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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 (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 resources in agricultural production and, especially, of human resources of high specialisation (e.g. operators of contemporary farm machinery), requires an effective decision making process for resource allocation to the various tasks involved in field operations (Guan, Nakamura, Shikanai, & Okazaki, 2009), as well as for the optimal execution of the field operations (Dionysis D. Bochtis, Sørensen, Busato, & Berruto, 2013; Zhou, Leck Jensen, Sørensen, Busato, & Bothtis, 2014). To that effect, manpower is a required input in decision support systems developed for various agricultural machinery management levels (Dionysis D. Bochtis et al., 2014) including, task times planning (Buckmaster & Hilton, 2005; Busato & Berruto, 2014; Sopegno et al., 2016; Sørensen, Halberg, Oudshoorn, Petersen, & Dalgaard, 2014) capacity planning (de Toro & Hansson, 2004; Gunnarsson, Spörndly, Rosenqvist, de Toro, & Hansson, 2009), and scheduling (D.D. Bochtis et al., 2013; Orfanou et al., 2013). In large scale operations, such as crop or biomass harvesting and transport 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 cost occurrence.

The work presented here deals with the operational practice in crop harvesting and transport operations according which the operators are fewer in number than the number of the machines/vehicles involved in the operation, either due to operator unavailability or due to cost reduction measures. This paper is the continuation of the work presented in Busato (2015) where the development of a simulation tool targeted to rice-harvesting and transport operations was presented. Logistics operations for rice are more complex compared to other grain crops due to the trafficability constraints. The muddy soil during the harvesting period does not allow for in-field (on-the-go or stationary) unloading of the combine to the transport units and this process has to take place when the combine is (stationary) on the headland area. Furthermore, the irrigation system (irrigation channels) used in rice production does not allow the access of the transport unit to one of the two field headlands, thereby placing another operational restriction. The irrigation system also limits the size of the fields used for rice cultivation which is typically 2-6 ha. To that effect, rice farms include numerous small dispersed fields that require various cycle times for the transport units within the logistics system. Finally, the practice of harvesting with reduced width makes harvesting operation a complex process in terms of decision making. Harvesting with reduced width in a field-work track takes place when the remaining capacity of the grain hopper is not sufficient for the crop to be harvested if the entire width of the header is implemented. Busato (2015) found that the capacity of the harvesting system can be increased as much as 7% by the implementation of the above mentioned practice. The simulation model developed in Busato (2015) incorporates all the above mentioned operational features unique to rice harvesting. In this paper, this simulation model is extended to include different ways to manage the manpower operating the transport units. Specifically, the practice where the transport units are operated by one less operator is implemented. During this type of process an operator leaves a transport unit at the designated unloading location and drives back to the delivery location a full transport unit left by another operator (or the same in the case that only one operator is used for the transportation task). The objectives of this paper were 1) define the logistics system’s components and their interaction, 2) extend the simulation model presented in Busato (2015) to describe the practice by adding functional modules to the existing simulation model, 3) conduct an evaluation of the various configurations of the system in terms of defined performance measures, and 4) evaluate manpower required for crops harvesting and transport operations taking account also the timeliness factor.

2. DEVELOPMENT OF THE MODEL

2.1 Work process modelling

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

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

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-stars 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 ant 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).

