Research Article

Simulation of forest harvesting alternative processes and concept design of an innovative skidding winch focused on productivity improvement

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Abstract: In contexts in which mechanized harvesting is limited, such as in the northwestern Black Sea region of Turkey, it is important to improve timber harvesting productivity while preserving operators' safety and reducing environmental damage. This study aims to introduce a methodology in which the harvesting process is simulated with discrete-event simulation (DES) software in order to identify bottlenecks. An alternative process is compared to the original within the DES software, carrying out further steps oriented to the generation of new innovative product concepts. As a case study, the design of an innovative skidding winch is proposed. The development of the product was focused towards customer satisfaction by collecting customer requirements and identifying quality characteristics with a quality function deployment approach. Contradictions identified in the design phase were solved using the TRIZ contradiction toolkit, generating different product concepts. Inventive solutions provided by TRIZ were designed within parametric CAD software. The concepts were compared in a virtual environment, eventually selecting an optimal solution. The results showed that, with the concept adopted, it is possible to achieve a substantial increase in productivity, from 121% to 133%, in terms of kilograms of logs per hour deposited on the landing.

Key words: Discrete-event simulation, forest harvesting, quality function deployment, TRIZ

1. Introduction

The application of advanced mechanized harvesting in Turkey is limited because harvesting machines are highly expensive and mechanization is considered to have negative effects on employment (Melemez et al., 2014). The benefits of small-scale forestry equipment are lower capital expenditure and operating costs, the possibility to have multiple uses, and ease of transport (Masson and Greek, 2006).

Skidding winches are widely adopted in a tractor-mounted configuration; farm tractors with a winch attached can skid tree lengths from stand to roadside. A three-point hitch allows the tractor to raise and lower the winch for winching or skidding operations (Masson and Greek, 2006). Farm tractors attached with a winch system can skid logs downhill at up to a 25% ground slope (Heinrich, 1987).

Forwarding with farm tractors is widely adopted as another mean of logging; it is accomplished using a small trailer attached to the tractor. Forwarding requires more of an initial investment compared to skidding, but it has some advantages, such as large payloads, less soil disturbance,

and off-ground transport of the logs (Akay, 2005). Only for long distances (up to about 1000 m) is forwarding with a forestry trailer required (Akay, 2005).

This study was conducted within the borders of the Devrek Forest District Directorate, one of the richest areas in terms of forest resources in the northwestern Black Sea region of Turkey, with 68% of the land covered with forests and heath. In this area, the ground slope ranges from 30% to 70%. Harvesting operations in the region are performed using traditional methods, including the use of animal power for skidding and tractors for winching and skidding. In the area, the skidding winch is the most widely used tractor-mounted harvesting attachment during logging operations. The goal of this study was to test a whole array of innovative methods borrowed from other industries, such as the aerospace field, and use them for the development of an innovative skidding winch, specifically adapted to the real conditions of Turkish forest operations. We based our methodological approach on a previous study in which we designed a forestry trailer (Melemez et al., 2013). We have improved the methodology to support process simulation in order to compare different harvesting approaches.

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2. Materials and methods

The methodology that we adopted is illustrated in Figure 1. In its initial phase, this method was focused on the identification of bottlenecks in the process, followed by a simulation step that involves a comparison with an alternative system. We collected several necessary product characteristics for skidders via a survey administered to a group of 30 people involved in forestry activities, consisting of forest rangers, technical staff, and forest workers. Subsequently, we used the House of Quality, in association with the TRIZ toolkit, to identify engineering solutions and solve contradictions. We eventually designed several product concepts with the help of CAD software.

