Optimisation tool for logistics operations in silage production

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OPTIMIZATION TOOL FOR LOGISTICS OPERATIONS IN SILAGE PRODUCTION

P. Busato[1], A. Sopegno[1], N. Pampuro[2] and R. Berruto[1]

[1] University of Turin, DISAFA Department Largo Braccini 2, 10095, Grugliasco, Turin, Italy

[2] Institute for Agricultural and Earth Moving Machines (IMAMOTER), Italian National Research Council (CNR), Strada delle Cacce, 73-10135 Torino (TO), Italy

*Corresponding author: patrizia.busato@unito.it

1 ABSTRACT

Silage is one of the typical systems to preserve biomass usually oriented from corn, sorghum, wheat, grass, and other forage and perennial crops. A critical task within the logistics operations in silage production, i.e. harvesting, transporting, and compacting, is the management of the biomass flow, in connection with the biomass storage system and the required conditions of the stored product depending on its further purpose of use. A key issue in large scale silage production operations is the matching of the material processing capacity of forage harvester with the material removal capacity of transport units and the material processing capacity of the compactor, in order to maintain a steady material flow. This allows for the optimisation of the working chain.

The objective of the paper is the development of a decision support system that for a given silage production system determines the configuration of the optimal number of transport units in each field of an area to be harvested that minimises the total operational cost of the production system under time constraints for the completion of the operation. The tool consists of the combination of two models, a simulation model and a linear programming based optimisation model. The simulation model was validated based on field trials. The simulation model generates a series of results in terms of total operating time and total operation cost for different configuration of the allocated transport units based on machinery and field features, which results are used to build the cost matrix of the optimisation model. The capabilities of both the simulation model, as an individual tool, and the complete decision support tool were demonstrated. The tool provides performance evaluation measures that consider the interaction of the various parts of the working chain and can be easily tuned for other silage operations with different crops.

Keywords: Biomass supply chain; operations management; optimisation; simulation.

2 INTRODUCTION

The majority of the barriers for the development of efficient biomass supply chains are related to the characteristics of the biomass products (De Meyer, Snoeck, Cattrysse, & Van Orshoven, 2016), and thus, to the processes performed at the first links of the chain. A critical task within this part is the management of the biomass flow (Sokhansanj, Kumar, & Turhollow, 2006; van Dyken, Bakken, & Skjelbred, 2010), in connection with the storage system and the required conditions of the stored product depending on its further purpose of use, which could be either bio-energy production, feedstock for bio-based material, or animal feed.

Silage is one of the typical systems for preserving biomass (usually oriented from corn, sorghum, wheat, and grass). Biomass silage production is a way to store the whole chopped plant (both grain, leaves, and stalks). This implies the fermentation of the mass in an anaerobic environment made by compaction of the chopped material and the subsequent coverage with a tarp to seal the silo to avoid the increase of oxygen concentration (Bartzanas, Bochtis, Green, Sørensen, & Fidaros, 2013; da Silva, Pereira, da Silva, Valadares Filho, & Ribeiro, 2016; Lengowski, Witzig, Möhring, Seyfang, & Rodehutscord, 2016). Scheduling is a critical task in the operational planning level (Dionysis D. Bochtis, Sørensen, & Busato, 2014) connected to the timeliness cost of the chain (Basnet, Foulds, & Wilson, n.d.; D. D. Bochtis et al., 2013; D. D. Bochtis, Sørensen, Green, Bartzanas, & Fountas, 2010; Edwards, Sørensen, Bochtis, & Munkholm, 2015; Guan, Nakamura, Shikanai, & Okazaki, 2009; Orfanou et al., 2013). If harvesting operations commence prior to the optimum crop maturity season the total silage yield tend to be modest, while, on the other hand, if harvesting operations commence after this season the risk of losing even the entire production is getting higher. On the scheduling task in silage production Põldaru and Roots, 2014 developed a nonlinear stochastic model to schedule silage maize harvesting on Estonian farms. The timeliness cost has been investigated as a cost factor in (Gunnarsson, Vågström, & Hansson, 2008) where a model was presented for the logistics of forage harvest to biogas production.

In the execution level, the logistics for silage production comprises from three operations running in parallel, namely: harvesting, transporting, and compacting. A key issue in large scale silage production operations is the matching of the material processing capacity of the forage harvester with the material removal capacity of the transport units, and the material processing capacity of the compactor, in order to maintain a steady material flow. An efficient silage production system requires a transport capacity that is able to keep the forage harvester to operate continuously. On the other hand, compactor's capacity should be able to prevent biomass flow bottlenecks at the silo site. Bottlenecks within transport or unloading operations can potentially reduce the system capacity below the throughput capacity of the harvester, and thus planning efforts are required. However, general tools for fleet management in agricultural operations (D.D. Bochtis & Sørensen, 2010; Dionysis D. Bochtis et al., 2014; Sørensen & Bochtis, 2010) cannot directly apply due to the above-mentioned particularities of the silage production chain.

The objective of this paper is the development of a decision support system that for a given silage production system determines the configuration of the optimal number of transport units in individual field of the area to be harvested, that minimizes the total operational cost of the production system under the presence of time constraints for the completion of the operation.

Analogous works on the simulation of the silage logistics system have already been presented in the literature. (Amiama, Pereira, Castro, & Bueno, 2015) developed a simulation-based decision support tool of the silage logistics system dedicated to the strategic level planning (system dimensioning at the beginning of harvest season) and the operational level planning (daily decision making), as well. The described tool determines the optimal combination of resources according to the fields to be harvested. The problem of the allocation of a different number of transport units to each individual field has been investigated by (Amiama, Cascudo, Carpente, & Cerdeira-Pena, 2015). However, the harvesting system simulated regards the case of the stationary unloading of the harvester to the transport unit. In work presented here, the transport units are not uniformly allocated to the whole system but in each individual field, based on a resources allocation optimisation problem, meaning that – potentially – a different number of transport units could be allocated among fields with different features, in terms of field-to-farm distance and yield levels. Furthermore, the harvester's field work is simulated in a track-by-track manner while the unloading process takes place on-the-go, where the harvester and the transport unit are moving in parallel field work tracks.

The rest of the paper is organised as follows: initially, the development of the tool is presented. The tool is composed of two models, the simulation model and the optimisation model. The simulation model runs instances of the operations chain iteratively and generates the cost matrix of the optimisation model which run subsequently. Next, in the material and methods section, a set of field trials is described, necessary for the quantification of the various operational inputs of the tool and for the validation of the model as well. The last part of this section defines the series of the scenarios to be run in order to demonstrate the functionality and the performance of the tool. In the results section, all related results on the input parameters quantification, the simulation model validation, and the demonstration scenarios are presented and analysed. Finally, in the conclusions section, the main findings and new insights of the work are discussed.

3 MODEL DEVELOPMENT

3.1.1 Overview of the tool

The decision problem at hand can be described in a compact form as follows: given a number of fields with individual features (area, distance from the facilities, yield, shape) and a machinery system (features of harvester, biomass compactor, and transport units, and the maximum number of transport units available) what is the set of transport units to be allocated that minimizes the total cost of the silage production (which includes the chain of harvesting-transporting-compacting) under the constraint of a given operational time window. In order to explain the effect of additional transport units on the performance of the harvesting chain at different field distances from the farm, the transport units are considered as identical in terms of their capacity and transport speed.

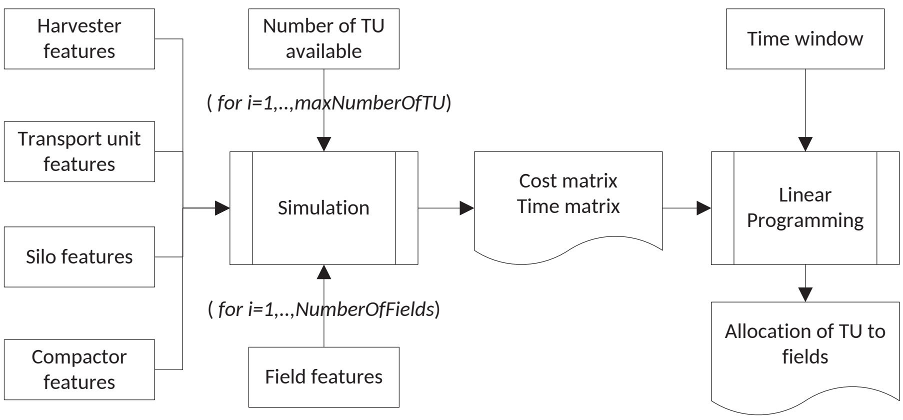

Figure 1 – Abstractive representation of the methodological approach

For modelling the above-mentioned problem in a general form, the field-to-storage distances and the biomass yield have been considered as discrete values. Let $D = \{1,2,3,\ldots\}$ denote the set of the various distance levels, and let $Y = \{1,2,3,\ldots\}$ denote the set of the various yield levels. A set of areas $A = \{A_{ij} / i \in D, j \in Y\}$ with common features, in terms of field-to-storage distance level and yield level is considered for the problem. Let u_{max} denote the maximum number of transport units available. Based on the above, a number of potential working chains, equal to $|D| \cdot |Y| \cdot u_{max}$, are generated. Each working chain is characterised by three features, namely, the field-to-storage distance $d_i, i \in D$, the yield y_j, $j \in Y$, and the number of the allocated transport units u_k, $k \in \{1,\ldots,u_{max}\}$.

Figure 1 presents the approach of the optimisation tool. Two main processes are taking place, namely, a simulation and a linear programming based optimisation. The input of the simulation model regards the machinery features and the operational features for the three operations (i.e. harvesting, transportation, and compaction). The simulation runs for each individual working chain (in a predefined number of repetitions due to the presence of stochastic parameters) generating a cost matrix and a time matrix both of the dimension of $|D| \cdot |Y| \cdot u_{max}$. Each element c_{ijk} of the cost matrix represents the cost per unit area for harvesting and transporting biomass of the particular working chain, while each element t_{ijk} of the time matrix represents the corresponding required operation time per unit area. Note that the harvesting cost and operation time are functions of the number of the transport units implemented since the simulation takes into account all the bottlenecks of the system.

The output generated by the simulation process consists of the matrices, namely the cost matrix and the time matrix. These matrices provide the input for the subsequent linear programming process. The linear programming problem can be stated as: given a set of areas to be harvested, the harvesting cost and the required operating time per unit area for each individual area, an available time window within which the total operation has to be completed, and a penalty cost for unit area that will remain unharvested, find the optimal part of each field that should be harvested and the optimal number of transport units to be allocated in each one these parts that minimize the total operation cost.

3.2 The simulation model

3.2.1 Description of the physical operation

The logistics operations of silage production include three operations running both in parallel (in terms of material processing) and in series (in terms of material flow). The biomass harvesting is carried out by a forage harvester, which represents the primary unit (PU) for the operation since it generates the material that has to be further processed (transported and compacted). Due to the high throughput material capacity of a forage harvester (up to 150 t h^{-1}) they are often not equipped with a temporary hopper, or in the case that such a hopper exists its capacity is relatively low. This fact diversifies the unloading process in forage harvesting for the one of grain harvesting since in the former case a continuous servicing by a transport unit (TU) is required for unloading on-the-go while both vehicles are moving in parallel. The harvesting operation includes the time elements allocated for the simultaneous cutting, chopping, and unloading on-the-go, the headland turnings, the idle times in the case of bottlenecks due to the unavailability of an empty transport unit, and the travelling times among fields to be harvested.

