting period  $p$  (d), that is  
187 related to the crop maturity, the workability coefficient  $w$ , connected with the weather condition, and the  
188 working hours per day  $t$  (h). Given this time availability, the area capacity,  $C$  ( $\text{ha h}^{-1}$ ), should comply with the  
189 constraint:

190 
$$C \geq \frac{A}{p \times w \times t}$$

191 This results to the requirement that the ratio:

192 
$$e = \frac{C}{C_0},$$

193 where  $C_o$  (ha h<sup>-1</sup>) represents the processed field area per time unit which corresponds to the net harvesting time  
194 and the accessory times<sup>1</sup>, should be higher than a threshold value:

$$195 \quad e \geq e^* = \frac{A}{C_o \times p \times w \times t}$$

196 It is worth noting that one would expect that since the time unit in the area capacity measure does not include  
197 bottleneck times, which are depended from the transport units – operators configuration, the area capacity should  
198 be a constant number for a specific combination of the combine’s operating features, and thus the same for all  
199 transport unit–operator configurations. However, the transport unit–operator configuration affect the operating  
200 time since transport units cycle times (which are affected by the configuration) affect the implementation of the  
201 harvesting with reduced width practice. Consequently, the threshold  $e^*$  is a function also of the transport units-  
202 operators configurations. The specific scenario regards the harvesting of an area  $A=215$  ha of the farm. This is  
203 actually the area that is allocated to one combine harvester. For the specific area, the harvesting period is  $p=45$   
204 d, with a workability coefficient  $\alpha=0.6$ , and  $t=6$  working hours per day (Bodria, Pellizzi, & Piccarolo, 2006).  
205 The area of the fields that contains the specific area has an average of 3.2 ha with an average distance of 7 km  
206 from the storage facilities.

207 For all the above mentioned experiments and for the simulation instances where the number of the transport  
208 units equals to the number of the corresponding operators (i.e. 1TU-1O, 2TU-2O, and 3TU-3O) the version of  
209 the model described in Busato (2015) was implemented.

210

## 211 **4. RESULTS AND DISCUSSION**

### 212 **4.1 Data quantification**

213 **The data on the recorded operational parameters for the field trials at fields F1 and F2, are listed in**

214

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<sup>1</sup>  $1-e$  represents the percentage of the bottlenecks time (due to the transport unit unavailability at the unloading location)

217 Table 3. The BestFit software (that is integrated in the ExtendSim® software package) was implemented for the  
 218 extraction of the statistical parameters for the recorded data

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223

**Table 3 – Measured parameters from field trials**

<b>Parameter</b>	<b>Number of observations</b>	<b>Best fit statistical distribution</b>	<b>Mean</b>	<b>Standard deviation</b>
Combine working speed on passes (km h <sup>-1</sup> )	62	Normal	3.85	0.76
Combine working speed on headlands (km h <sup>-1</sup> )	18	Lognormal	2.32	1.40
Combine turning time for a 90° turn (min per turn)	24	Lognormal	0.24	0.30
Combine turning time for a 180° turn (min per turn)	30	Lognormal	0.28	0.45
Combine in-field travelling speed (km h <sup>-1</sup> )	21	Lognormal	5.13	1.34
Combine unloading time (min)	12	Lognormal	1.76	0.8
Transport unit travelling speed with empty wagon (km h <sup>-1</sup> )	6	Normal	27.6	2.32
Transport unit travelling speed with full wagon (km h <sup>-1</sup> )	6	Normal	29.7	3.41
Weighting time at storage facilities (min)	6	Lognormal	1.25	0.82
Time to move from the weighing station to the unloading location*	6	Lognormal	4.1	3.82

(min)				
Transport unit unloading time (min)	6	Lognormal	0.81	1.24
Operator's time for vehicle change	5	Lognormal	1.98	1.35

224 \* Including the time for positioning

## 225 4.2 Model validation

226 As mentioned previously, the validation of the simulation model was based on the comparison of the simulated  
 227 and measured output parameters on fields F3 and F4. For the simulation of the operation in these fields the  
 228 quantified data from fields F1 and F2 were used (as listed in Table 3). All other parameters including, field  
 229 shape, field size, crop yield, and filed-to-storage distances, were the measured values for fields F3 and F4. One  
 230 hundred (100) simulation runs took place for each field. The average simulated output validation parameters, the  
 231 measured ones, and the absolute error between simulated and measured are presented in Table 4. In this case the  
 232 simulations implement the configuration with 2 transport units – 1 operator (2TU-1O) which was the one  
 233 implemented in the physical operations in the field trials.