2.1. Time study

Time measurements in the area were conducted during timber harvesting practices. We chose compartment 10A (harvesting unit) of the Devrek Forest District Directorate for data collection. This compartment was harvested in accordance with the forest management plan from April to June 2011. The compartment has typical land characteristics of the region and is suitable for implementation of various extraction methods. The average slope of the compartment is about 30%, ranging from 20% to 40%. The stand type is a mixture of beech (*Fagus orientalis* Lipsky) and oak (*Quercus* spp.). The average skidding distance considered in this study was 100 m for all extraction methods. Timber
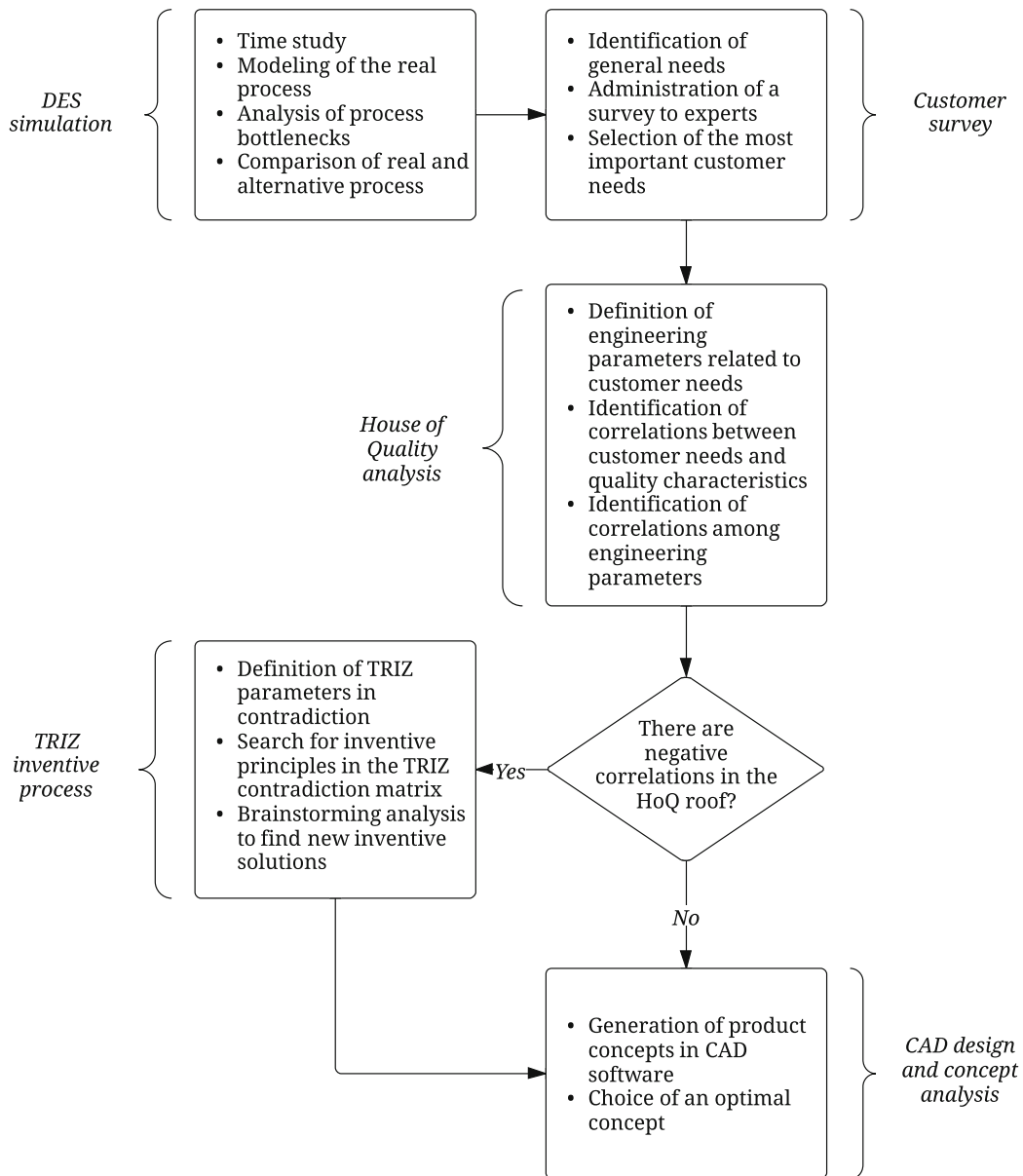

Figure 1. Flowchart of the methodology adopted.

was skidded uphill except when skidding with animal power on skid trails. The logs used in the study were chosen from those ranging 20 cm to 50 cm in diameter and 1.5 m to 4 m in length. The volume of logs was calculated according to Huber's formula. We recorded the diameters and lengths of the transported logs and calculated their volumes. The elapsed time of each working phase, moving the trees from the stump to the roadside, was measured and manually recorded on prepared forms. These forms were arranged separately for each skidding method. In addition, the skidding or hauling distance, slope, and direction of the skid were measured and recorded on the recording forms (Melemez et al., 2014). The analyzed process was essentially divided into 3 subprocesses: cut-to-length logging, pulling/winching, and skidding.