The interruption of the PU operation has a high-cost implication. Thus a number of TUs should be available, depending on the field-to-storage distance, in order to reduce cycle times of the TUs' work, not allowing for any interruption in the PU operation. On the other hand, an oversized fleet of TUs leads to an unnecessary increase in operating cost. In large scale silage production operations, the biomass has to be transported from a number of fields with distances from the packing location that can be varied considerably. Thus a fix-sized fleet of TUs could be either oversized or undersized for each individual field leading either to an unnecessary increase in operation cost or to bottlenecks to PU operation (which in turn results in rising cost and operating time).

The biomass is transported by the TU to the silage packing location for its storage. The transport task is divided into a series of time elements including, travelling empty to the field location; in-field travelling for reaching the harvester; on-the-go loading; in-field turning; in-field travelling for reaching the road network; travelling fully loaded to the storage location; manoeuvring next to the storage structure; and unloading.

The packing (compaction) of silage is carried out by tractors or loaders (compaction units - CU) making repetitively back and forth passages over the silo. The capacity of the operation (compacted $t\ h^{-1}$) is a function of the vehicle weight, which depends on the tractor power (Harrigan, 2003). For narrow bunkers, the compaction vehicle has to move out of the silo when a TU has to unload, and thus reducing the capacity of the operation. In contrast, wide bunker entrance allows the continuous functioning of the compactor even during the unloading process of a TU, and this speeds up the compaction process. The unloaded product in front of the bunker silo entrance cannot be higher than a certain level – corresponding to a number of loads - to prevent blocking of the bunker. When the amount of product to be compacted is greater than this quantity, the packing operation will have the priority over the TU unloading, so the TU will wait idly until a part of packing has been completed. In the case of low compaction capacity, the packing operation could interrupt the biomass transportation flow and consequently the harvesting operation, resulting in the overall lower performance of the chain.

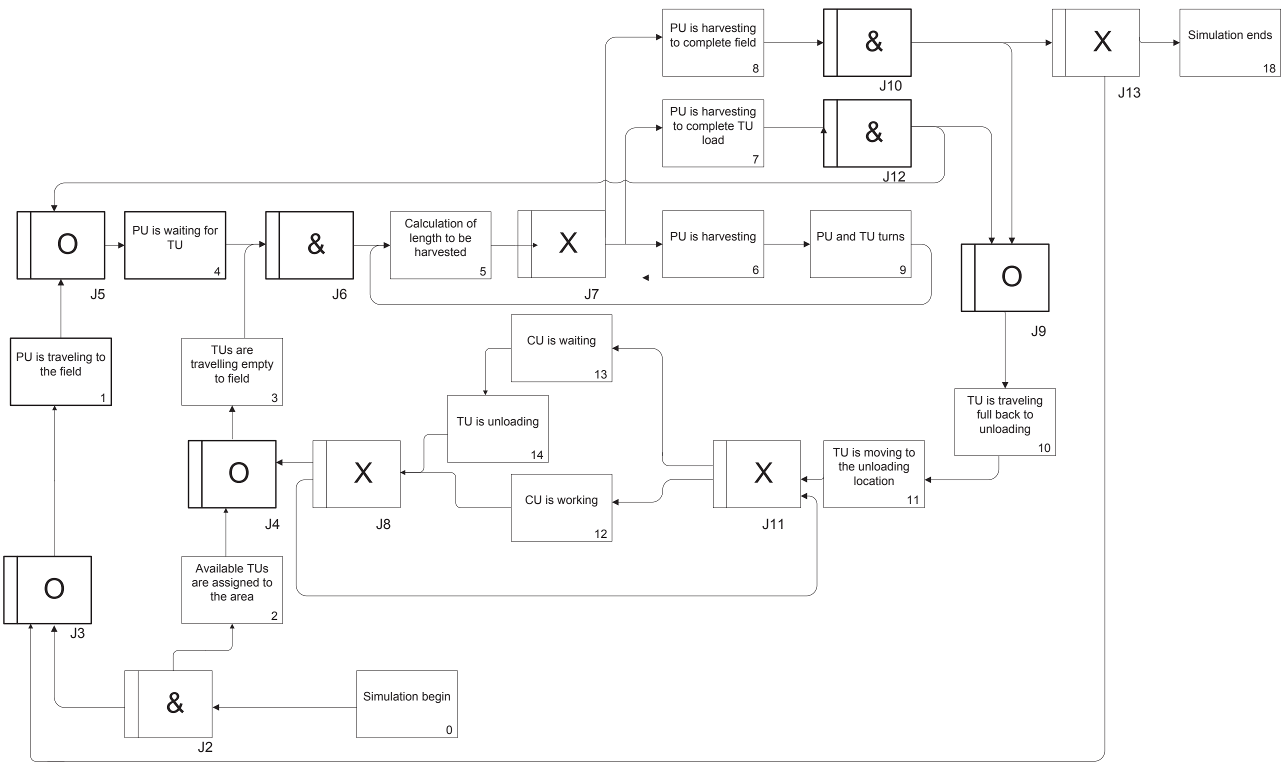

Figure 2 - IDEF process diagram of the simulation model (PU: primary unit – the forage harvester; TU: a transport unit; CU: compaction unit). For the IDEF3 junctions, asynchronous AND (&): all of the preceding (following) activities must be completed (begin); asynchronous OR (O): one or more of the preceding (following) activities must be completed (begin); exclusive OR (X): exactly one preceding (following) activity is completed (begins).

3.2.2 Description of the simulation process

In a pre-processing phase, each field area is divided into linear segments, corresponding to single passes of the forage harvester using as an input the field boundary polygon, the operating width, and the headland area to be allocated for turnings. The output of this process provides the coordinates of the two edges for each one of the passes as well as for the segments that constitute the headland passes. Also, the fieldwork pattern is provided by the user based on the selection of standard motifs. Due to unloading-on-the-go needs for the forage harvester, a pass-to-pass motion is adopted. The fieldwork pattern also determines the type of turning between two subsequent passes. Since a uniform yield distribution is assumed for the whole field area, the dry matter (t ha^{-1}) to be harvested in each individual pass is a linear function of its length and the operating width of the forage harvester.

Figure 2 illustrates the simulation process of the silage production. The various activities and junctions are listed and explained in Table 1.

Table 1 - The list of the activities and junctions of the IDEF3 diagram

ID	Activity	Description
UOB0	Simulation initiation	The PU object is created. The TUs objects are created. The field(s) object(s) are created. The simulation begins with the loading of the various items (e.g. fields, PU, TU, CU, etc.) and assigning their properties (e.g. working width, distributions of task times, distributions of working speeds, etc.). All of the field passes and their features are uploaded from the database created during the pre-processing (e.g., length, type of pass, filed-work motif, unitary yield, etc.). The configuration parameters are written into the internal database. All objects created are sent to J2
J2		In this junction, the objects generated in UOB0 follows a separate path in the simulation. The TUs are assigned to the area in UOB2 while the PU object proceeds to J3
J3		In junction J3 the PU is sent to the first activity, that is travelling to the first field. PU also comes from J3 in the case a following field has to be processed.
UOB1	PU is travelling to	The PU is travelling to the first field in order to start harvesting operation

	the field	or to the following field to be harvested.
UOB2	Available TUs are assigned to field	The TUs are allocated to the field where the PU operates.
J4		In this junction a TU, either being assigned from OUB2 or coming empty from J8, is send to UOB3 after the unloading process.
UOB3	TU travelling empty to the field	In this operation, TUs are travelling empty to the assigned field, where the PU operates. The TUs objects are sent to J6 and wait to be engaged with the PU in the on-the-go unloading activity.
J5		The PU is coming either from the storage location or from another field (UOB1), or from a harvested fieldwork track (J12) in order to complete the current track.
UOB4	PU is waiting for TU	The PU is waiting idly for the next TU to resume the unloading activity. UOB4 implies the computation of waiting times for the PU, in the case the TUs are not available.
J6		In the J6 the PU is coupled with the empty TU coming from UOB3.
UOB5	Calculation of length to be harvested	The calculation of the remaining volume capacity of the TU takes place. Both PU and the engaged TU are sent to J7.
J7		Based on the calculation made in UOB5, the PU could either proceed to harvest of the next track (UOB6), complete unloading at the engaged TU (UOB7), or complete harvesting of the current field (UOB8).
UOB6	PU is harvesting	The PU is harvesting the next track (given the availability of a TU).
UOB9	PU and TU turns	Both PU and TU are performing a turn (there is always an idle time for PU). Both objects are sent back to UOB5 where the next action is assessed.
UOB7	PU is harvesting to complete TU load	In this case harvesting on the current track interrupted after a length necessary to fill-in the remaining TU wagon space. After that, both objects are sent to J12.
UOB8	PU is harvesting to complete field	The PU is harvesting a track to finish the operation in the field. After the completion of the track harvesting, both objects are sent to J10.
J12		TU is fully loaded and is sent to travel back to the storage location, while PU is sent to J5 waiting for the next TU available.
J10		The junction sends PU to J13, for verification if there is a new field to be harvested, and TU to J9
J9		The junction receives a TU loaded fully and sent it to UOB10.
J13		PU is sent either to the next field to be harvested, or, if all fields have been harvested, back to the farm.
UOB18	Simulation ends	The simulation is completed once all field has been harvested. This process

		collects all measures and statistics for the whole system performance.
UOB10	TU is travelling back to unloading	The TU is travelling back to the silage storage facilities fully loaded
UOB11	TU is moving to the unloading location	The TU is positioned for the unloading process.
J11		The decision to either unload the TU or to wait takes place. Packing could be stopped in favour of the unloading of the TU, or the TU unloading operation could be set on hold.
UOB13	CU is waiting	The CU activity is temporarily stopped. Subsequently to this activity, (UOB14) takes place.
UOB12	CU is working	After J1, the CU operates in order to free space for the TU unloading.
UOB14	TU is unloading	The TU is unloading in front of the bunker silo.
J8		This junction receives both TU and CU from UOB12 and UOB14, respectively. TU is sent to J4 to travel back to the field empty while CU is sent back to J11 to carry out another compaction cycle.

3.3 The optimisation model

For modelling the problem as a linear programming problem, two decision variables are defined, namely:

- a_{ijk}, which denotes the part of area $A_{ij}, i \in D, j \in Y$, to be harvested supported by $k \in \{1,\ldots,u_{max}\}$ transport units committed to the operation, and
- b_{ij} which denote the part of the area $A_{ij}, i \in D, j \in Y$ to remain un-harvested.

The problem can be formulated as follows:

$$minimize \qquad \sum_{i=1}^{i=|D|} \sum_{j=1}^{j=|Y|} \left[\sum_{k=1}^{u_{max}} a_{ijk} c_{ijk} + b_{ij} M_{ij} \right]$$

$$subject\ to \qquad \sum_{k=1}^{u_{max}} a_{ijk} + b_{ij} = A_{ij} \qquad \forall i \in D, j \in Y$$

$$\sum_{i=1}^{|D|} \sum_{j=1}^{|Y|} \sum_{k=1}^{u_{max}} a_{ijk} t_{ijk} \leq W$$

The first constraint ensures that the summation of the total harvested and non-harvested areas of a working chain equals to the total area of the operation, while the second constraint ensures that the operations at all of the selected areas to be harvested will be completed within the operating time window.