234 **Table 4 – Comparison between the measured and the simulated output parameters**

Parameter		F 3	F 4
Area capacity	Measured (ha h <sup>-1</sup> )	1.34	1.53
	Simulated (ha h <sup>-1</sup> )	1.37	1.56
	Abs. error (%)	<b>2.2</b>	<b>2.0</b>
Combine utilisation	Measured	0.89	0.96
	Simulated	0.92	0.98
	Abs. error (%)	<b>3.4</b>	<b>2.1</b>
Transport units utilisation	Measured	0.52	0.51
	Simulated	0.51	0.50
	Abs. error (%)	<b>1.9</b>	<b>2.0</b>
Manpower utilisation	Measured	1.52	1.32
	Simulated	1.46	1.28
	Abs. error (%)	<b>3.9</b>	<b>3.0</b>

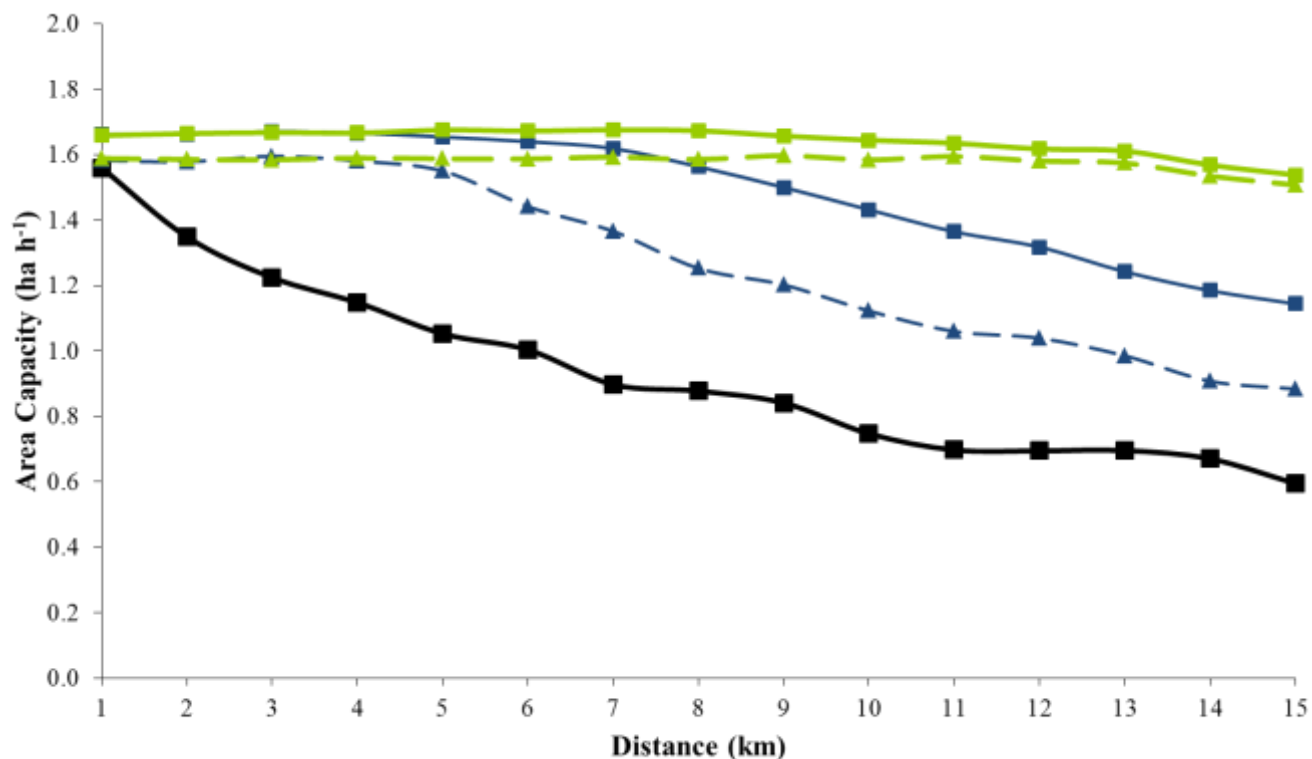


	Actual (m <sup>2</sup> )	28,200	38,920
Area	Simulated (m <sup>2</sup> )	28,460	38,820
	Abs. error (%)	<b>0.9</b>	<b>0.3</b>

235

236

### 4.3 Scenarios simulation and analysis



237

238 **Figure 3 - Area capacity for various field-to-storage distances for the selected TUs-operators configurations, yield 7 t**  
 239 **ha<sup>-1</sup>. (TU: transport unit(s); O: operator(s)). Legend: ■ 1TU-1O; ▲ 2TU-1O; ■ 2TU-2O; ▲ 3TU-2O;**