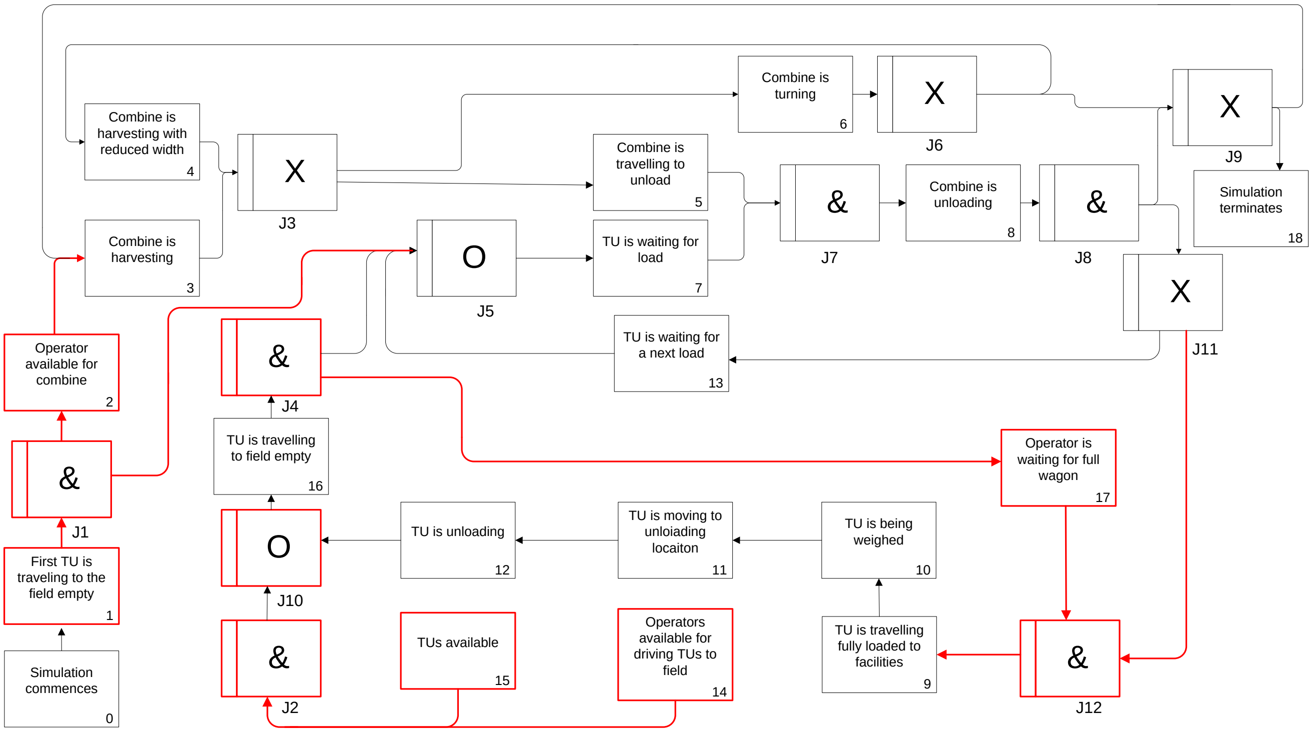

Figure 1 - IDEF process diagram of the rice harvest model. The part of the diagram in black represents the previous model developed in Busato (2015) while the part in red represents the description of the reduced number of operators practice. (TU: transport unit). For the IDEF0 junctions, asynchronous AND (&): all of the preceding (following) activities must be completed (begin); asynchronous OR (O): one or more of the preceding (following) activities must be completed (begin); exclusive OR (X): exactly one preceding (following) activity is completed (begins).

2.2 Simulation model

The ExtendSim® (Imagine That Corporation, San Jose, CA, USA) software was implemented for the development of the simulation model. The model has been connected with a Microsoft Access® database for the insertion of the input parameters and the presentation of the results. In total the model required 592 blocks (both pre-built and customised ExtendSim® blocks) from different types of libraries including discrete event, value, and tools libraries. The field area was decomposed to linear segments (corresponding to field-work tracks and headland passes) generated dynamically and characterised by a series of properties, including the current operating width, length, and the direction of harvest. For the stochastic parameters a random value was generated (each time that the parameter is acquired) based on the statistical measures of the parameter. All modified parameters (e.g. current grain hopper space, harvested passes) were continuously updated and a time stamp assigned in each update. All time elements of the different tasks during the activity are allocated to the corresponding object (combine, operator, transport unit). After the completion of the activity all locked objectives are released.

3. MATERIALS AND METHODS

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

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

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

3.1 Data quantification

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

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

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

Figure 2 – The machinery systems surveyed in the field trials

3.2 Model validation

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

3.3 Simulated experiments scenarios

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

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

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

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

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

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

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

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

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

b) the manpower requirements,

c) the utilisation coefficient of the combine, and

d) the utilisation coefficient of transport units.

The area capacity (ha h^{-1}) represents the performance of the entire operational system. The manpower measure considered the man-hours required for an area unit (h ha^{-1}) and expressed the average of the summation of the hours of each individual operator committed to the operation for the competition of the work in a one hectare area. The utilisation coefficient of the combine expressed the ratio between the active working time and the total operation time of the combine. Analogously, the transport unit utilisation coefficient expressed the ratio between the average active working time per transport unit and the total operation time. Both ratios were always less than 1 since the total operating time includes non-working time elements of the combine that are: potential waiting times to be serviced by a transport unit, unloading times, headland turnings times, and other accessory times, and non-working time elements for the transport units which potentially include the waiting times for the combine unloading and the queue times at the weighing location and the elevator availability at the storage location.