For each working chain the term M_{ij} represents the cost penalty per unit area to be applied in the case of not harvesting the corresponding biomass. This penalty has a specific value for each working chain since it is a function of both the yield (which diversifies the loss revenue) and the distance (which diversifies the required operational cost). For the specific formulation of the problem the value of the penalty number can be any arbitrary number under the condition that $M_{ij} \geq max(c_{ijk}),\ i \in D, j \in Y, k \in \{1,\ldots,u_{max}\}$.

3.4 System implementation

The discrete simulation model was developed using the ExtendSim® programming environment (Imagine That Corporation, San Jose, CA, USA). ExtendSim® has been implemented in the simulation of various processes in manufacturing (Dong & He, 2012; Lee, Ko, Kim, & Lee, 2013; Onyeocha, Khoury, & Geraghty, 2015; Xu, Shao, Yao, Zhou, & Pham, 2016), general supply chains and logistics (Jia, Wang, Mustafee, & Hao, 2016; Springer & Davidson, 2015; Xu et al., 2016), and in a series of works on biomass supply chains (Busato, 2015; Ebadian, Sowlati, Sokhansanj, Stumborg, & Townley-Smith, 2011; Mobini, Sowlati, & Sokhansanj, 2011, 2013; Pavlou et al., 2016; Sokhansanj et al., 2006; Springer & Davidson, 2015). For running the linear programming optimisation, the Matlab® optimisation module was used.

4 Materials and methods

4.1 Quantification of the inputs

For the quantification of the input parameters of the simulation, four sets of field trials took place at four dispersed locations of NW Italy, namely at Canavere (CN, Italy) (Figure 3), Torre Balfredo, Buriasco, and Carmagnola. The features of the locations are listed in Table 2. The trails regarded the monitoring of the PU, TUs, and CU activities during the harvesting operation in a corn silo fields.

Table 2 – The four locations where the field trials were carried out

Farm	Total Area (ha)	Number of fields	Range of field areas (min-max / ha)	Average field-to-storage (km)	Range of field-to-storage distances (min-max / (km)
Canavere	21.39	5	1.01 - 7.52	2.37	2.10 - 2.56
Torre Balfredo	8.45	2	3.32 - 5.13	4.68	4.56 – 4.80
Buriasco	8.51	2	3.95 - 4.56	4.39	4.32 – 4.45
Carmagnola	6.37	3	1.83 – 2.36	2.57	2.50 – 2.60

The parameters that were measured in the field trials included:

- The working speed for the PU
- The time required for the execution of a 90^0 turn – for both PU and TUs
- The time needed for the execution of an 180^0 turn – for both PU and TUs
- The travelling speed of the TUs with full load
- The travelling speed of the TUs with empty wagon
- The in-field travelling speed of the TUs
- The positioning time of the TU at the silage storage facilities
- The unloading time of the TUs at the silage storage facilities
- The working capacity of the compactor

Furthermore, and to be used in the validation of the tool, the dimensions of each field, the field-to-storage distances, and the yield of each field were also measured.

Figure 3 – One of the four locations (Canavere) where the field trials were carried out. Field areas: Field 1 – 6.3 ha; Field 2 - 7.52 ha; Field 3 – 4.17 ha; Field 4 - 2.4 ha; Field 5 – 1.01 ha. Distance from the silo location: Field 1 – 2,100 m; Field 2 – 2,420 m; Field 3 – 2,350 m; Field 4 – 2,430 m; Field 5 - 2,560 m.

4.2 Simulation model validation

Three of the four areas where the field trials were carried out (Torre Balfredo, Buriasco, and Carmagnola) were used for the quantification of the input data. These input data were used in the next step for the simulation of the operation in the fourth area (Canavere). The actual output parameters monitored during the field trials in the latter area were compared with the output parameters of the simulation. The parameters include:

- Area capacity for each field (which is related to the operating time)
- Forage harvester utilisation (which is related to the bottlenecks of the chain)

4.3 Simulated experiments scenarios

In order to demonstrate and analyse the simulation module functionalities, a series of simulated experiments were carried out. The simulated experiments regard the operations in an area of 27.3 ha composed for 10 fields in various shapes and areas (Figure 4). The implemented machinery system, in terms of the operational features, e.g. PU's working width, TUs' payload, PU machine power, TUs' tractors power, etc., was the one used in the monitored physical operations. Finally, the task times elements and the various working speeds which provided to the simulation module were the ones resulted from the quantification process on the field trials.

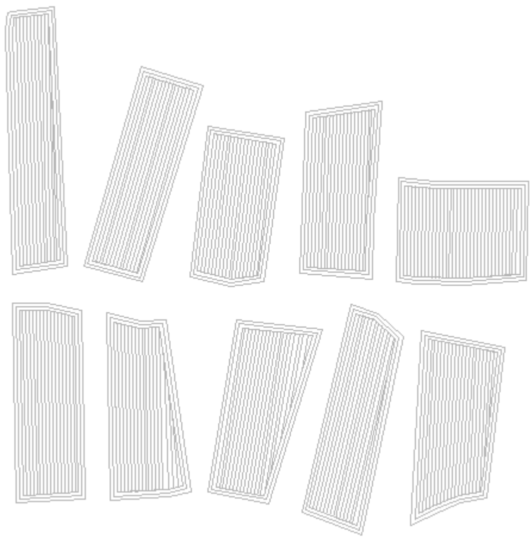

Figure 4 – The shape of the ten fields implemented for the simulated experiments

The simulated experiments consist of a series of scenarios generated by the combination of the scaled values of the following operational input parameters (as depended values):

- Filed-to-storage distances ranged from 1 km to 20 km with 1 km increment step;
- Maize yield of 18 tDM ha^{-1};
- Number of TUs available ranged from 2 to 6 with increment step of 1

The combinations of these factors yield to 100 simulated experiments. In each one of the experiments the ten fields were processed one-by-one by the simulator, and the values of the output parameters represent the average values resulted for each field. Due to the implementation of stochastic parameters, each experiment was carried out repeatedly for 100 times.

For each scenario the results were provided with the following performance indicators (as depended values):

- Area capacity (ha h^{-1}). It refers to the field area that maize is harvested, transported, and compacted in the unit time.
- The PU utilisation coefficient. It relates to the ratio of the active working time of the PU to the total operation time, providing a measure of the non-productive time that the PU remains idle without being serviced by a TU. This measure is very crucial for forage harvesting operations given the fact that forage harvesters (in general) do not carry a temporary biomass hopper.
- The TU utilisation coefficient. It refers to the ratio of the active working time of a TU to the total operation time. This index provides a measure of the non-working time elements of a TU, i.e. waiting time in the field to be engaged with the PU and waiting time for unloading at the bunker silo entrance.
- The CU utilisation coefficient. It refers to the ratio of the active working time of the CU to the total operation time.
- The man-hours per unit area (h ha^{-1}). It relates to the total hours that all operators are committed to the operation.

For the demonstration of the linear programming module, as well as for the optimisation tool as a whole, three diversified scenarios in terms of the spatial distribution of the area to be harvested were considered. The total area chosen was of 400 ha being a sufficient area to provide feed for a typical biogas plant of 1 MW electric power. Three scenarios include:

- Scenario A: The 400 ha area is distributed within a distance from the silage storage facilities up to 5 km and consists of 5 groups of fields, each group of an area of 80 ha, located uniformly at distances scaled from 1 km up to 5 km.
- Scenario B: The 400 ha area is distributed within a distance from the silage storage facilities up to 10 km and consists of 10 groups of fields, each group of an area of 40 ha, located uniformly at distances scaled from 1 km up to 10 km.
- Scenario C: The 400 ha area is distributed within a distance from the silage storage facilities up to 20 km and consists of 20 groups of fields, each group of an area of 20 ha, located uniformly at distances scaled from 1 km up to 20 km.

The output of the simulated experiments for the scenarios above is the optimal allocation of the TUs to each group of fields.

The machinery costs were estimated according to the ASAE D497.4 standard (ASAE, 2009). The costs estimation were based on equipment used to harvest 400 ha of maize silo (for a yield of 18 tDM.ha^{-1}) for biogas production. The hourly costs of the equipment used in the calculation were the followings:

- 201 € h^{-1} for a 6-rows forage harvester (working width: 4.5 m);
- 53 € h^{-1} for a 140 kW - 4WD tractor and leveller;
- 48 € h^{-1} for each TU (104 kW - 4WD tractor and a wagon of 30 m^3 volume capacity);
- 13 € h^{-1} labour cost.

5 RESULTS

5.1 Input quantification by field trials

The collected data related to machinery performance during the field trials on the four fields are presented in Table 3. For generating the statistical distribution, the BestFit software package was used (the tool is embedded in ExtendSim® software).

Table 3 - Statistical distribution of the PU (forage harvester) and TUs data, recorded during the field trials

Operational elements	Number of observations	Statistical distribution	Parameters (mean, standard deviation)
PU working speed (km h^{-1})	366	Normal	N(5.03;1.66)
TU travelling speed in the field (km h^{-1})	29	Normal	N(10.2;2.35)
PU turning 180° (min)	246	Lognormal	0.125+LN(0.368,0.228)
PU turning 90° (min)	48	Lognormal	0.175+LN(0.42,0.428)
TU turning 180° (min)	117	Lognormal	0.325+LN(0.378;0.332)
TU turning 90° (min)	32	Lognormal	0.15+LN(0.54,0.695)
TU positioning at bunker silo (min)	29	Lognormal	0.200+LN(1.88;0.85)
TU unloading (min)	29	Lognormal	0.125+LN(1.27;0.63)

The compactor was a 15.9 t front-wheel loader of a power of 140 kW. The compactor capacity was estimated as 31.5 tDM h^{-1}. For the specific value of the compactor capacity, the packing operation was not a limiting factor for the harvesting operation.

According to the field trials, the maximum speed of the TUs was 29 km h^{-1} for a full wagon and 31 km h^{-1} for the empty wagon. Based on the approach described in Harrigan, 2003 the travelling speed (expressed in km h^{-1}) of the TUs was provided by the following equations:

Full loaded wagon: $s = \min(17.2 + 4d,\ 29)$

Empty wagon: $s = \min{(23 + 3d,\ 31)}$

Where s denotes the travelling speed and d denotes the field-to-storage distance (km).

5.2 Simulation model validation

The validation of the simulation module was based on the comparison between the measured and the simulated output parameters on five fields (located at the Canavere farm). As mentioned earlier, for the simulation of the operation of these fields, the quantified data from seven fields (located at Torre Balfredo, Buriasco, and Carmagnola farms) were used (as listed in Table 2). For the validation purposes, the simulation was repeated for 100 times for each one of the fields, using the distributions presented in Table 4. The same number of TUs available was also utilized in the validation.

Table 2 – Comparison between the actual and the simulated results for the simulation module validation

Parameter		Actual value	Simulated value	Error (simulated-actual)	STD
System capacity		(ha h^{-1})	(ha h^{-1})	(%)	
3 TU	Field 1	1.4	1.43	2.1	0.08
3 TU	Field 2	1.38	1.44	4.3	0.11
3 TU	Field 3	1.4	1.43	2.1	0.11
2 TU	Field 4	1.13	1.09	-3.5	0.06
2 TU	Field 5	1.12	1.08	-3.6	0.06
PU utilisation		Dimensionless (0-1)	Dimensionless (0-1)	(%)	
3 TU	Field 1	0.78	0.79	1.3	0.23
3 TU	Field 2	0.77	0.78	1.3	0.23
3 TU	Field 3	0.76	0.78	2.6	0,23
2 TU	Field 4	0.62	0.59	-4.8	0.16
2 TU	Field 5	0.59	0.56	-5.1	0.16

The variation of TUs available results in changes in the total productivity of the chain and in different waiting times for the PU, and consequently in lower utilisation for the Field 4 and Field 5, where only two TUs were available. The slight increment in the performance during field trials vs. simulation performance (negative error) when the 2 TU are available is due to the fact that the operators in these fields were travelling a bit faster to serve better the PU since they know the TUs were limiting the PU capacity. The low error encountered is due to the fact that the model mimics with a great detail the working pattern of the PU and of the TUs.