240

■ 3TU-3O

241

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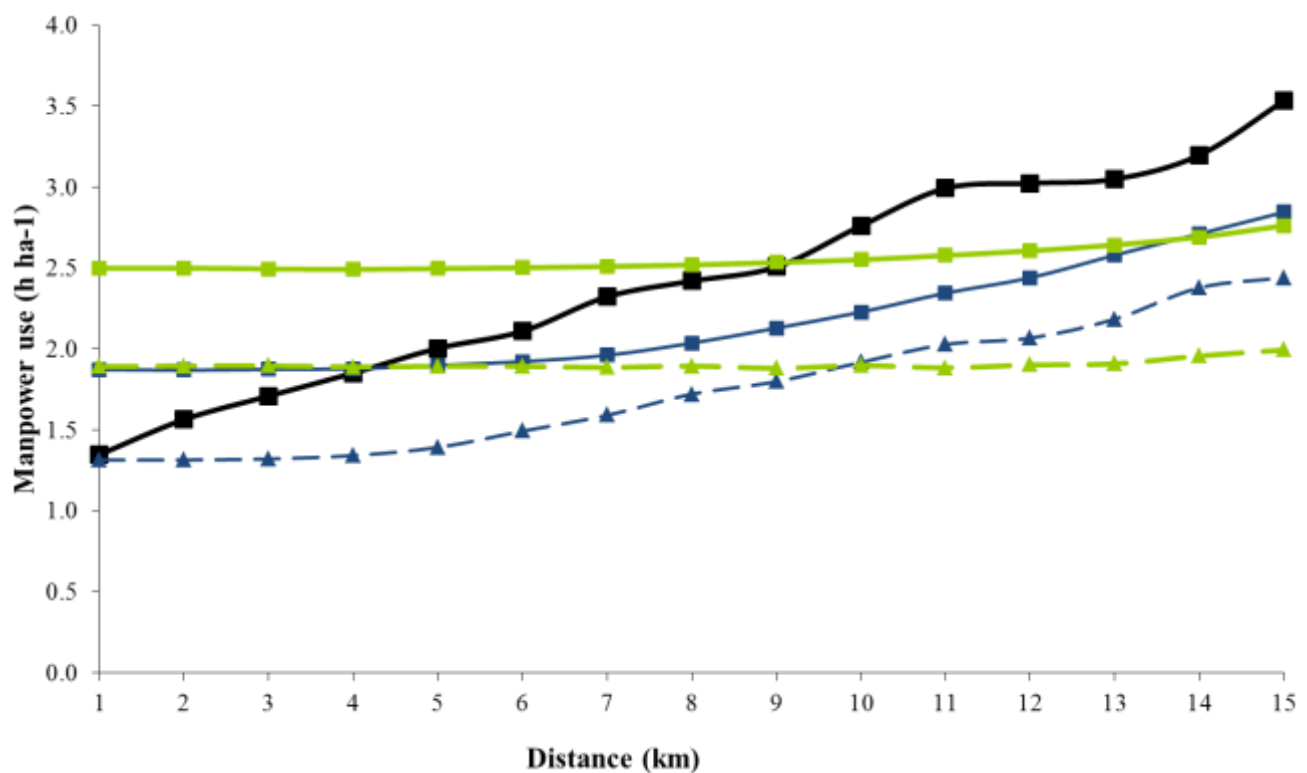
243

244 Figure 3 presents the area capacity (for the combine and also for the whole system) for the five selected  
 245 configurations and various field-to-storage distances. It is clear, as it was expected, that the configuration 3TU-

246 30 results to the higher capacity for all examined distances. It can be seen also that the area capacity decreases  
 247 as the transport distance increase and the transport units available could not provide enough transport capacity  
 248 for the combine. This occurs at 4 km for the scenario 2TU-2O and at 8 km for the scenario 3TU-3O. The  
 249 reduced manpower available in scenario 2TU-1O is a limiting factor for the transport capacity and distances  
 250 above 4 km, and the decrease in the area capacity is very steep. The configuration 3TU-2O although that allows  
 251 manpower savings, results to an area capacity that is reduced slightly compared to 3TU-3O.