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

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

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

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

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

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

This results to the requirement that the ratio:

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

where C_o (ha h^{-1}) represents the processed field area per time unit which corresponds to the net harvesting time and the accessory times[1], should be higher than a threshold value:

$$e \geq e^{*} = \frac{A}{C_0 \times p \times w \times t}$$

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

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

4. RESULTS AND DISCUSSION

4.1 Data quantification

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

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[1] 1-*e* represents the percentage of the bottlenecks time (due to the transport unit unavailability at the unloading location)

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

Table 3 – Measured parameters from field trials

Parameter	Number of observations	Best fit statistical distribution	Mean	Standard deviation
Combine working speed on passes (km h^{-1})	62	Normal	3.85	0.76
Combine working speed on headlands (km h^{-1})	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^{-1})	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^{-1})	6	Normal	27.6	2.32
Transport unit travelling speed with full wagon (km h^{-1})	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

* Including the time for positioning

4.2 Model validation

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

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

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

Area	Actual (m^2)	28,200	38,920
	Simulated (m^2)	28,460	38,820
	Abs. error (%)	**0.9**	**0.3**

4.3 Scenarios simulation and analysis

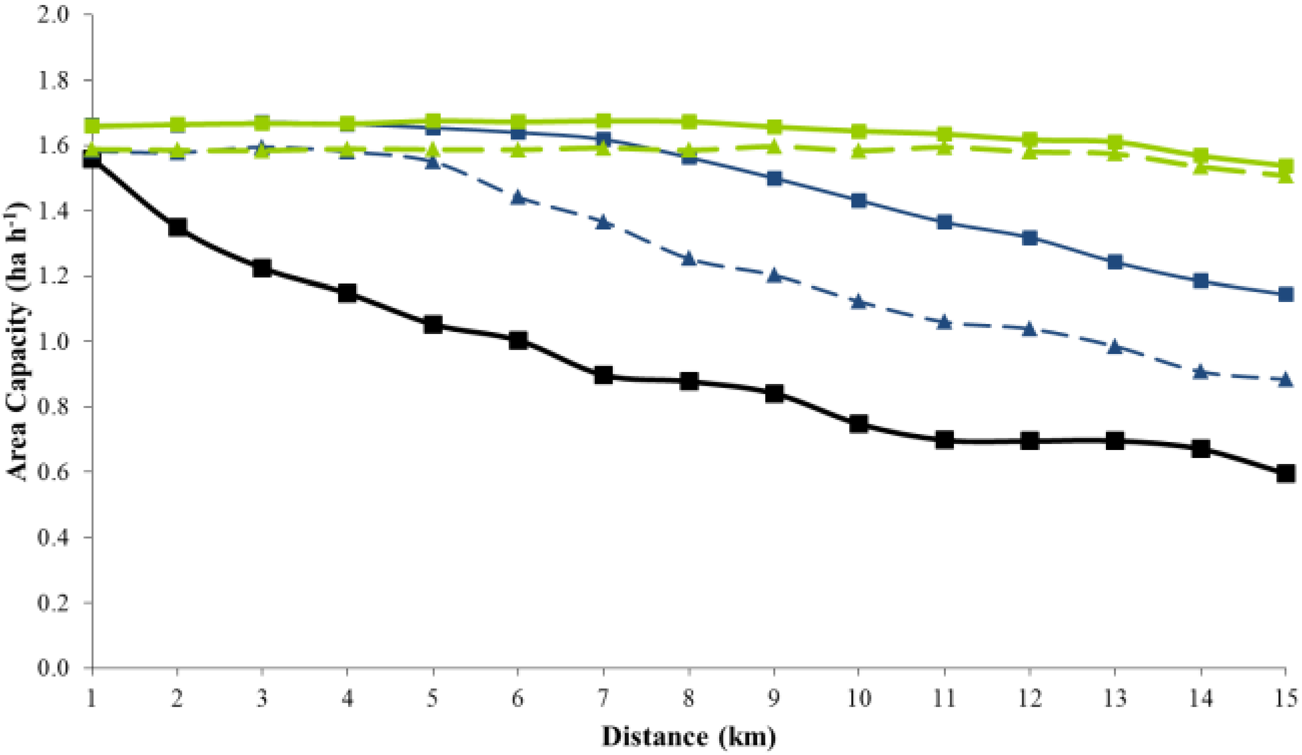

Figure 3 - Area capacity for various field-to-storage distances for the selected TUs-operators configurations, yield 7 t ha^{-1}. (TU: transport unit(s); O: operator(s)). Legend: ━■━1TU-1O; ━▲━ 2TU-1O; ━■━ 2TU-2O; ━▲━ 3TU-2O; ━■━ 3TU-3O