2.2. Discrete-event simulation

Starting with the information collected from the real practice, a rough flowchart draft of the process was created. A simulation model was then designed using Arena 14 to obtain the final process map. In the field of simulation, a discrete-event simulation (DES) models the operation of a system as a discrete sequence of events in time (Di Gironimo et al., 2015). Each event occurs at a particular instant in time and marks a change of state in the system (Robinson, 2003). In Arena, what flows through the chart is an object called an entity (Kelton et al., 2009). For this particular case study, the entity was designed to be a single load skidded from pad to landing. The process itself was modeled so that each load goes through several activities (e.g., is loaded or transferred), is affected by delays, and eventually is collected at the landing site.

Data were captured from time study forms into spreadsheet software (Microsoft Excel). The data were then copied and pasted into text files, from which they could be imported into Input Analyzer, a distribution-fitting software compatible with Arena 14. Statistical distributions were tested in terms of how well they described the data, using the Kolmogorov–Smirnov (K-S) test. Distributions with a P-value of less than 0.05 were rejected, while distributions with a P-value of greater than 0.05 were not rejected (in this particular case, we used empirical distributions generated from the real data). No normal distributions were used to fit theoretical distributions to empirical data, even if they had higher P-values than any of the other distribution options; the reason for this is that a normal distribution can result in the return of negative values during simulation runs from the function's tail (Kelton et al., 2009). We obtained the speed of transports (and their relative distributions) from recorded times and route distances. Thus, it was possible to carry out sensitivity analyses aimed to see how the system reacted to a change in the distances covered. Load variables important in skidding include weight, number of

logs grappled, and number of trees hooked (Akay et al., 2004). To simplify the model, a constant load of 800 kg was considered for each run; 30 replications, each of 8 h, were simulated in the software. For each replication, 5 different distances were simulated: 50 m, 100 m, 150 m, 200 m, and 250 m.

We used the simulation to confirm that the system had a queue on the operation of "Travel empty". This meant that the skidding operation was a bottleneck for the whole process. Therefore, we modeled a different extraction technique; in particular, we designed a process in which a skidder and a trailer were used in a combined way. The main constraint of this alternative solution was that the trailer needed to be able to connect directly to the skidder. This system was compatible with a forwarding process; in the actual process, after bringing the logs to the pad (from a very steep slope requiring the use of a skidding winch for the operation of pulling), they were carried across a forest road suitable for a tractor and a trailer. Since the two alternative systems shared the same initial and final steps (felling and pulling), both systems were modeled with respect to the transport of logs from landing to pad. A constant load of 6000 kg was assumed in the alternative system, because of the much bigger load capacity of the trailer rather than the skidding winch. Statistics used to model the forwarding operation were based on a large set of data provided by the Italian Trees and Timber Institute of the National Research Council of Italy (CNR IVALSA) in 2013. The time study contained information from about 500 chipper cycles and as many forwarder cycles, and it was adopted also to model delays. We considered our process compatible with this time study, since forwarding operations were performed using a tractor-trailer combination and ground conditions were similar to those of our study area. Discrete events (rest, planning, and other work) and delays (breakdown and other delays) were included in the model, following the same approach of Spinelli et al. (2014).

We calculated productivity in terms of kilograms of logs per hour deposited on the landing for each distance and for both systems.

2.3. Collection of customer needs

After the DES phase, which demonstrated the convenience of adopting a combined skidding/forwarding process, we developed new skidding winch equipment. To focus the design towards customer satisfaction, we obtained information from the customer about the desired product's characteristics, formulating a Likert-scale survey. In particular, we adopted a five-point Likert scale because it gives a good granularity to the choice range and an "indifferent" option (Bertram, 2009). The questions were formulated as statements that people could answer by selecting one of the following options that represent the

degree of adherence to the statement: strongly disagree (1), disagree (2), undecided (3), agree (4), and strongly agree (5). The aim of the questionnaire was to collect the voice of the customer, providing an input to the House of Quality. Several different needs were identified and proposed to people involved in forestry operations to obtain the classification from the survey. We started by focusing on the following general needs: tractor stability, prevention of cable breaks, preservation of environment, improvement of productivity, and ergonomic operations. A set of demanded quality elements was then identified in several statements (Table 1).