252

253



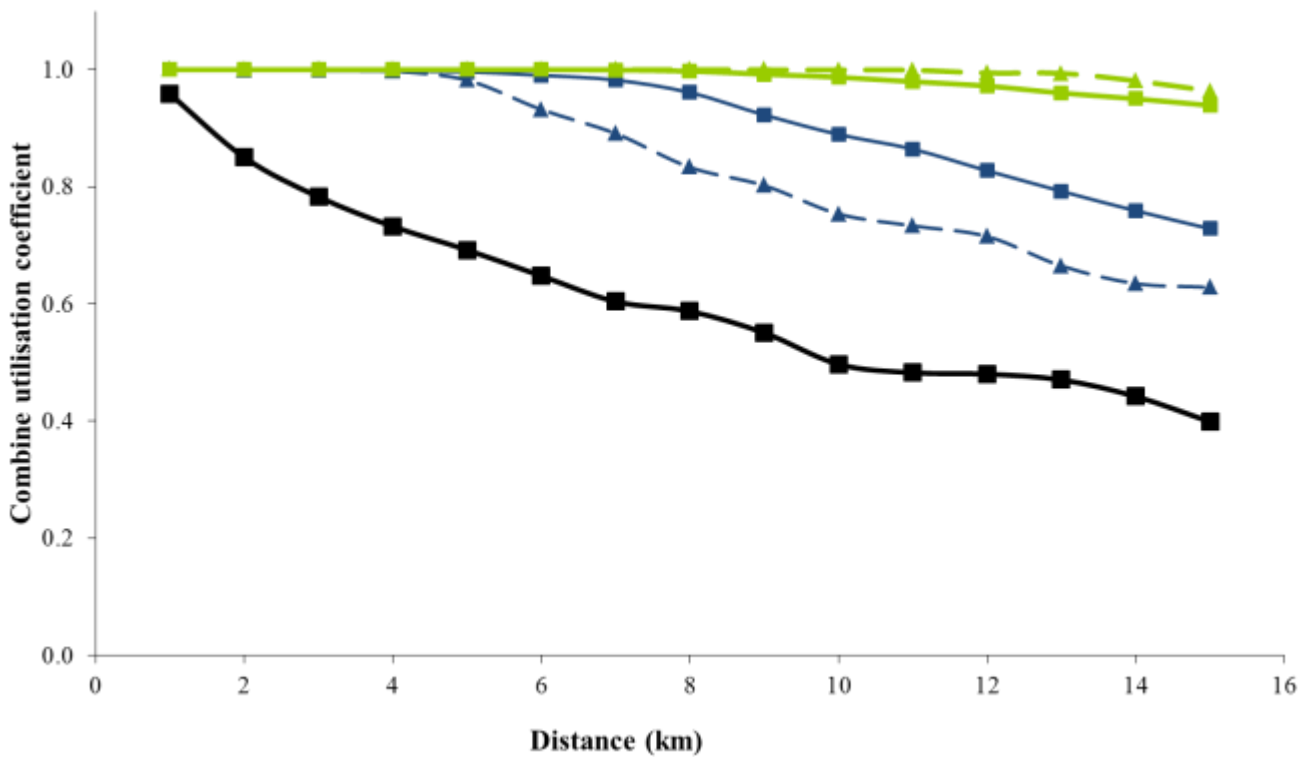
254

255 **Figure 4 – Manpower per area unit requirements for various distances between the field and the storage facilities for**  
 256 **the selected transport units-operators configuration. Legend: ■ 1TU-1O; ▲ 2TU-1O; ■ 2TU-2O; ▲**  
 257 **3TU-2O; ■ 3TU-3O**

258

259 Figure 4 presents the total manpower use per area unit (including the combine operator and the TUs operators)  
 260 and also considering the idle times of the operator(s) for the five selected configurations and various field-to-

261 storage distances. As can be seen in Figure 4 there are high reductions in the required manpower use when less  
 262 operators than the number of TUs are implemented in the operation. Specifically, there is an average reduction  
 263 of 20% (min 12% - max 30%) for the various distances when the configuration 2TU-1O is implemented  
 264 compared to the 2TU-2O configuration, and an average reduction of 22% (min 20% - max 23%) for the various  
 265 distances when the configuration 3TU-2O is implemented compared to the 3TU-3O configuration.  
 266