5.3 Simulated experiments

As mentioned above in the Materials and Methods Section, the performance indexes that are analysed were the area capacity, the PU utilisation coefficient, the TU utilisation coefficient, the CU utilisation coefficient, and the required man-hours per unit area (h ha^{-1}). These metrics are presented in the following.

5.3.1 Area capacity

Figure 5 illustrates the area capacity as a function of the field-to-storage distance for different numbers of TUs available. The maximum achievable area capacity was 1.71 ha h^{-1} and resulted for the cases of 3 TUs for the distance of 1 km; 4 TUs for distances up to 2 km; 5 TU for distances up to 4 km; and 6 TUs for distances up to 5 km. It worth noting that for the cases where the TUs are not a limiting factor for the PU, the area capacity remains the same regardless of the distance.

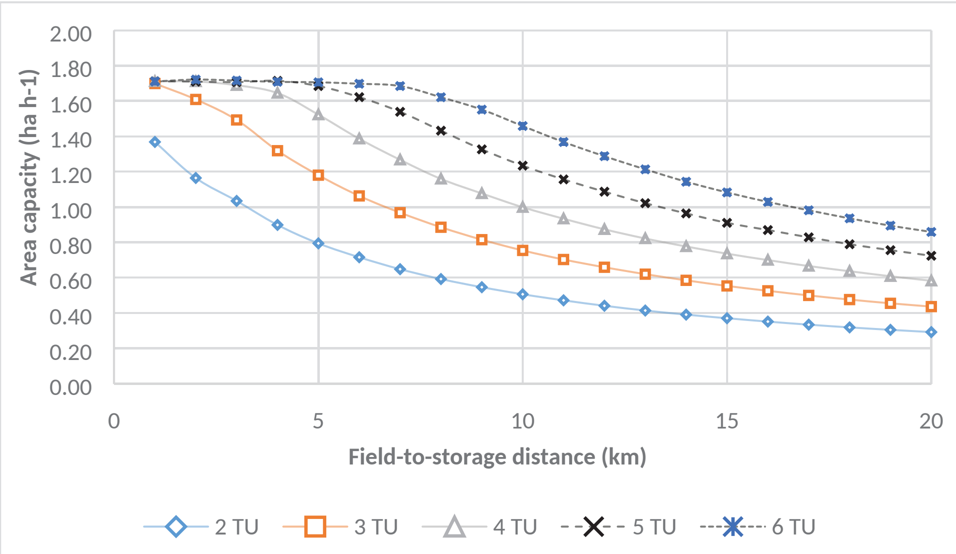

Figure 5 - System chain area capacity (ha h^{-1}) as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

5.3.2 Primary unit utilisation

Figure 6 illustrates the utilisation coefficient of the PU as a function of the field-to-storage distance for the five cases of the number of TUs available. The nearly 100% utilisation of the PU occurs for exactly the same cases as the maximum area capacity occurs as previously described, meaning that for these cases there is not any interruption on the PU operation due to a failure to be served by a TU.

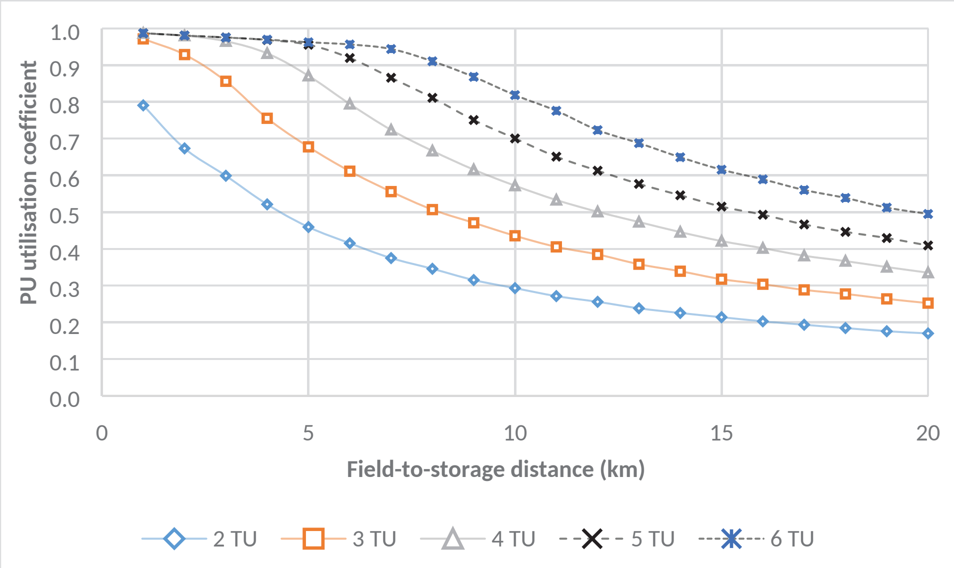

Figure 6 - Primary unit (forage harvester) utilisation as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

As mentioned previously in the Materials and Methods section, the utilisation coefficient of the PU is a different measure than the field efficiency which represents the ratio between the effective operating time and the total time that a unit is committed to an operation. Figure 7 illustrates the field efficiency of the harvesting operation as a function of the field-to-storage distance for the various cases of TUs available. Based on ASAE standards, field efficiency for forage harvesting ranges from 60% to 85%, with a typical value 70% (ASAE, 2009). In the simulated experiments, field efficiency is below the mean of this range, and in the majority of the cases, it is even below its minimum value. This is because the accumulated capacity of the TUs for the examined distances is generally below the throughput capacity of the PU. Furthermore, the field sizes where operations were simulated are relatively small resulting in higher times allocated to headland turnings, a fact that highly affects the field efficiency of an agricultural machine.

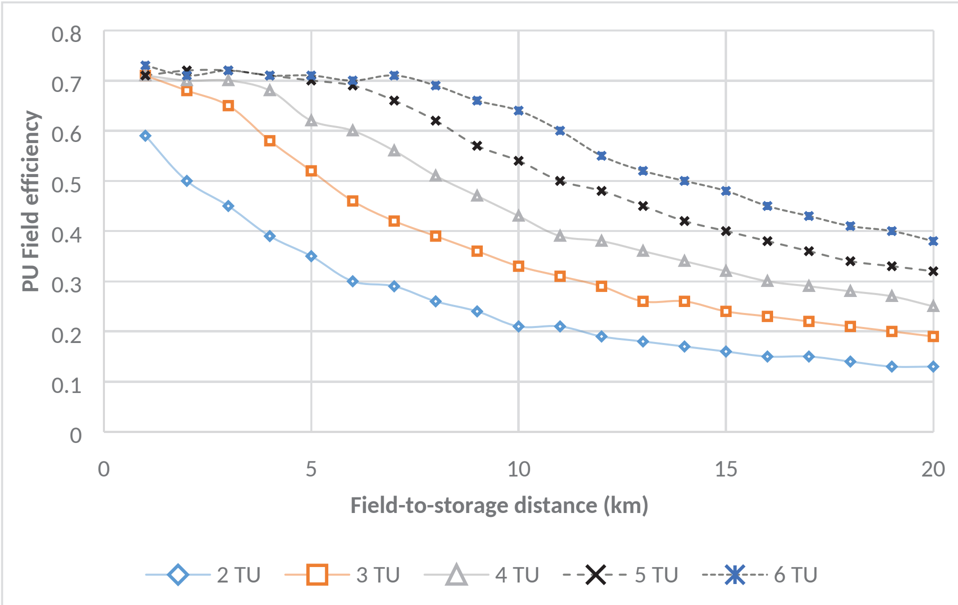

Figure 7 - Average field efficiency of the Primary Unit (forage harvester) utilisation as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

5.3.3 Transport units utilisation

Figure 8 illustrates the average utilisation coefficient for the TUs as a function of the field-to-storage distance for the various groups of TUs. Over the distance of 10 km, all TUs are continuously engaged in the operation. Compared to the PU's utilisation coefficient (as illustrated in Figure 6) the trend in the case of the TU's utilisation coefficient is the opposite of the PU as the field-to-storage distance increase. This means that the product of the two coefficients can provide a measure of the performance of the system. Figure 9 illustrates the multiplication of the two coefficients. As it will be presented in the following subsection regarding the operational cost, the higher value of the product corresponds to the lower cost of the operation. Consequently, this product could be potentially used as an index for the optimal selection of the machinery system without estimating the actual cost if for example a number of cost input parameters are not known.

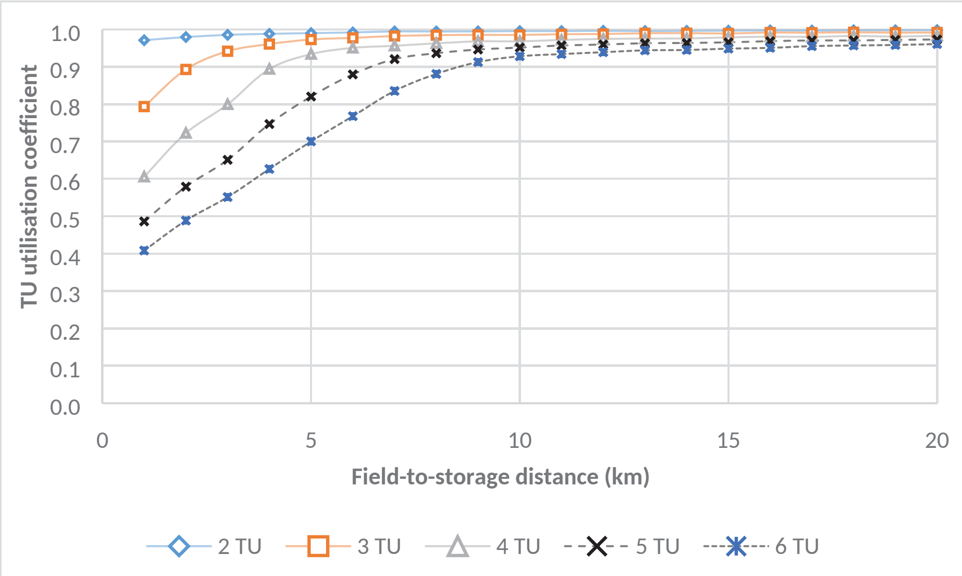

Figure 8. The transport units (TU) utilisation coefficient as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

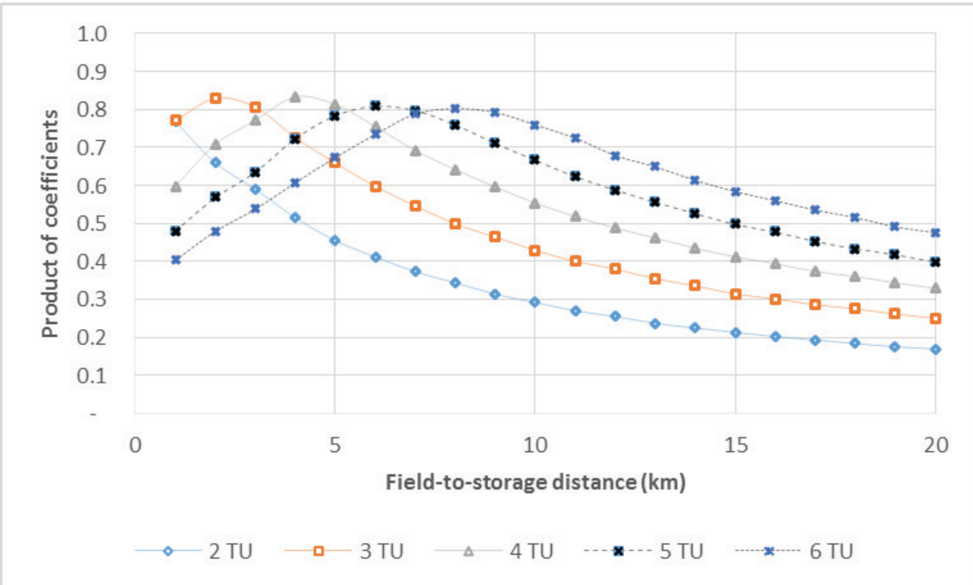

Figure 9 – The product of the primary unit (PU) utilisation coefficient and the transport units (TU) utilisation coefficient as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

Figure 9 presents the product of the PU utilisation and TU utilisation factors. The maximum value of this parameter (for example for 4 TU at 4 km, 5 TU at 6 km, etc.) represent the best chain available and generally, correspond to the lowest manpower requirement (Figure 10) and the lowest cost for the operation (Table 5).