For example, statements 1 and 2 concern the possibility of vehicle rollover. Lateral and back rollovers are taken separately into account since the risk for them to occur is different, although the negative effects are similar. We administered the survey to a group of 30 experts involved in forestry activities, consisting of forest rangers, technical staff, and forest workers.

2.4. Identification of quality characteristics within the House of Quality

After collecting information via the survey, we adopted the House of Quality to find product characteristics that reflected the customer needs identified in the previous phase. Figure 2 shows the complete House of Quality.

The customer requirements identified using the survey (Table 1) were inserted into the left column of the House of Quality, in the section dedicated to the voice of the customer (Demanded Quality). A set of quality characteristics of the product was identified to satisfy these needs and was inserted into the top row of the table. These parameters describe the product in measurable terms and directly affect customer perceptions. Each parameter was also associated with a direction of improvement,

Table 1. Demanded quality elements.

No.	Demanded quality
1	Back rollover prevention
2	Lateral rollover prevention
3	Back tires protection
4	Damage to remaining stand trees and plants must be prevented
5	Soil damage must be prevented
6	Capability to pull in high-density stand
7	Capability to pull in high-slope conditions
8	Prevent cable break
9	Ease of loading operation
10	High productivity

indicated with a downward arrow if the parameter was to be minimized or an upward arrow if the parameter was to be maximized. We used the "x" when the parameter had a particular target value or performance. Once both the customer requirements and quality characteristics were added, the associations between both of them were identified and illustrated in the middle matrix of the House (Relationships Matrix).

2.5. Generation of innovative solutions with TRIZ

TRIZ is an engineering problem-solving toolkit that successfully summarizes past solutions and successes to provide a methodology useful to systematically solve future problems (Gadd, 2011). In the House of Quality we identified two types of contradictions that we solved using the TRIZ approach:

(1) In the roof matrix, the contradictions between engineering parameters were solved with the 40 TRIZ Inventive Principles and the Matrix of Contradictions;

(2) In each column of the Quality Characteristics section, the contradictions related to functional requirements were mutually exclusive between 2 opposite states. We solved physical contradictions with the TRIZ principles of separation.

The use of brainstorming analysis and technical knowledge was very useful in this phase, because TRIZ analysis works at a high level of abstraction (Domb et al., 1998; Terninko et al., 1998). Different concepts were generated within the CAD software Catia V5, using a top-down modeling approach (Melemez et al., 2013).