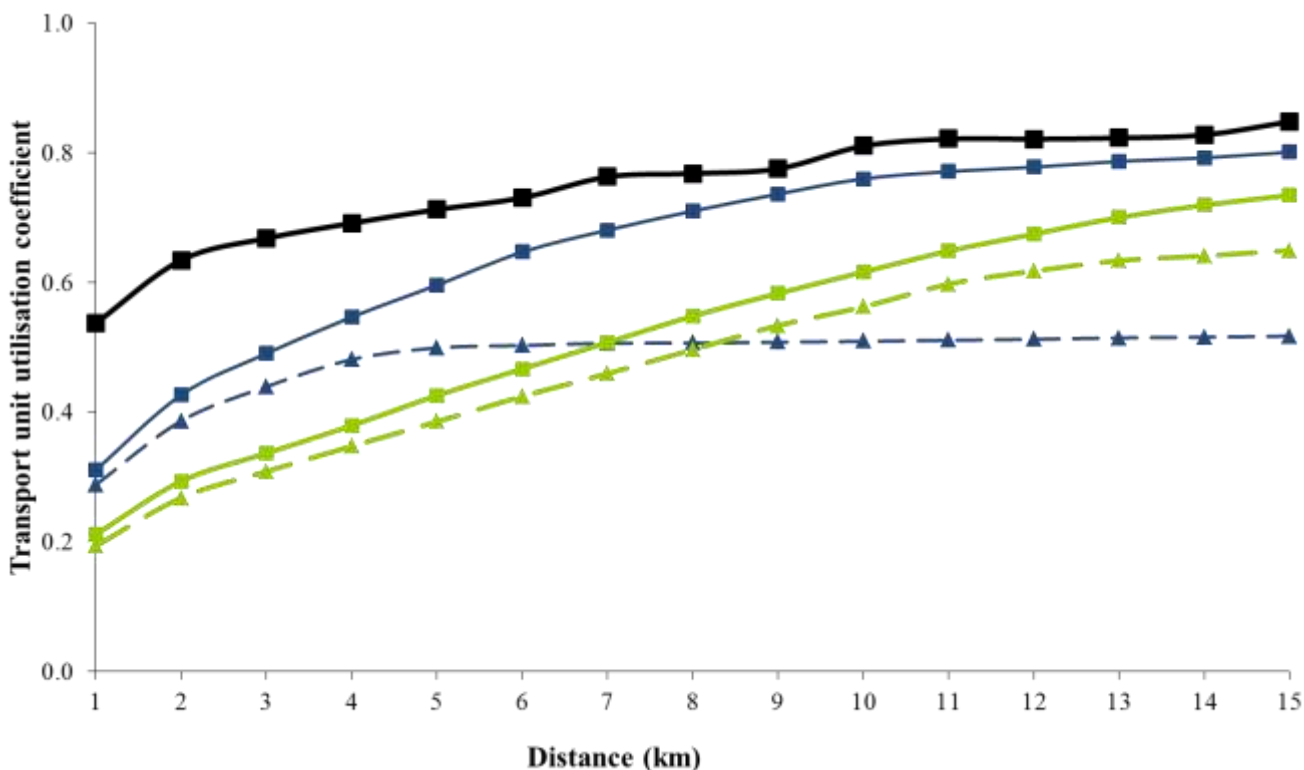


267  
 268 **Figure 5 – Combine utilisation coefficient for various field-to-storage distances for the selected transport units-**  
 269 **operators configuration. Legend: ■ 1TU-1O; ▲ 2TU-1O; ■ 2TU-2O; ▲ 3TU-2O; ■ 3TU-3O**  
 270

271 Figure 5 presents the combine utilisation coefficient for the five selected configurations and various distances  
 272 between the field and the storage facilities location. A coefficient of value equal to 1 means that there are no  
 273 waiting times for the combine and occurs up to 9 km for the configurations 3TU-2O and 3TU-3O, up to 4 km for  
 274 configuration 2TU-1O, and 5 km for the configuration 2TU-2O.

275 For high distances (beyond 10 km) the combine utilisation is higher in the case of 3TU-2O compared to the case  
 276 of 3TU-3O although the bottlenecks times are higher. This is due the fact that in the former configuration the  
 277 increased occurrence for non-availability of a TU at the unloading location forces the combine to harvest with  
 278 reduced width and thus increasing the time that it operates. This is not true for the rest of the cases since due to  
 279 the higher bottlenecks duration the combine's grain hopper is getting full and there is no more the option of  
 280 harvesting with reduced width and consequently the harvesting operation is interrupted.

281



282

283 **Figure 6 – Transport units utilisation coefficient for various field-to-storage distances for the selected transport**  
 284 **units-operators configuration. Legend: —■— 1TU-1O; —▲— 2TU-1O; —■— 2TU-2O; —▲— 3TU-2O; —■— 3TU-**  
 285 **3O**

286

287 **Figure 6 presents the transport units utilisation coefficient for various distances and for the selected system's**  
 288 **configurations. It can be seen that the transport units utilisation coefficient deviates of the general trend for**  
 289 **distances longer than 5 km and remains constant with a value of approximately 0.5. The explanation on this comes**  
 290 **from the fact that there is one operator for the two available transport units and when the distance between the field**