5.3.4 Labor requirements

Figure 10 illustrates the labour needs of the operation. Labour requirements increase with the distance increase since the utilisation of the TUs is also increased. When the transport part of the chain is oversized, providing for the PU the exploitation of its full capacity, the labour requirements do not vary as a function of the distance. On the presented case, the chain is oversized up to 3 km for 4 TUs and over, up to 4 km for 5 TUs and over, and up to 5 Km for 6 TUs, while after that distance an oversized chain cannot occur since 6 TUs is the maximum number of the TUs available. On the opposite, when the transport part of the chain is undersized, meaning that the TUs available are not able to guarantee a full capacity for the PU, the labour requirements increased considerably with the shortage in TUs. For example, at the distance of 15 km, the labour requirements for the case of 6 TUs available are 7.39 h ha^{-1}, while if only 2 TUs are available the labour requirements are 10.79 h ha^{-1} resulting to an increase of 46% in labour cost.

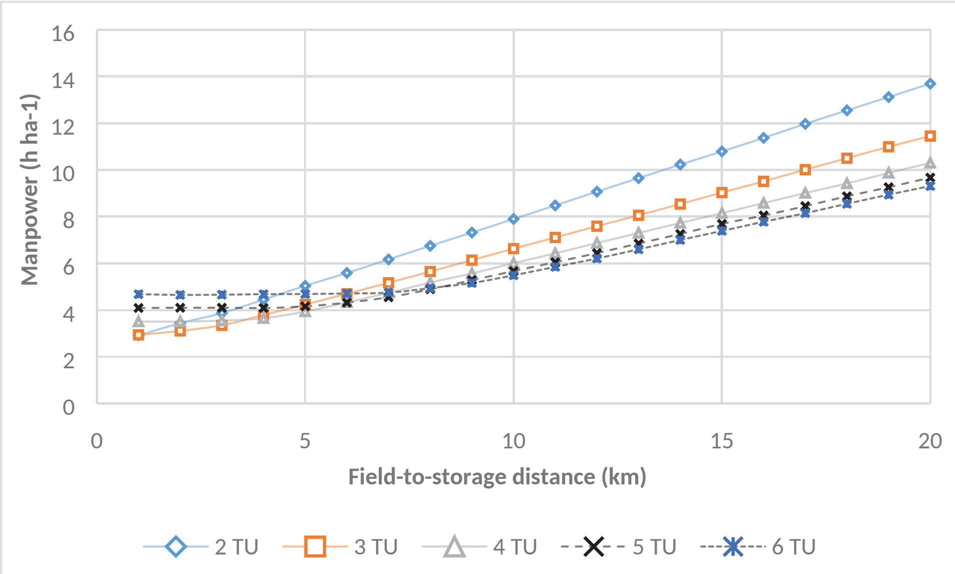

Figure 10. Labor requested (h ha^{-1}) as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

5.3.5 Operation costs

Table 5 presents the total cost for the silage operations for all combinations of the selected field-to-storage distances (1-20 km) and the number of TUs available (2-6). The figures in bold represent the minimum cost that corresponds to the selection of the optimal number of TUs for a specific field-to-storage distance. It is evident that when the availability of the TUs is a limiting factor for the PU performance, the optimal cost corresponds to the implementation of the maximum number of available TUs (as in the specific scenario happens for field-to-storage distances over 9 km). Figure 11 illustrates the total cost increase when the optimal number of TUs is not implemented for the operation. It is clear that selecting either an oversized or an undersized transportation system compared to the optimal one leads to a higher cost.

Table 5 - Total cost for the operation (€ ha^{-1}). In bold are presented the minimum cost for a specific distance

Field-to-storage distance (km)	Number of TUs available				
	2	3	4	5	6
1	293	**276**	314	355	395
2	345	**292**	314	355	393
3	388	**314**	318	356	394
4	447	356	**326**	354	395
5	505	397	**352**	360	396
6	561	441	387	**374**	398
7	619	485	423	**394**	401
8	677	530	463	424	**417**
9	735	575	498	458	**436**
10	793	622	537	492	**463**
11	850	667	574	525	**494**
12	909	711	614	558	**525**
13	968	756	653	594	**557**
14	1,026	801	690	630	**591**
15	1,082	847	729	667	**624**
16	1,141	892	766	698	**657**
17	1,200	938	805	732	**688**
18	1,258	985	842	769	**722**
19	1,316	1,031	882	803	**755**
20	1,373	1,074	920	838	**786**

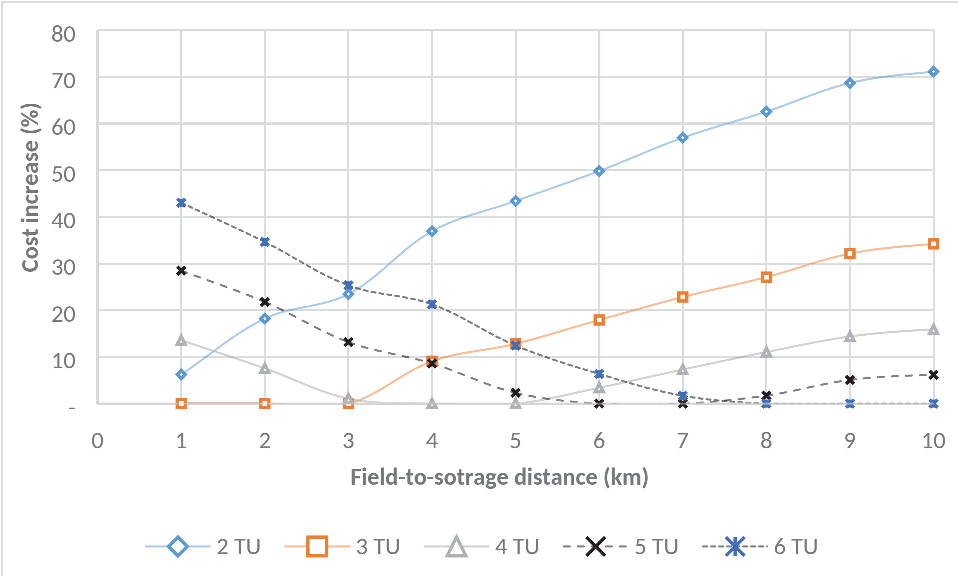

Figure 11. Total cost percentage increase compared to the cost corresponding to the optimal number of TUs for field-to-storage distances from 1 to 10 km.

5.4 Optimisation model results

The three scenarios described in the materials and methods section were run having as an operational, available time limit of 320 h (corresponding to a typical time availability in the area where the field trials were carried out). Results are presented in Table 6. The optimisation model output provides the configuration with the optimal number of TUs to be allocated to each individual field group (as they are defined based on the field-to-storage distance) in order to minimise the total operation cost. For the scenarios A and B (5 km and 10 km maximum distance, respectively) the constraint of the available time is not binding, so the optimisation model provides the solution purely characterised by minimum unitary cost, like they were presented in bold in Table 5. For scenario C (20 km maximum distance) the available time constraint holds, the number of TUs used is higher than for the minimum operation cost (Table 6) and the optimal solution results in a part of the area that should remain unprocessed, so the optimisation model provides most economical option within the imposed time limit. In this scenario, a small portion of the area could not be harvested within the available time (320 h). This field belongs to the farthest group of fields because these are the fields most expensive to be harvested and leaving them undone yields to the least cost for the operation. In this work, we consider the fields were located next to each other, and we consider only PU transfer from one field to the next, while TUs, once the field was completed, go back to the farm.

Table 6 - Linear programming output: logistic cost for silage of 400 ha and selected working chains for each selected field- to-storage distance.

	Scenario A			Scenario B			Scenario C		
Distance (km)	Area (ha)	Optimal number of TUs	Minimum cost (€ ha^{-1})	Area (ha)	Optimal number of TUs	Minimum cost (€ ha^{-1})	Area (ha)	Optimal number of TUs	Minimum cost (€ ha^{-1})
1	80	3	275	40	3	275	20	3	275
2	80	3	290	40	3	290	20	4	311
3	80	3	314	40	3	314	20	4	316
4	80	4	329	40	4	329	20	5	356
5	80	4	352	40	4	352	20	5	360
6	--	--	--	40	5	373	20	6	399
7	--	--	--	40	5	395	20	6	402
8	--	--	--	40	6	416	20	6	416
9	--	--	--	40	6	434	20	6	434
10	--	--	--	40	6	462	20	6	462
11	--	--	--	--	--	--	20	6	493
12	--	--	--	--	--	--	20	6	525
13	--	--	--	--	--	--	20	6	557
14	--	--	--	--	--	--	20	6	590
15	--	--	--	--	--	--	20	6	622
16	--	--	--	--	--	--	20	6	658
17	--	--	--	--	--	--	20	6	689
18	--	--	--	--	--	--	20	6	722
19	--	--	--	--	--	--	20	6	754
20	--	--	--	--	--	--	19.31[#]	6	787
Total costs (€)			124,836			145,614			203,765
Cost per unit area (€ ha^{-1})			312			364			509
Cost per unit material (€ tDM^{-1})			17.34			20.22			28.30

[#] Due to the time limitations the specific group of fields could not be operated within the available time period of 320 h, and for this reason an area of 0.69 ha remains unharvested.