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

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

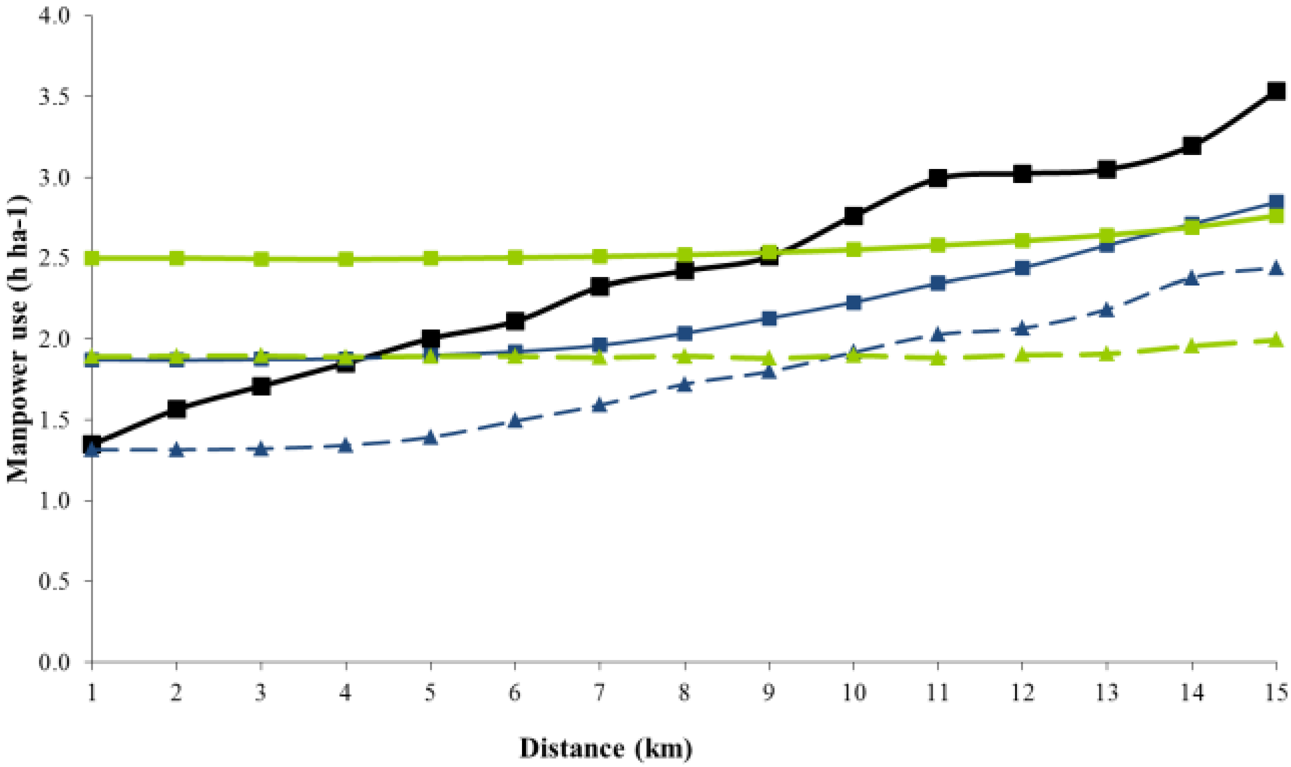

Figure 4 – Manpower per area unit requirements for various distances between the field and the storage facilities for the selected transport units-operators configuration. Legend: –■– 1TU-1O; –▲– 2TU-1O; –■– 2TU-2O; –▲– 3TU-2O; –■– 3TU-3O

Figure 4 presents the total manpower use per area unit (including the combine operator and the TUs operators) and also considering the idle times of the operator(s) for the five selected configurations and various field-to-storage distances. As can be seen in Figure 4 there are high reductions in the required manpower use when less operators than the number of TUs are implemented in the operation. Specifically, there is an average reduction of 20% (min 12% - max 30%) for the various distances when the configuration 2TU-1O is implemented compared to the 2TU-2O configuration, and an average reduction of 22% (min 20% - max 23%) for the various distances when the configuration 3TU-2O is implemented compared to the 3TU-3O configuration.