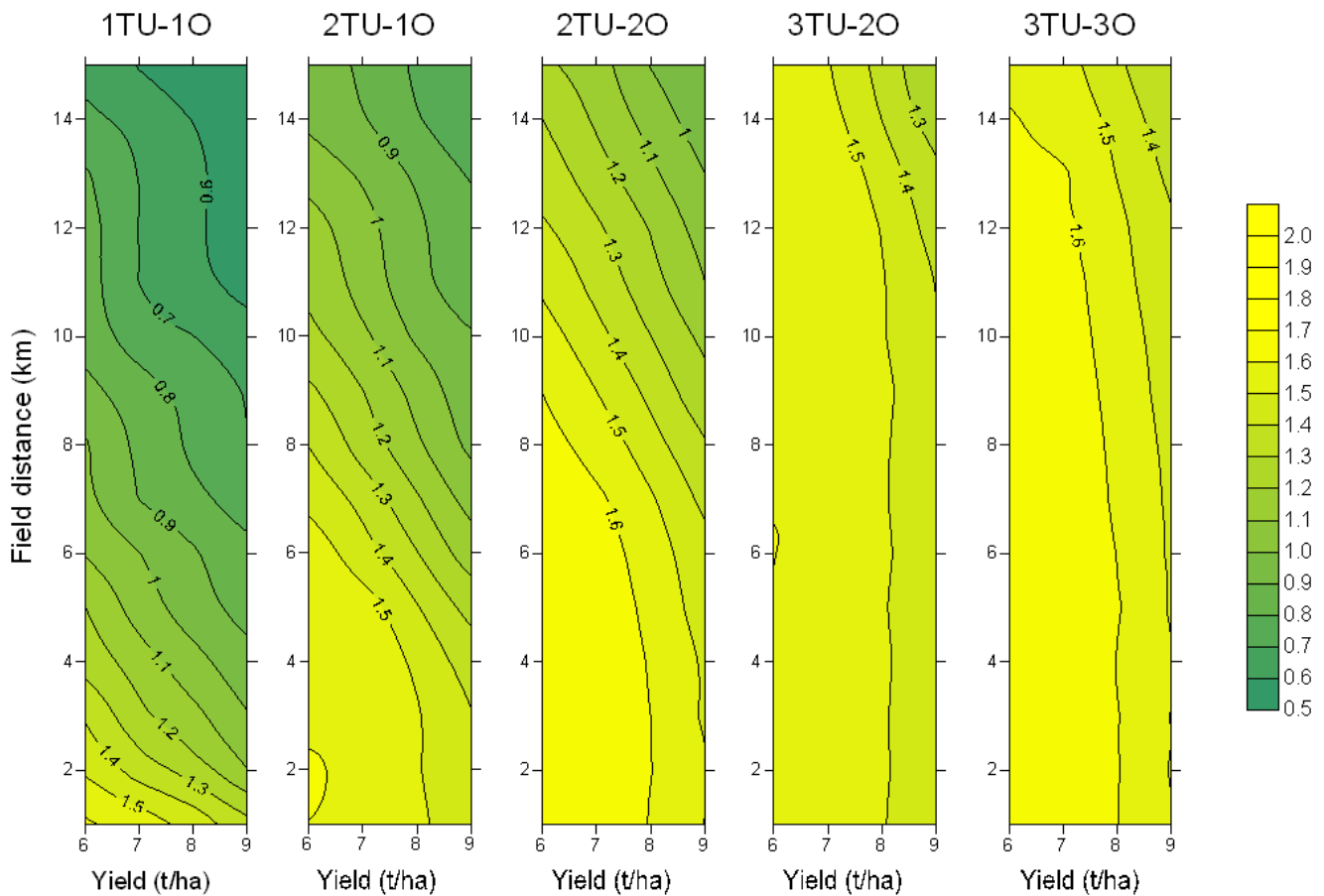
291 and the storage facilities increases, and consequently the travelling times increase, the operator, and consequently  
 292 only one of the two trailers, is continuously utilised in the operation. The only time that in this case two transport  
 293 units are utilised simultaneously is when the combine unloads on the unit that is not operated from the operator.  
 294 However, this utilisation time is compensated by the time spent by the operator for moving from one transport  
 295 unit to the other, since both time elements have similar values (1.98 min and 1.76 min in average, respectively,

296

297

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299 Table 3).