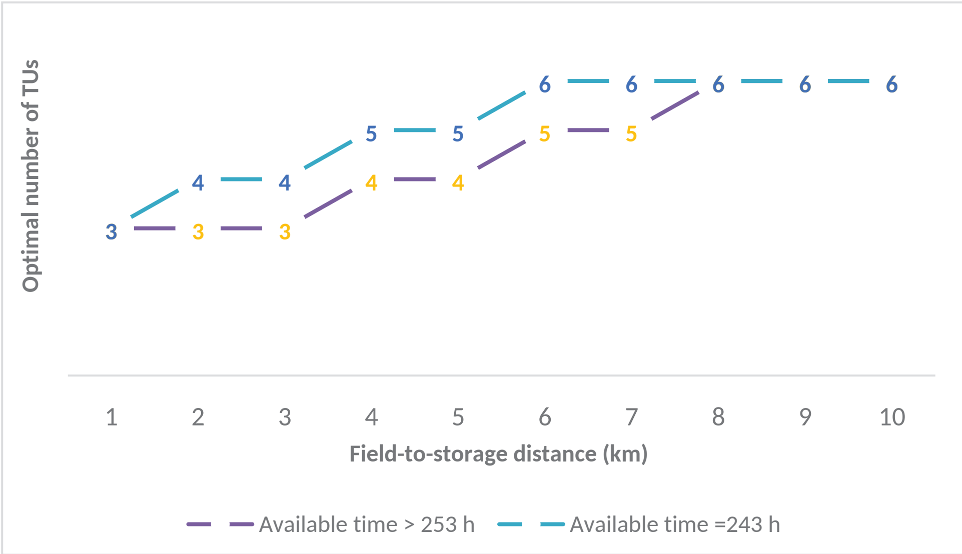

Figure 12 – Configuration of optimal number of TUs (transport units) for the different operational time available to complete the operation (=243 h and >253 h) for scenario B (Fields dispersed over 10 km distance from the Farm).

Figure 12 presents a sensitivity analysis of the solutions provided by the optimisation tool. The scenario B (fields dispersed over 10 km distance from the farm) was optimised while progressively reducing the number of hours available to complete the operation, to find out when the binding time constraint holds.

As we can see from the Figure 12, when the available operational time is higher than 253 h, the configuration of the optimal number of TUs in the various groups (field-to-storage distances) remains the same and identical to the one of the basic scenario (320 h operational time available), as presented in Table 6.

If the available hours drop (e.g. due to weather conditions), an increased number of TUs is required. In the range between 243 h and 253 h of operational time available, there is a combination of the number of TUs to be used for the same field groups, that vary from field distances between 2 and 7 km.

The configuration of the optimal number of TUs remains the same for any operational time available below the threshold of 243 h. When the available time drops below the 243 h, there will be a part of the total area that cannot be processed. The non-processed area is always allocated to the longer distanced group of fields as a result also from the optimisation process. As for example, at the level of 240 h available time, there will be 4.12 ha un-processed, while at the level of 220 h available time the unprocessed area will be increased to 33.53 ha. In both of the cases, the unprocessed area is allocated to the group located at the distance of 19-20 km since it is the most expensive area to be processed.

6 Conclusions

A decision support tool for the logistics of silage production was presented. The tool consists of the combination of two models, a simulation model and a linear programming based optimisation model. The simulation model generates a series of results in terms of total operating time and total operation cost for different configurations of the allocated transport units based on machinery and field features. These results are used for building the cost matrix of the optimisation model. The simulation model was validated based on field trials. The mean (absolute) error between the simulated and actual data was 3.15% and 3.03% for the system capacity and the primary unit utilisation, respectively. The optimisation model output provides the configuration with the optimal number of transport units to be allocated in field groups in order to minimise the total operating cost. Under the presence of operating time limitations (available working hours to complete the operation within) the optimal solution results in a part of the area that should remain unprocessed, and consequently, the optimisation model provides most economical option within the imposed time limit.

The capabilities of both the simulation model, as an individual tool, and the complete decision support tool were demonstrated. The tool provides performance evaluation measures that consider the interaction of the various parts of the chain, namely harvesting, transporting, and compacting of the silage.

Within the planning process for silage production, the developed tool provides the resources allocation management task. However, at the operational level, the resources allocation problem has to interact with the managerial tasks of scheduling and machinery routeing. Although that the tool can allocate for each field the exact number of transport units, the order in which the specific area should be harvested is not provided. Furthermore, the case of multiple-harvesters operating simultaneously in dispersed fields, a case that requires routeing optimisation for the transport units, is also a planning function that should be connected to the developed tool. The above consists issues for further research and expansion of the presented work.

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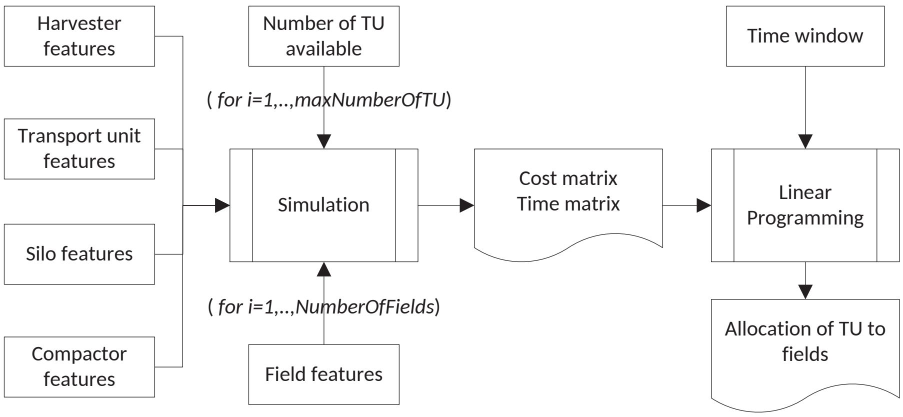

Figure 1 – Abstractive representation of the methodological approach

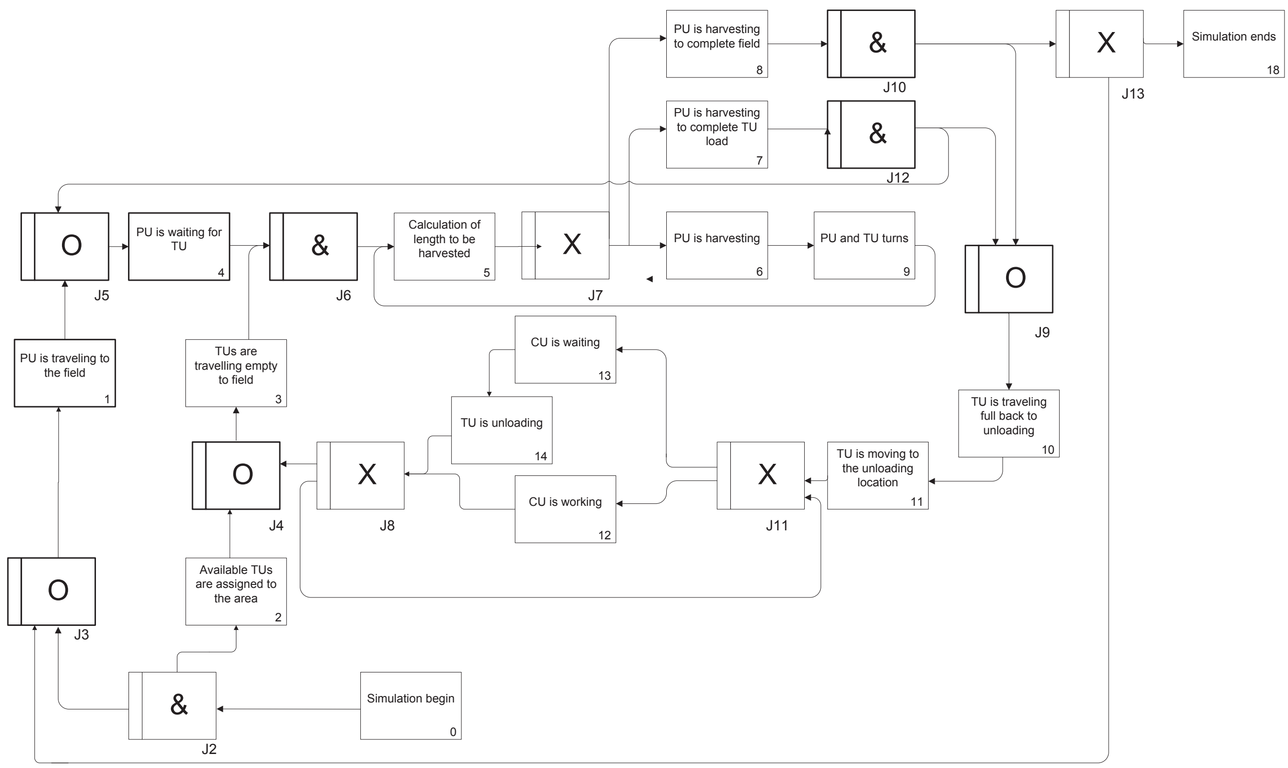

Figure 2. IDEF process diagram of the simulation model (PU: primary unit – the forage harvester; TU: a transport unit; CU: compaction unit). For the IDEF0 junctions, asynchronous AND (&): all of the preceding (following) activities must be completed (begin); asynchronous OR (O): one or more of the preceding (following) activities must be completed (begin); exclusive OR (X): exactly one preceding (following) activity is completed (begins).

Figure 3. One of the four locations (Canavere) where the field trials were carried out. Field areas: Field 1 – 6.3 ha; Field 2 - 7.52 ha; Field 3 – 4.17 ha; Field 4 - 2.4 ha; Field 5 – 1.01 ha. Distance from the silo location: Field 1 – 2,100 m; Field 2 – 2,420 m; Field 3 – 2,350 m; Field 4 – 2,430 m; Field 5 - 2,560 m.

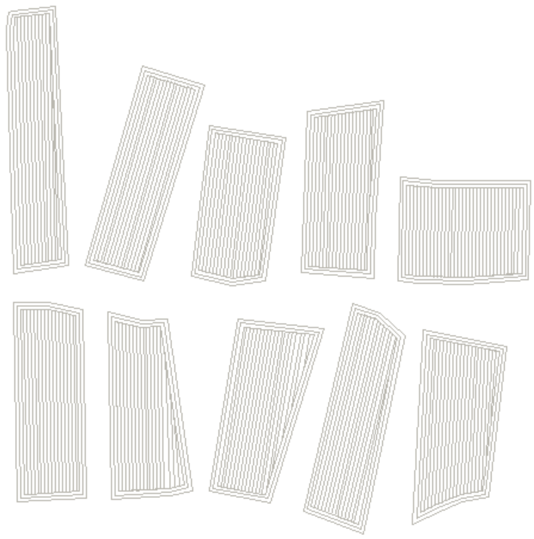

Figure 4. The ten fields areas and shapes implemented in for the simulated experiments

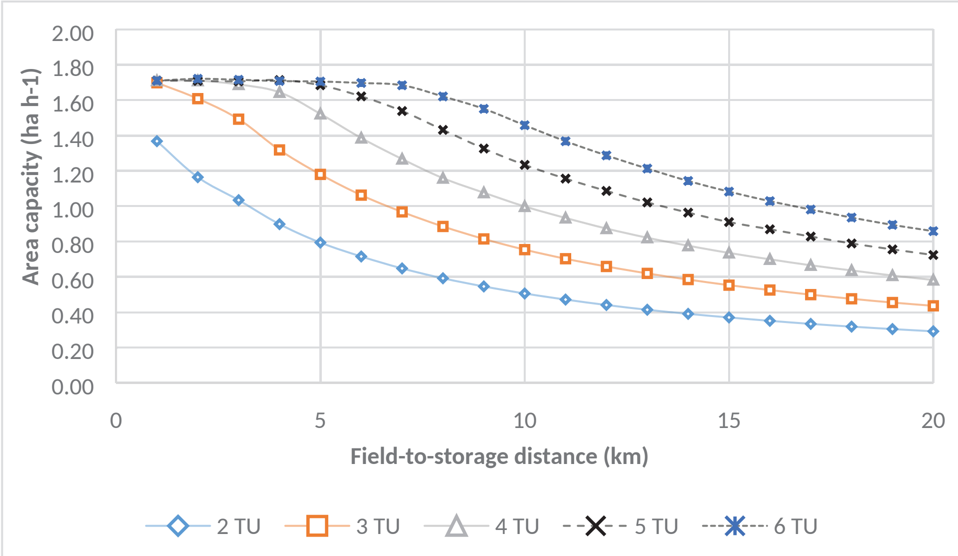

Figure 5. System chain area capacity (ha h^{-1}) as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