3. Results and discussion

The methodological approach that we adopted, in terms of requirements collection and generation of inventive solutions, is consistent with our previous study (Melemez et al., 2013). However, we chose to also introduce a DES simulation to analyze the real process and study the resulting impacts in productivity adopting an alternative one. According to Akay et al. (2004), different harvesting systems can be chosen based on the characteristics of the forest; different machine types and levels of intensity of the harvest operation reflect the variable factors that affect the productivity of the equipment. With respect to the simulation phase of the study, we followed the same methodological approach proposed by Hogg et al. (2010). Simulation models in forest harvesting operations aim to improve machine operating methods and interactions between machines, as well as minimize system bottlenecks, thus improving the system as a whole. According to Reisinger et al. (1988), since the birth of forest harvesting operation simulations, computers have aided in decision-making and improvement of system cost and production factors by balancing equipment within systems and assessing potential advances associated with stand and
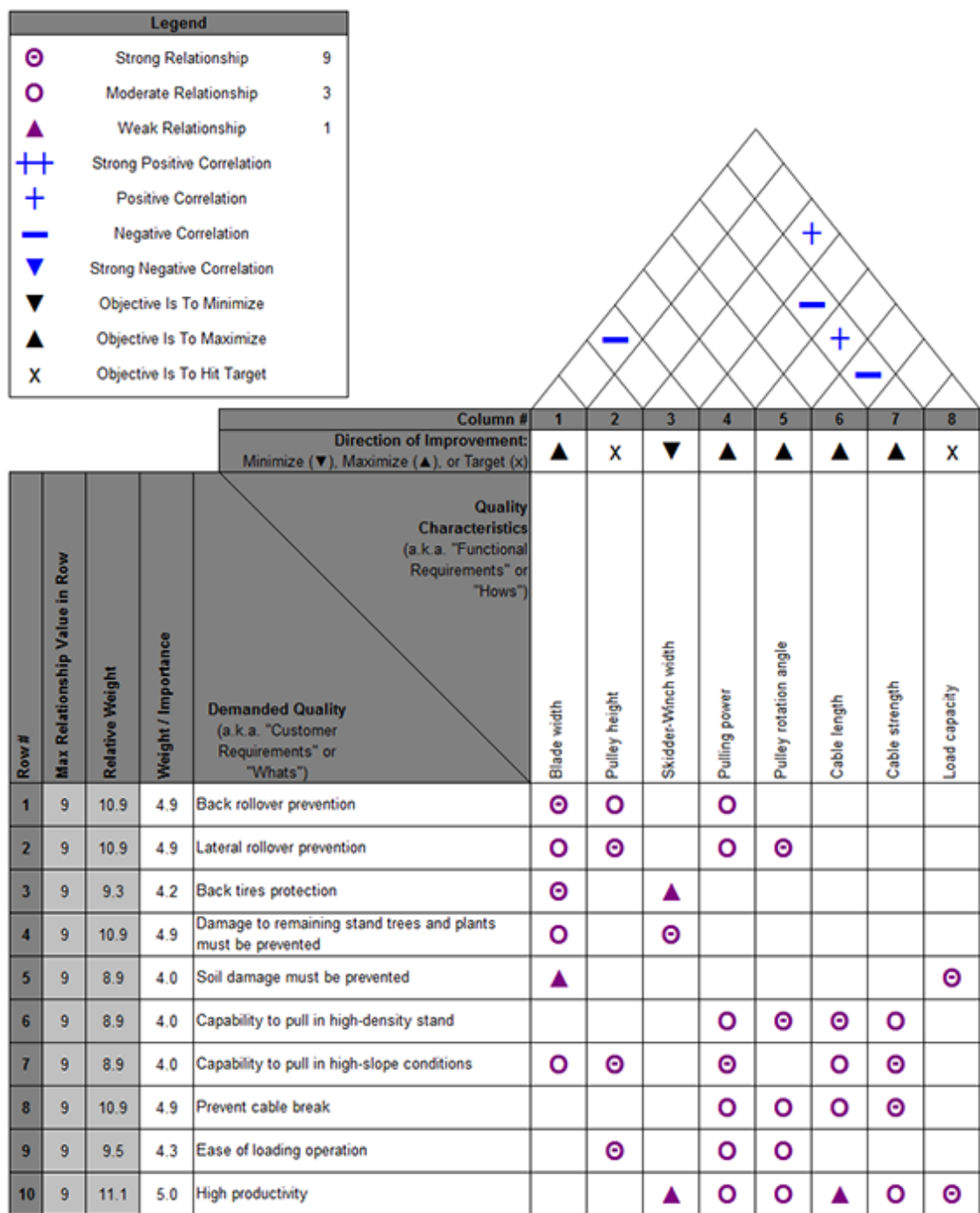
Legend

Symbol	Meaning	Value
⊙	Strong Relationship	9
○	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
X	Objective Is To Hit Target	

Column #				1	2	3	4	5	6	7	8
Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)				▲	X	▼	▲	▲	▲	▲	X
Row # / Max Relationship Value in Row / Relative Weight / Weight / Importance / Demanded Quality ("Whats")				Blade width	Pulley height	Skidder-Winch width	Pulling power	Pulley rotation angle	Cable length	Cable strength	Load capacity
1 · 9 · 10.9 · 4.9 · Back rollover prevention				⊙	○		○				
2 · 9 · 10.9 · 4.9 · Lateral rollover prevention				○	⊙		○	⊙			
3 · 9 · 9.3 · 4.2 · Back tires protection				⊙		▲					
4 · 9 · 10.9 · 4.9 · Damage to remaining stand trees and plants must be prevented				○		⊙					
5 · 9 · 8.9 · 4.0 · Soil damage must be prevented				▲							⊙
6 · 9 · 8.9 · 4.0 · Capability to pull in high-density stand							○	⊙	⊙	○	
7 · 9 · 8.9 · 4.0 · Capability to pull in high-slope conditions				○	⊙		⊙		○	⊙	
8 · 9 · 10.9 · 4.9 · Prevent cable break							○	○	○	⊙	
9 · 9 · 9.5 · 4.3 · Ease of loading operation					⊙		○	○			
10 · 9 · 11.1 · 5.0 · High productivity						▲	○	○	▲	○	⊙