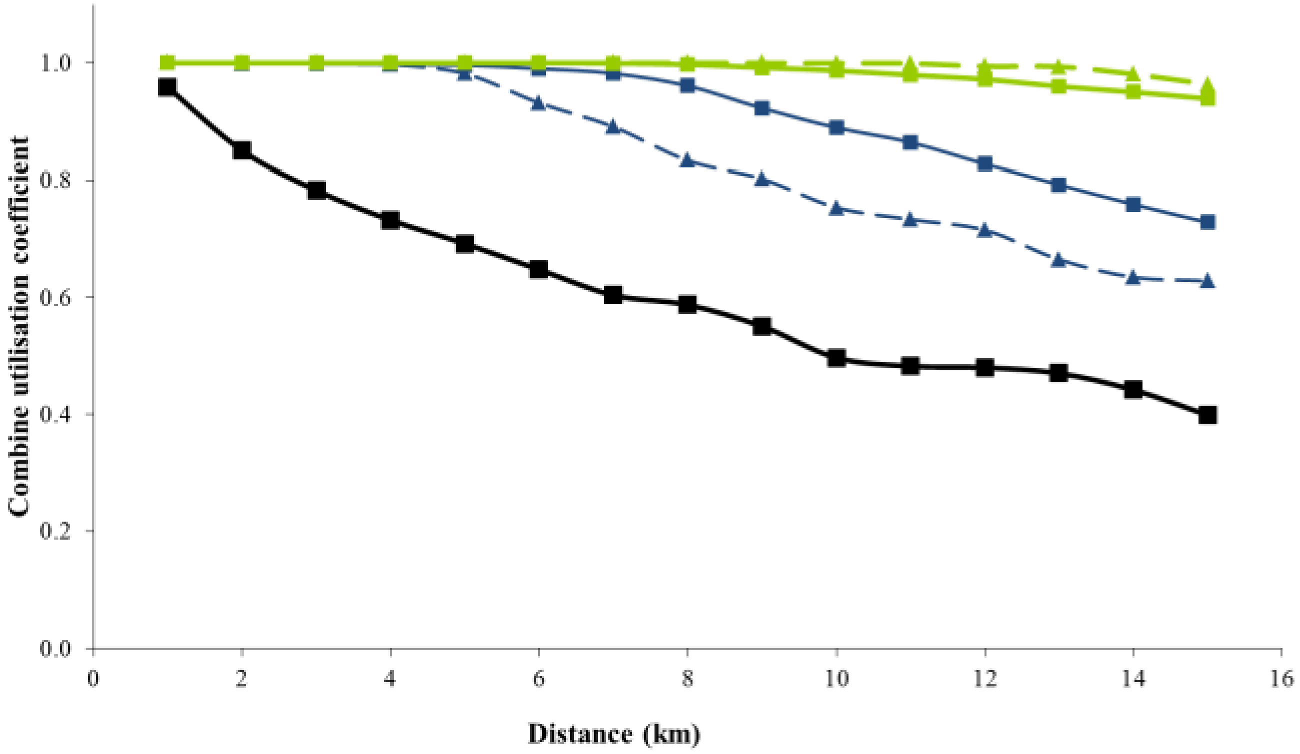

Figure 5 – Combine utilisation coefficient for various field-to-storage distances for the selected transport units-operators configuration. Legend: —■— 1TU-1O; –▲– 2TU-1O; —■— 2TU-2O; —▲— 3TU-2O; —■— 3TU-3O