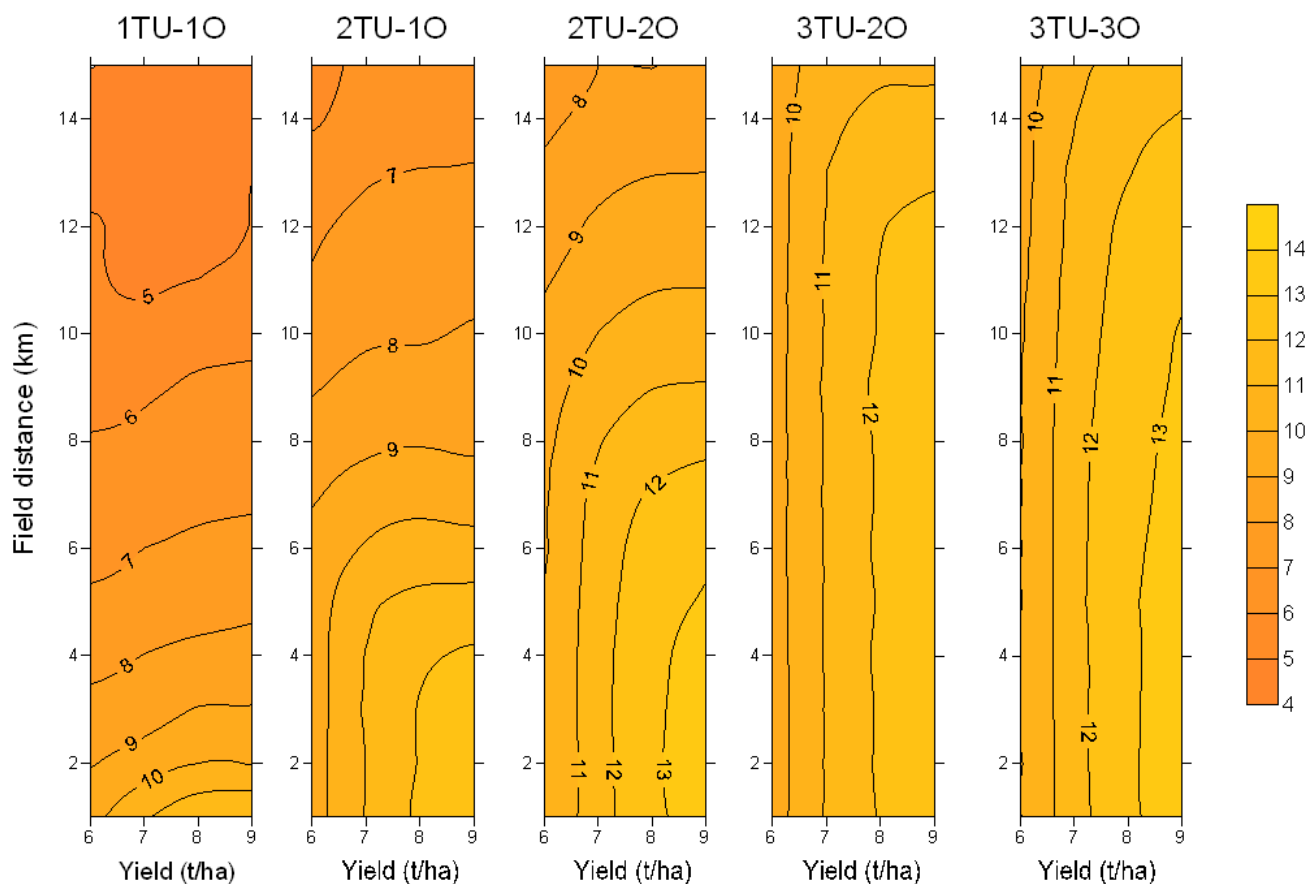


300

301 **Figure 7 – The area capacity (ha h<sup>-1</sup>) for different yields and different distances between the field and the storage**  
 302 **facilities for the five selected transport units – operators configurations**

303

304 Figure 7 presents the area capacity for the selected configurations and various field-to-storage distances and crop  
 305 yields. The higher area capacity (i.e.  $1.68 \text{ ha h}^{-1}$ ) corresponds to the case of 3TU-3O and for the lower values of  
 306 the yield and distance. Correspondingly, the lower area capacity ( $0.59 \text{ ha h}^{-1}$ ) corresponds to the case of the 1TU-  
 307 1O and for the higher values of yield and distance. As it can be seen from the figure, when transport capacity is a  
 308 limiting factor the area capacity is sensitive in both distance and yield. When this limitation is softened  
 309 compared to the harvesting capacity (e.g. in the configuration 3TU-3O) the area capacity is sensitive almost  
 310 exclusively to yield.



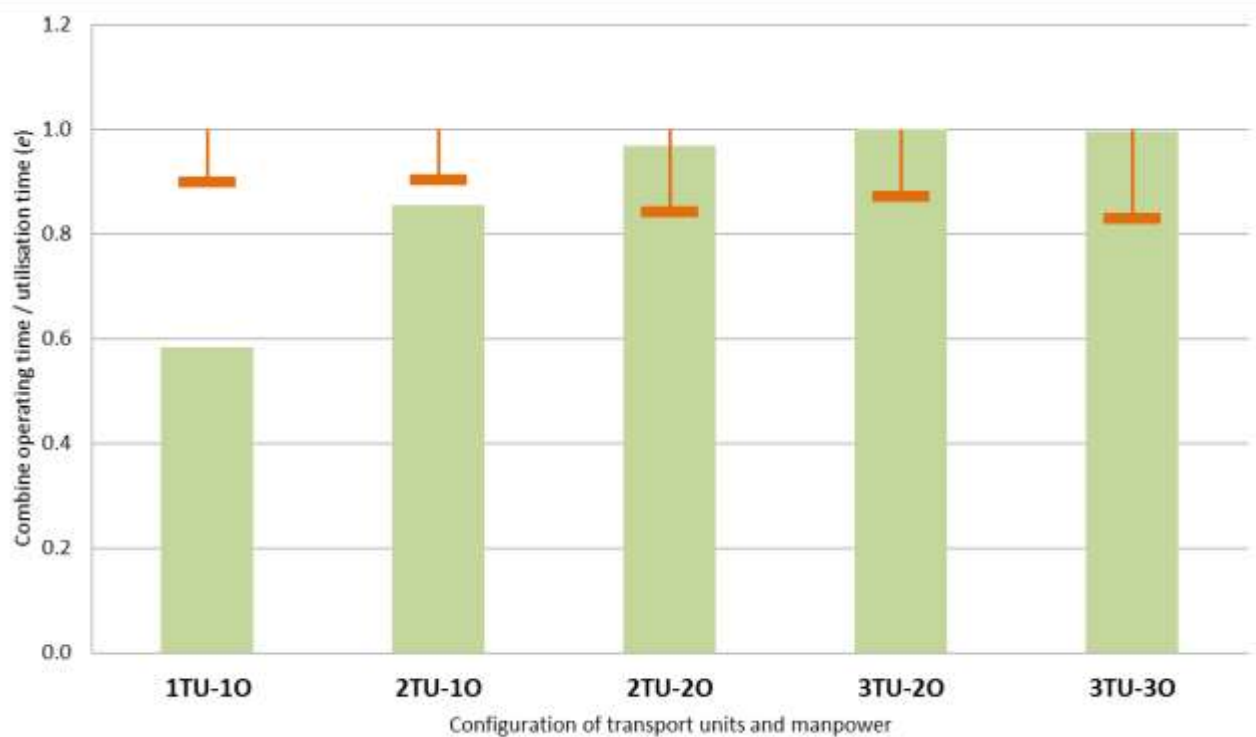
311  
 312 **Figure 8 - The material throughput capacity ( $\text{t h}^{-1}$ ) for different yields and different distances between the field and**  
 313 **the storage facilities for the five selected transport units – operators configurations**