Figure 2. The House of Quality for the skidding winch equipment.

machine variables. In fact, forest harvesting operation simulation models were launched in the late 1960s as a method of evaluating forest machine concepts (Goulet et al., 1979; McDonagh, 2002). Simulation has been proven as an acceptable method of harvesting operations' assessment in a wide range of machine, harvest, and stand condition variables (Wang and Greene, 1999; Hartsough et al., 2001; Wang and LeDoux, 2003). Eliasson (1999) stated that simulation allows the researcher to standardize certain variables, so that focus can be directed towards the variable(s) of interest, leading to more robust results. In particular, after the simulation phase, we proved how much the process of timber harvesting benefits from a different extraction technique using a tractor-

trailer combination, combining a skidding system with a forwarding system. Removal of logs is done with minimal damage to the residual stand, using a small maneuverable skidding machine. In fact, a trailer is less likely to be able to get to the log because of its size and handling features, such as the inability to turn in the woods. On the other hand, during the forwarding step, the vehicle stays on well-marked trails, as recommended by Masson and Greek (2006).

With reference to the real process, data were coming from the time study and were being processed for implementation inside the DES software, which generated 7 distributions. Only one of these distributions was statistically rejected (Table 2). The rejected distribution returned a P-value of less than 0.01 when performing the Kolmogorov–Smirnov test; an empirical distribution was therefore required to describe that data set inside the DES software.

For the alternative process, the data proved to be robust enough to fit all the statistical distributions evaluated in the Input Analyzer software (Table 3).

The results of the simulation showed that with the combined pulling-forwarding process, it is possible to achieve a substantial increase in productivity (Table 4).

Forwarding, in comparison with skidding, guarantees a productivity growth from 121% to 133%.

The simulation gave the opportunity to recognize the best alternative to current practices, based on a real set of data coming from time studies conducted during real situations. This means that the data replicated in the software related with skidding and forwarding operations were based on traditional machinery. Therefore, the simulation results do not take into account design improvements made in the subsequent steps of this study, and, in particular, the results are consequential to the choice of the skidding or forwarding process. However, the innovative solutions provided by TRIZ were also intended to improve machine performance with respect to the process selected. Under these premises, it could be interesting to iterate the method adopted in this study and perform another simulation session taking into account the contribution of innovative solutions in machine parameters configured in the DES model. The results of the survey administered to the forestry experts are reported in Table 5. All statements of the set of 10 possible customer needs achieved an average score of at least 4.

We used Quality Function Deployment functionalities to identify relationships between user requirements and

Table 2. Statistical distributions related to pulling operation.

Operation	Unit	Distribution	Expression	Test	P-value
Preparation	s	Weibull	6 + WEIB(56.2, 1.15)	K-S	>0.15
Felling	s	Erlang	37 + ERLA(61.6, 1)	K-S	>0.15
Cross-cutting	s	Beta	29 + 921 × BETA(1.17, 2.83)	K-S	>0.15
Delay	s	Weibull	2 + WEIB(48.4, 0.598)	K-S	>0.15
Pulling	s	Beta	4 + 313 × BETA(1.26, 2.07)	K-S	>0.15
Travel empty	m/s	Lognormal	EMPIRICAL	K-S	<0.01
Travel load	m/s	Lognormal	LOGN(1.09, 1.28)	K-S	>0.15

Table 3. Statistical distributions related to forwarding operation.

Operation	Unit	Distribution	Input analyzer expression	Test	P-value
Travel empty	m/s	Beta	1.2 + 1.8 × BETA(1.97, 1.43)	K-S	>0.15
Maneuver	s	Beta	12 + 473 × BETA(1.47, 2.67)	K-S	>0.15
Load	s	Triangular	TRIA(588,1.06e+003,2.8e+003)	K-S	>0.15
Travel load	m/s	Triangular	TRIA(1.11,2.15,2.59)	K-S	0.086
Discrete events	s	Exponential	18 + EXPO(220)	K-S	>0.15
Delays	s	Exponential	62 + EXPO(385)	K-S	>0.15
Unload	s	Beta	285 + 1.18e + 003 × BETA(0.828, 1.4)	K-S	>0.15

Table 4. Results of the DES simulation in terms of productivity.

Distance [m]	Skidding productivity [kg/h]	Forwarding productivity [kg/h]
50	3210	7275
100	3200	7175
150	3177	7025
200	3113	6975
250	2930	6825

Table 5. Results of the survey.