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

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

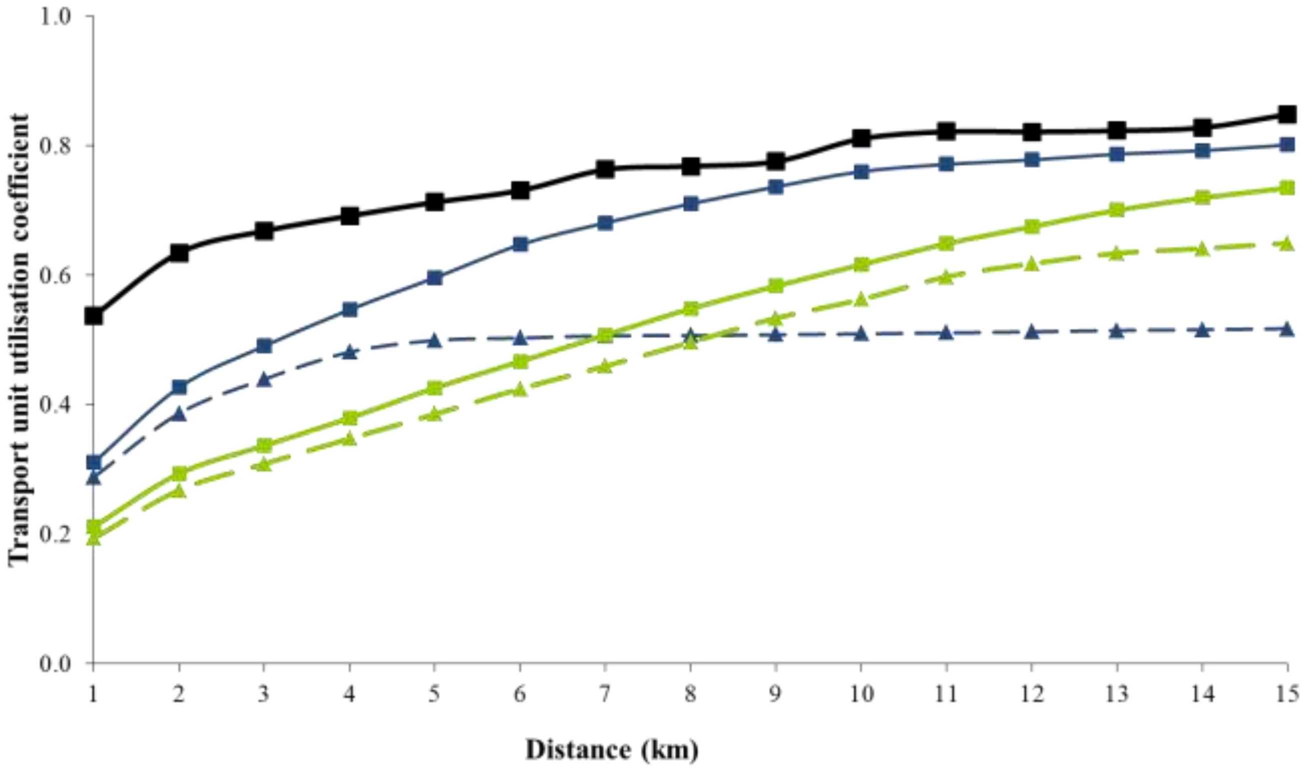

Figure 6 – Transport units utilisation coefficient for various field-to-storage distances for the selected transport units-operators configuration. Legend: ■ 1TU-1O; ▲ 2TU-1O; ■ 2TU-2O; ▲ 3TU-2O; ■ 3TU-3O

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

and the storage facilites increases, and consequently the travelling times increase, the operator, and consequenlty only one of the two trailers, is continuously utilised in the operation. The only time that in this case two transport units are utilised simultanesusly is when the combine unloads on the unit that is not operated from the operator. However, this utilisation time is compensated by the time spended by the operator for moving from one transport unit to the other, since both time elements have similar values (1.98 min and 1.76 min in average, respectively, Table 3).