314  
 315  
 316 Figure 8 presents the material throughput for the selected configurations and various yields and distances  
 317 between the field and the storage facilities. The minimum value ( $3.97 \text{ t h}^{-1}$ ) corresponds to configuration 1TU-

318 1O for the longest distance (15 km) and the highest yield (9 t ha<sup>-1</sup>), while the maximum value (13.55 t h<sup>-1</sup>)  
319 corresponds to configuration 3TU-3O for the shortest distance (1 km) and the lowest yield (6 t ha<sup>-1</sup>).

320 For the case of 1TU-1O the material throughput is affected mainly of the field distance rather than the yield  
321 (horizontal trend of the contour lines), while this trend is reversed when moving to systems of higher capacity  
322 with the case of 3TU-3O configuration where the material throughput is affected mainly by the yield (vertical  
323 trend in the contour lines), similarly to what seen in the area capacity, but with different shapes of the curves in  
324 the chart.

325



326

327 **Figure 9 – The ratio between the combine operating time and utilisation time (*e*) in comparison with its threshold**  
328 **value (*e\**) for a timely harvesting of the whole farm area for the selected configurations**

329 Figure 9 presents the actual and the threshold value for the combine utilisation in the case study area, for the  
330 yield of 7 t.ha<sup>-1</sup>. As can be seen in Figure 9, the threshold value is different for each configuration, as explained  
331 in section 3.3. This reveals the importance of the simulation tool compared to the case that average norms are  
332 used for the computing various operating time elements. The configurations 1TU-1O and 2TU-1O do not cope  
333 with workability requirements for the specific area configuration and region. In the cases of 2TU-2O, 3TU-2O,

334 and 3TU-3O the difference between the  $e$  and  $e^*$  represents the tolerance of the logistics system towards worst  
335 weather conditions, in terms of workability, compared to the expected according to historical data.

## 336 **5. CONCLUSIONS**

337 A model was developed for the simulation of rice harvesting and logistics operations which implements the practice where  
338 the number of transport units' operators is lower than the number of the transport units. It was shown that the  
339 implementation of this practice can potentially reduce the required manpower use. For the specific transport units –  
340 operators configurations examined in this work, the reduction of manpower use ( $\text{h ha}^{-1}$ ) for various distances was in the  
341 range of 12% to 30%.

342 The presented model can be used as a decision support system for capacity planning and specifically for the  
343 selection of the machinery system and manpower required for crops harvesting and transport operations taking  
344 account also the timeliness factor. In the presented work, in order to evaluate the performance of each  
345 configuration in a large-scale harvesting operation (in a farm area of 215 ha), each one of the selected transport  
346 unit-operator configurations was applied uniformly in all of the fields constituting the whole area. However it is  
347 expected that the implementation of different configurations in different fields could provide an optimal capacity  
348 plan. This can be achieved by combining the simulation model with an analytical optimisation process, e.g.  
349 linear programming where the decision variables are the TU-O configuration for each individual field that  
350 maximises the area capacity of the whole large scale harvesting system. This is a topic for future research.  
351 Furthermore, the incorporation of cost and energy measures in the simulation, in addition to time, could provide  
352 a complete decision making tool for capacity planning for rice harvesting and transport operations.

353 Finally, although the presented work considered rice harvesting, the presented tool can be implemented in all  
354 cases of harvesting where the unloading process takes place outside of the main field area, including the case of  
355 harvesting under controlled traffic farming and any crop harvesting where soil compaction restrictions do not  
356 allow for on-the-go in-field unloading.

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