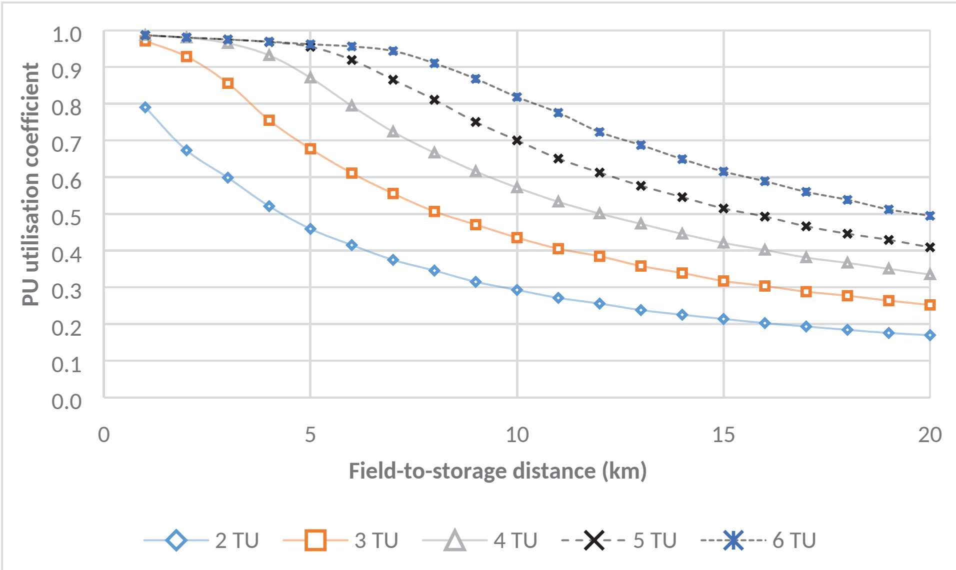

Figure 6. Primary unit (forage harvester) utilisation as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

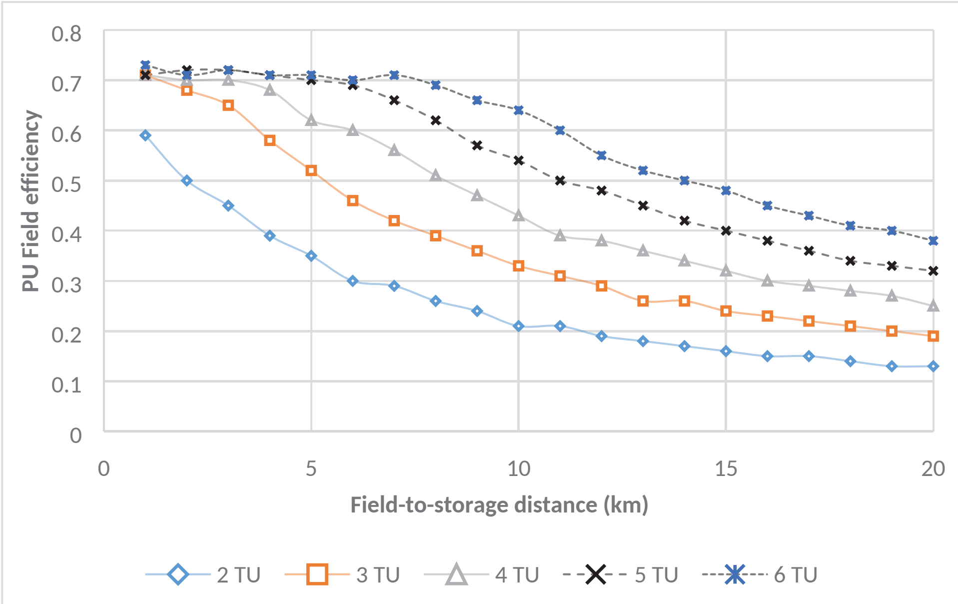

Figure 7. Average field efficiency of the Primary Unit (forage harvester) utilisation as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

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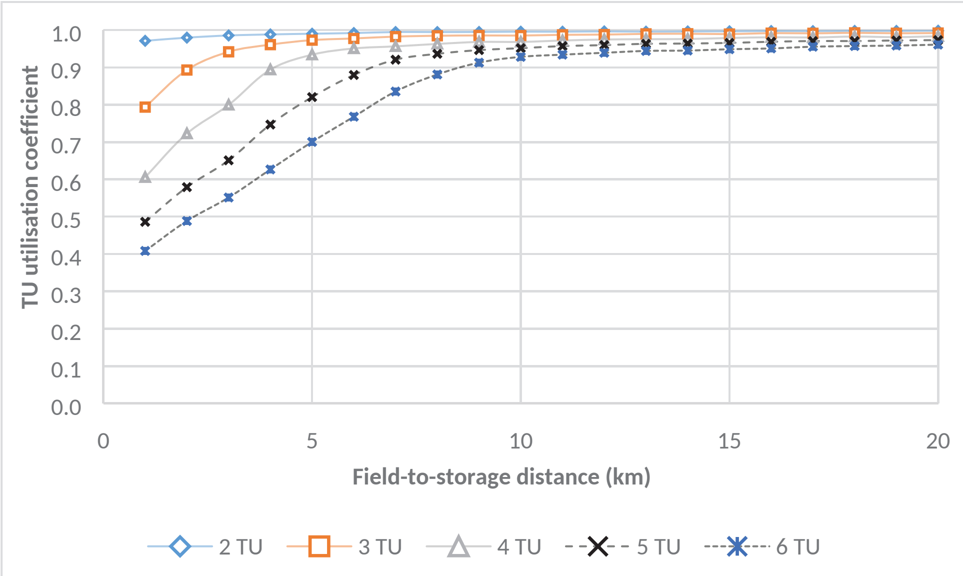

Figure 8. The transport units (TU) utilisation coefficient as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

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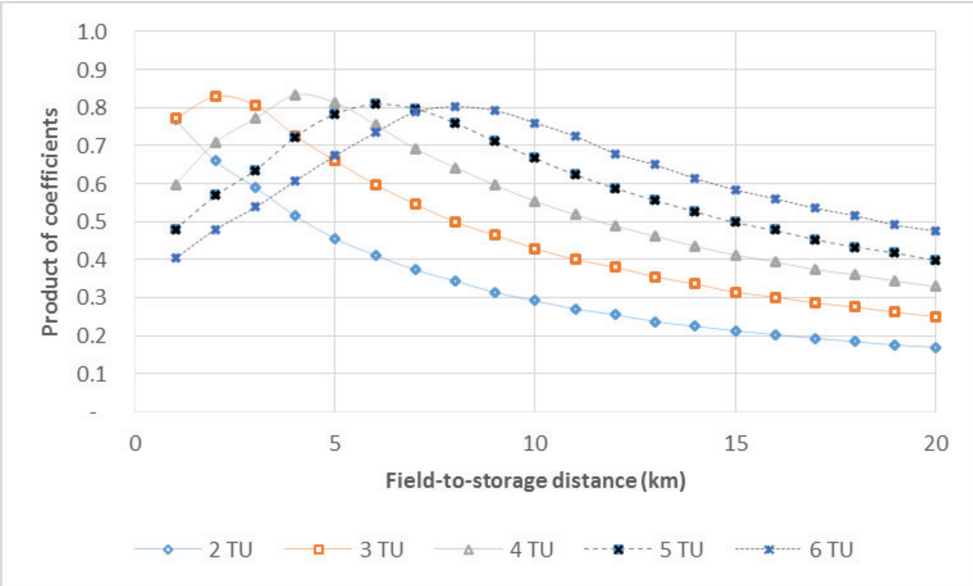

Figure 9. The product of the primary unit (PU) utilisation coefficient and the transport units (TU) utilisation coefficient as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

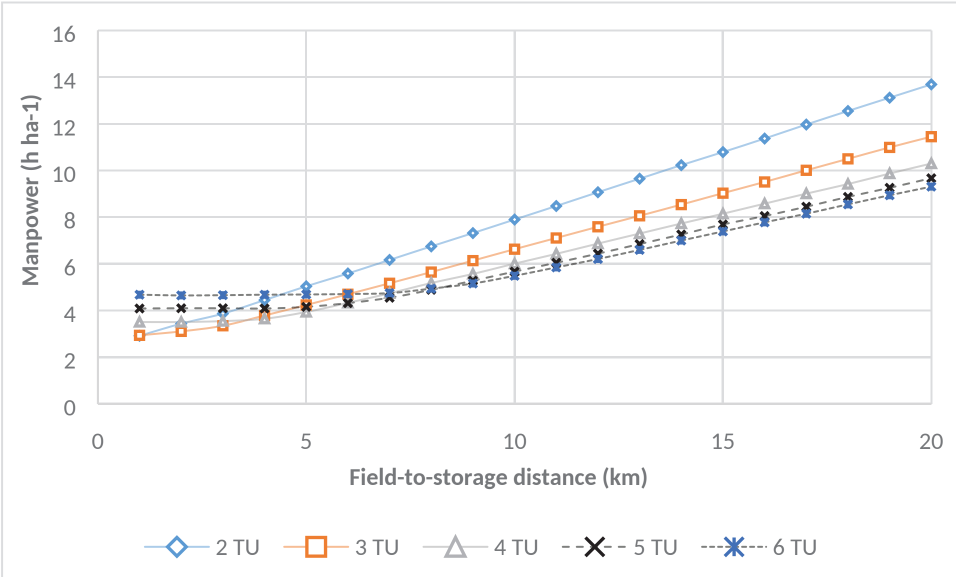

Figure 10. Labor requested (h ha^{-1}) as a function of field distance (1 to 20 km) for a different number of transport units (TU) available (from 2 to 6).

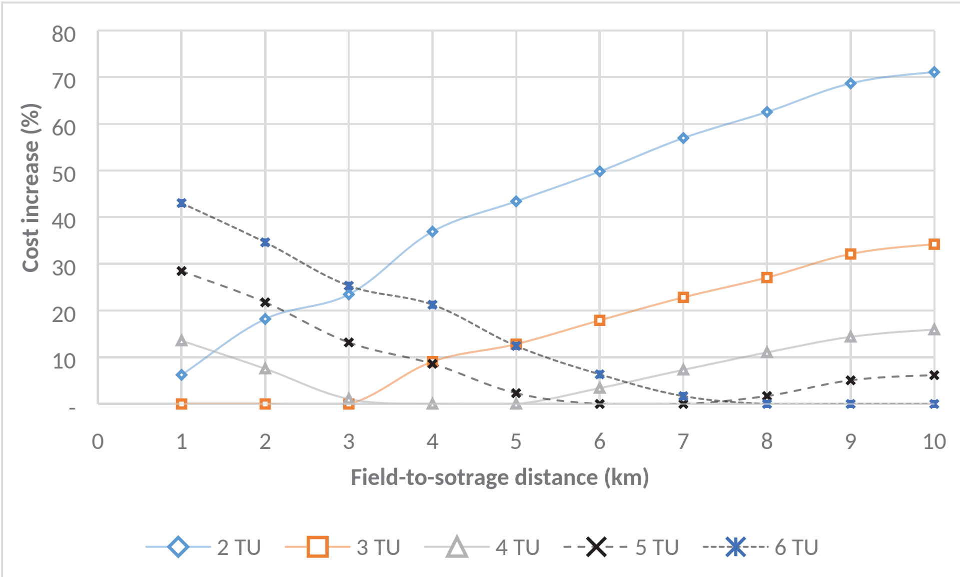

Figure 11. Total cost percentage increase compared to the cost corresponding to the optimal number of TUs for field-to-storage distances from 1 to 10 km.