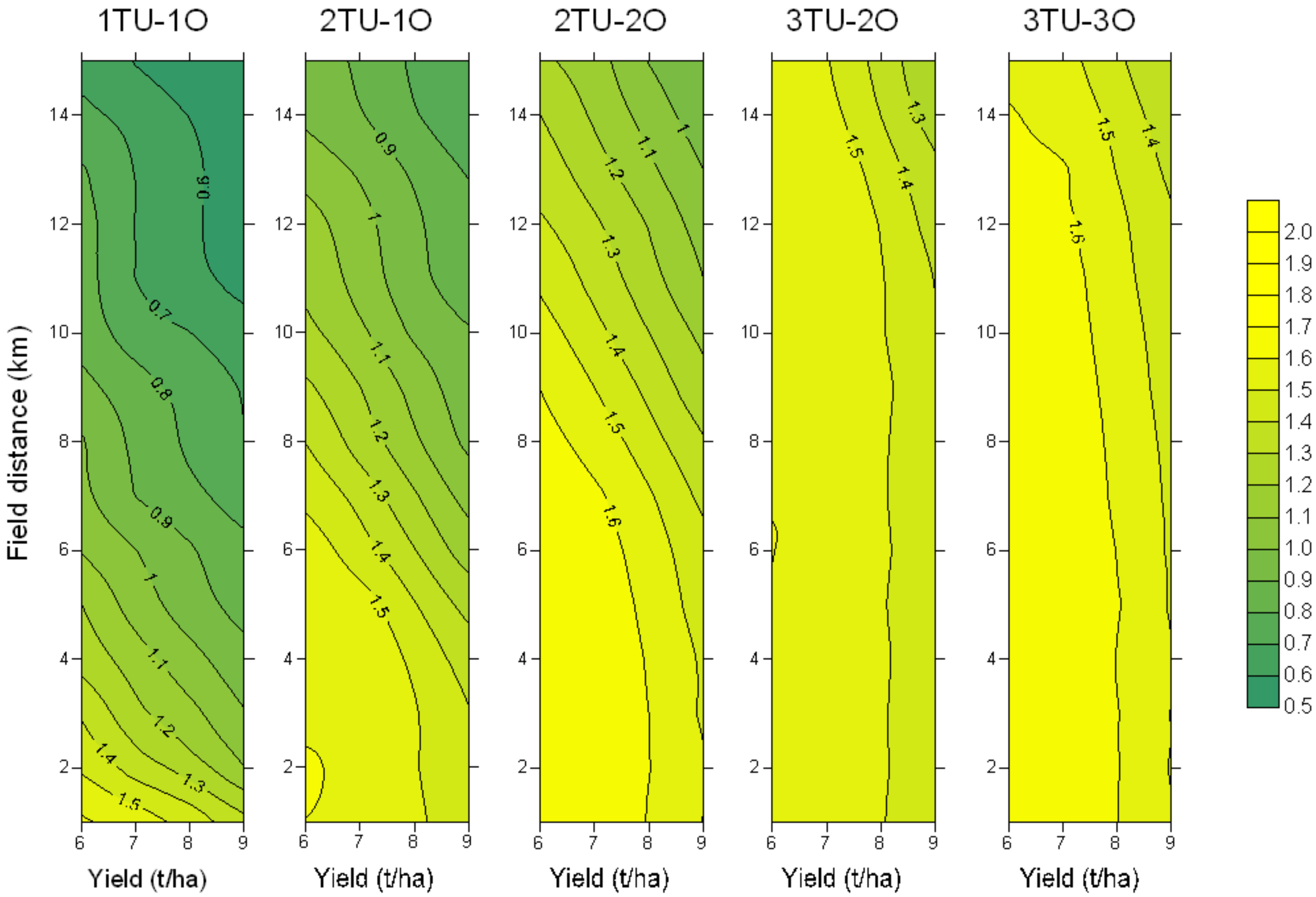

Figure 7 – The area capacity (ha h^{-1}) for different yields and different distances between the field and the storage facilities for the five selected transport units – operators configurations

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

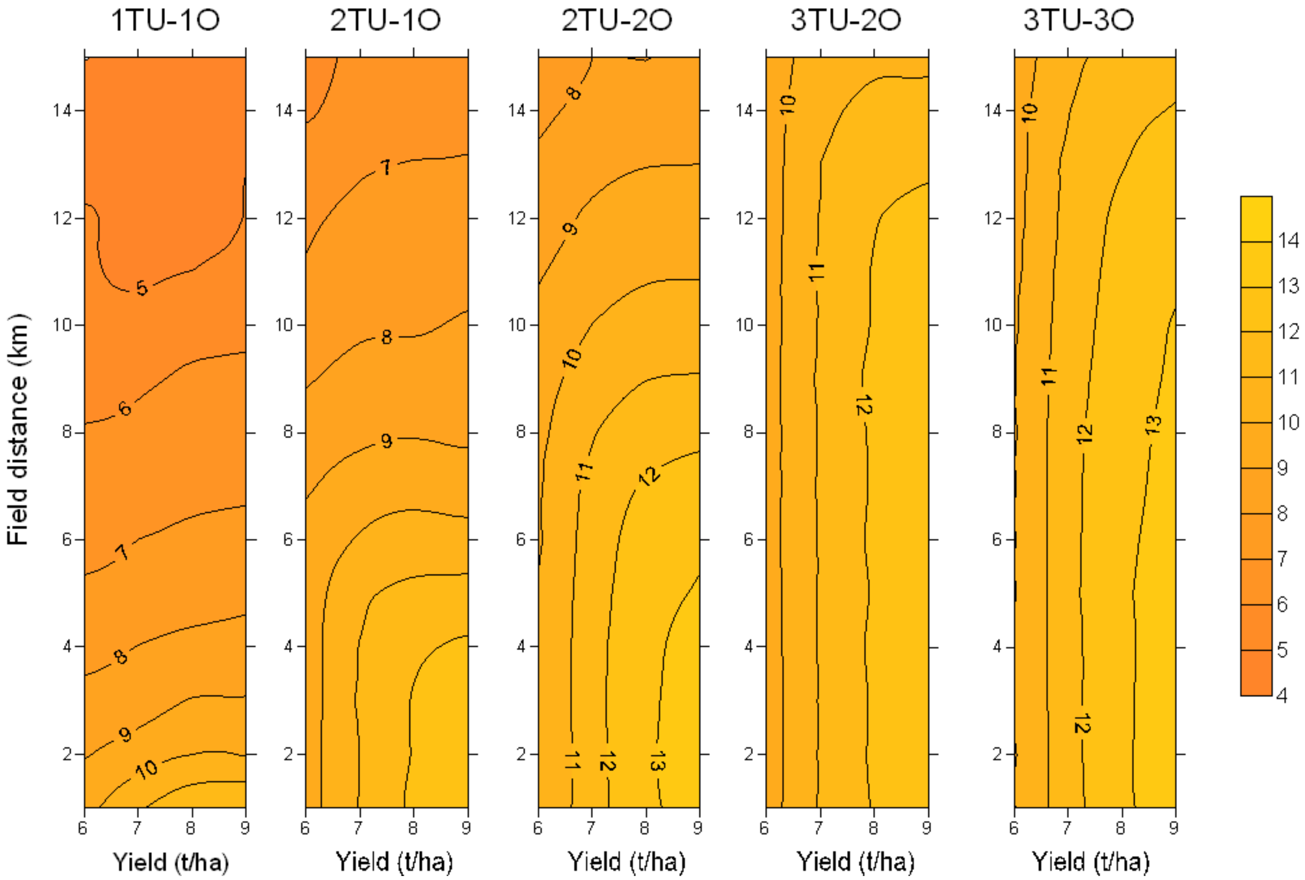

Figure 8 - The material throughout capacity (t h^{-1}) for different yields and different distances between the field and the storage facilities for the five selected transport units – operators configurations

Figure 8 presents the material throughout for the selected configurations and various yields and distances between the field and the storage facilities. The minimum value (3.97 t h^{-1}) corresponds to configuration 1TU-

1O for the longest distance (15 km) and the highest yield (9 t ha^{-1}), while the maximum value (13.55 t h^{-1}) corresponds to configuration 3TU-3O for the shortest distance (1 km) and the lowest yield (6 t ha^{-1}).

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

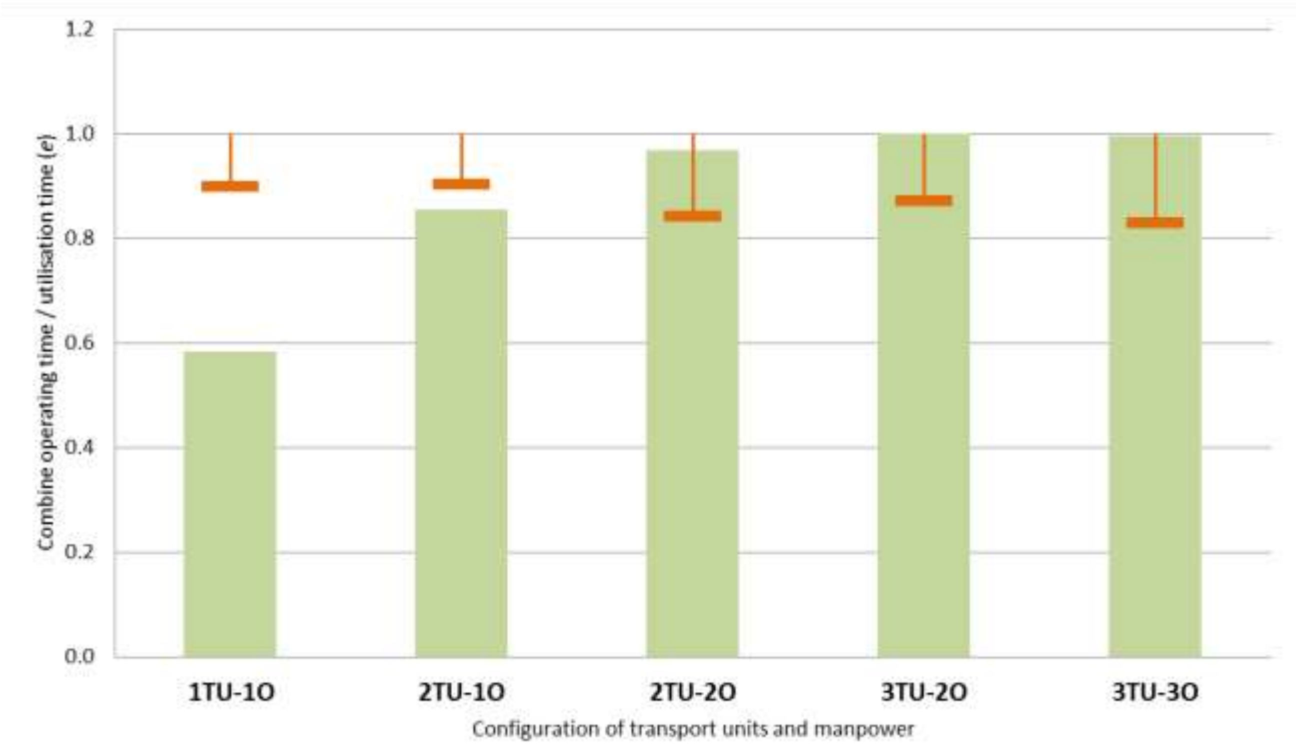

Figure 9 – The ratio between the combine operating time and utilisation time (*e*) in comparison with its threshold value (*e) for a timely harvesting of the whole farm area for the selected configurations**

Figure 9 presents the actual and the threshold value for the combine utilisation in the case study area, for the yield of 7 t.ha^{-1}. As can be seen in Figure 9, the threshold value is different for each configuration, as explained in section 3.3. This reveals the importance of the simulation tool compared to the case that average norms are used for the computing various operating time elements. The configurations 1TU-1O and 2TU-1O do note cope with workability requirements for the specific area configuration and region. In the cases of 2TU-2O, 3TU-20, and 3TU-3O the difference between the *e* and *e** represents the tolerance of the logistics system towards worst weather conditions, in terms of workability, compared to the expected according to historical data.

5. CONCLUSIONS

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

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

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

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