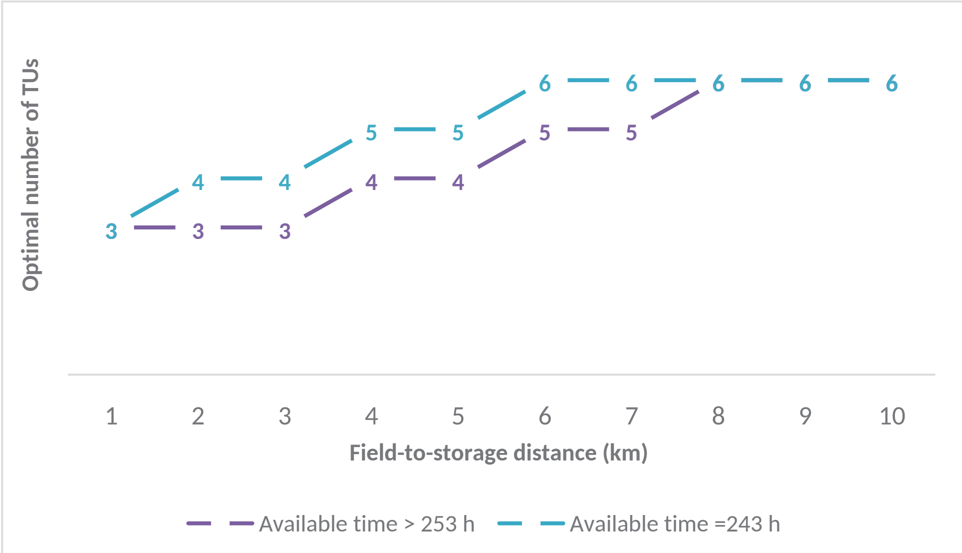

Figure 12. Configuration of optimal number of TUs (transport units) for the different operational time available to complete the operation (=243 h and >253 h) for scenario B (Fields dispersed over 10 km distance from the Farm).

Table 1. The list of the activities and junctions of the IDEF3 diagram

ID	Activity	Description
UOB0	Simulation initiation	The PU object is created. The TUs objects are created. The Field(s) object(s) are created. The simulation begins with the loading of the various items (e.g. fields, PU, TU, CU, etc.) and assigning of properties to them (e.g. working width, distributions of task times, distributions of working speeds, etc.). All of the field passes and their features are uploaded from the database created during the pre-processing (e.g., length, type of pass, filed-work motif, etc.). The configuration parameters are written into the internal database. All objects created are sent to J2
J2		In this junction, the objects generated in UOB0 have separated patterns. The TUs are assigned to the area in UOB2; the PU proceed to J3
J3		In junction J3 the PU is sent to the first activity, that is travelling to the first field. PU also comes from J3 in the case a following field has to be processed.
UOB1	PU is travelling to the field	The PU is travelling to the first field in order to start harvesting operation or to the following field to be harvested.
UOB2	Available TUs are assigned to field	The TUs are allocated to the field where the PU operates.
J4		In this junction a TU, either being assigned from OUB2 or coming empty from J8, is send to UOB3 after the unloading process.
UOB3	TU travelling empty to the field	In this operation, TUs are travelling empty to the field where the PU is operating. The TUs objects are sent to J6 and wait to be engaged with the PU in the on-the-go unloading activity.
J5		The PU is coming either from the storage location or from another field (UOB1), or from a harvested fieldwork track (J12) in order to complete the current track.
UOB4	PU is waiting for TU	The PU is waiting idly for the next TU to resume the unloading activity. UOB4 implies the computation of waiting times for the PU, in the case the TUs are not available.
J6		In the J6 the PU is coupled with the empty TU coming from UOB3.
UOB5	Calculation of length to be	The calculation of the remaining volume capacity of the TU takes place. Both PU and the engaged TU are sent to J7.

	harvested	
J7		Based on the calculation made in UOB5, the PU could either proceed to harvest of the next track (UOB6), complete unloading at the engaged TU (UOB7), or complete harvesting of the current field (UOB8).
UOB6	PU is harvesting	The PU is harvesting the next track (given the availability of a TU).
UOB9	PU and TU turns	Both PU and TU are performing a turn (there is always an idle time for PU). Both objects are sent back to UOB5 where the next action is assessed.
UOB7	PU is harvesting to complete TU load	In this case harvesting on the current track interrupted after a length necessary to fill-in the remaining TU wagon space. After that, both objects are sent to J12.
UOB8	PU is harvesting to complete field	The PU is harvesting a track to finish the operation in the field. After the completion of the track harvesting, both objects are sent to J10.
J12		TU is fully loaded and is sent to travel back to the storage location, while PU is sent to J5 waiting for the next TU available.
J10		The junction sends PU to J13, for verification if there is a new field to be harvested, and TU to J9
J9		The junction receives a TU loaded fully and sent it to UOB10.
J13		PU is sent either to the next field to be harvested, or, if all fields have been harvested, back to the farm.
UOB18	Simulation ends	The simulation is completed once all field has been harvested. This process collects all measures and statistics for the whole system performance.
UOB10	TU is travelling back to unloading	The TU is travelling back to the silage storage facilities fully loaded
UOB11	TU is moving to the unloading location	The TU is positioned for the unloading process.
J11		The decision to either unload the TU or to wait takes place. Packing could be stopped in favour of the unloading of the TU, or the TU unloading operation could be set on hold.
UOB13	CU is waiting	The CU activity is temporarily stopped. Subsequently to this activity, (UOB14) takes place.

UOB12	CU is working	After J1, the CU operates in order to free space for the TU unloading.
UOB14	TU is unloading	The TU is unloading in front of the bunker silo.
J8		This junction receives both TU and CU from UOB12 and UOB14, respectively. TU is sent to J4 to travel back to the field empty while CU is sent back to J11 to carry out another compaction cycle.

Table 2. The four areas where the field trials were carried out

Farm	Total Area (ha)	Number of fields	Range of field areas (min-max / ha)	Average field-to-storage (km)	Range of field-to-storage distances (min-max / (km)
Canavere	21.39	5	1.01 - 7.52	2.37	2.10 - 2.56
Torre Balfredo	8.45	2	3.32 - 5.13	4.68	4.56 – 4.80
Buriasco	8.51	2	3.95 - 4.56	4.39	4.32 – 4.45
Carmagnola	6.37	3	1.83 – 2.36	2.57	2.50 – 2.60

Table 3. Statistical distribution of the harvester and TUs data, recorded during the field trials

Operational elements	Number of observations	Statistical distribution	Parameters (mean, standard deviation)
PU working speed (km h^{-1})	366	Normal	N(5.03;1.66)
TU travelling speed in the field (km h^{-1})	29	Normal	N(10.2;2.35)
PU turning 180° (min)	246	Lognormal	0.125+LN(0.368,0.228)
PU turning 90° (min)	48	Lognormal	0.175+LN(0.42,0.428)
TU turning 180° (min)	117	Lognormal	0.325+LN(0.378;0.332)
TU turning 90° (min)	32	Lognormal	0.15+LN(0.54,0.695)
TU positioning at bunker silo (min)	29	Lognormal	0.200+LN(1.88;0.85)
TU unloading (min)	29	Lognormal	0.125+LN(1.27;0.63)

Table 1 – Comparison between the actual and the simulated results for the simulation module validation

Parameter		Actual value	Simulated value	Error (simulated-actual)	STD
System capacity		(ha h^{-1})	(ha h^{-1})	(%)	
3 TU	Field 1	1.4	1.43	2.1	0.08
3 TU	Field 2	1.38	1.44	4.3	0.11
3 TU	Field 3	1.4	1.43	2.1	0.11
2 TU	Field 4	1.13	1.09	-3.5	0.06
2 TU	Field 5	1.12	1.08	-3.6	0.06
PU utilisation		Dimensionless (0-1)	Dimensionless (0-1)	(%)	
3 TU	Field 1	0.78	0.79	1.3	0.23
3 TU	Field 2	0.77	0.78	1.3	0.23
3 TU	Field 3	0.76	0.78	2.6	0,23
2 TU	Field 4	0.62	0.59	-4.8	0.16
2 TU	Field 5	0.59	0.56	-5.1	0.16

Table 5. Total cost for the operation (€ ha^{-1}). In bold are presented the minimum cost for a specific distance

Field-to-storage distance (km)	Number of TUs available				
	2	3	4	5	6
1	293	**276**	314	355	395
2	345	**292**	314	355	393
3	388	**314**	318	356	394
4	447	356	**326**	354	395
5	505	397	**352**	360	396
6	561	441	387	**374**	398
7	619	485	423	**394**	401
8	677	530	463	424	**417**
9	735	575	498	458	**436**
10	793	622	537	492	**463**
11	850	667	574	525	**494**
12	909	711	614	558	**525**
13	968	756	653	594	**557**
14	1,026	801	690	630	**591**
15	1,082	847	729	667	**624**
16	1,141	892	766	698	**657**
17	1,200	938	805	732	**688**
18	1,258	985	842	769	**722**
19	1,316	1,031	882	803	**755**
20	1,373	1,074	920	838	**786**

Table 6. Linear programming output: logistic cost for silage of 400 ha and selected working chains for each selected field- to-storage distance.

	Scenario A			Scenario B			Scenario C		
Distance (km)	Area (ha)	Optimal number of TUs	Minimum cost (€ ha^{-1})	Area (ha)	Optimal number of TUs	Minimum cost (€ ha^{-1})	Area (ha)	Optimal number of TUs	Minimum cost (€ ha^{-1})
1	80	3	275	40	3	275	20	3	275
2	80	3	290	40	3	290	20	4	311
3	80	3	314	40	3	314	20	4	316
4	80	4	329	40	4	329	20	5	356
5	80	4	352	40	4	352	20	5	360
6	--	--	--	40	5	373	20	6	399
7	--	--	--	40	5	395	20	6	402
8	--	--	--	40	6	416	20	6	416
9	--	--	--	40	6	434	20	6	434
10	--	--	--	40	6	462	20	6	462
11	--	--	--	--	--	--	20	6	493
12	--	--	--	--	--	--	20	6	525
13	--	--	--	--	--	--	20	6	557
14	--	--	--	--	--	--	20	6	590
15	--	--	--	--	--	--	20	6	622
16	--	--	--	--	--	--	20	6	658
17	--	--	--	--	--	--	20	6	689
18	--	--	--	--	--	--	20	6	722
19	--	--	--	--	--	--	20	6	754
20	--	--	--	--	--	--	19,31[#]	6	787
Total costs (€)			124,836			145,614			203,765
Cost per area unit (€ ha^{-1})			312			364			509
Cost per material unit (€ tDM^{-1})			17.34			20.22			28.30

[#] Due to the time limitations the specific group of fields could not be completed, and an area of 0.69 ha remain unharvested