Mean score	Customer need
5.00	High productivity
4.90	Back rollover prevention
4.90	Lateral rollover prevention
4.90	Prevent cable break
4.90	Damage to remaining stand trees and plants must be prevented
4.30	Ease of loading operation
4.20	Back tires protection
4.00	Soil damage must be prevented
4.00	Capability to pull in high-density stand
4.00	Capability to pull in high-slope conditions

the derived design parameters; the same approach was carried out in a study by Sørensen et al. (2010). This is a description of the first quality characteristics identified: larger blade widths have positive effects in terms of back and lateral rollover prevention and rear tire protection, but they can cause damage to the environment and can reduce the capability to pull in high-slope conditions. In particular, we identified the following conflicts in the roof of the House:

- Blade width vs. frame width: a big blade is a good solution to improve the tractor stability to prevent rollover, but this increases the maximum width of the vehicle, resulting in an increase of the damage to the remaining standing trees;
- Pulling power vs. cable strength: power is useful to pull the logs in conditions of high gradients and to increase productivity by pulling more logs simultaneously, but it affects the resistance of the cable, increasing the cable breaks when a single cable is used;
- Cable length vs. cable strength: a long cable allows reaching distant logs and ensures the possibility of bypassing obstacles, but the cable resistance is reduced.

The House of Quality gives the opportunity to identify contradictions between engineering parameters (Hauser and Clausing, 1988). However, it does not give suggestions to solve these contradictions, only a way to prioritize in order to make a trade-off selection.

Table 6 shows the engineering parameters in conflict, the relative TRIZ parameters, the inventive principles chosen, and the solutions adopted.

For example, in the first conflict, the blade width and the frame width were involved. The improving parameter was "area of stationary object" (6), i.e. the surface formed by the blade. The worsening parameter was "object-generated harmful factors" (31), i.e. the maximum size of the skidding winch causing damage to the remaining standing trees. The contradiction matrix gave the following inventive principles: "blessing in disguise", "segmentation", and "composite materials". The principle chosen was "segmentation". The blade was divided into a fixed part and two additional parts.

Physical contradictions were all solved using the principle of separation in time:

Table 6. Solution of conflicts between quality characteristics.

Conflict number	1	2	3
Quality characteristic improved	Blade width	Pulling power	Cable length
Quality characteristic worsened	Main frame width	Cable strength	Cable strength
TRIZ parameter improved	Area of stationary object (6)	Power (21)	Durability of moving object (15)
TRIZ parameter worsened	Object-generated harmful factors (31)	Durability of moving object (15)	Stress or pressure (11)
Inventive principle chosen	1: Segmentation	35: Parameter change	3: Local quality
Solution adopted	Modular blade	Double-drum system	Protection for the cable

- The blade width contradiction was solved with the modular blade solution generated in the previous step, since the adoption of additional parts allows the blade to be wider when the vehicle is pulling and narrower during the skidding operation;
- The pulley height contradiction was solved introducing a second position for the pulley in the bottom of the skidding winch, which is a solution already adopted on many commercial forestry winches;
- The load capacity contradiction was solved adding a tow bar on the main frame of the skidding winch in order to attach a trailer for the operations of transport. In this way the skidding operation can be replaced with a forwarding operation, loading on the trailer the logs after the pulling operation.

In the CAD design phase, we adopted the same approach of Di Gironimo et al. (2012). With a top-down approach, the designer has a complete view of the whole assembly, and it is possible to make considerations and adjustments of the entire assembly in real time, saving time.

All the concepts that were designed share these solutions: a double-drum system consisting of two pulleys aligned one above the other in the centerline of the main frame, in order to enhance stability; a second position for the pulley, with the introduction of a permanent support on the frame, which protrudes from the lower part of the main frame, in order to have the possibility to carry out the pulling operation from two different heights; and a tow bar, proposed with the introduction of the support mentioned above, in order to have the possibility to connect a trailer and transform the skidder into a forwarder.

What distinguishes the three concepts is the different ways the blade of the skidding winch can be widened by adding additional parts. We designed three alternatives:

(1) The first concept is equipped with totally removable extensions of the blade (Figure 3). The main frame has cylindrical supports to store the additional parts when these are not in use and other supports on the lower part to mount the additional parts when required.
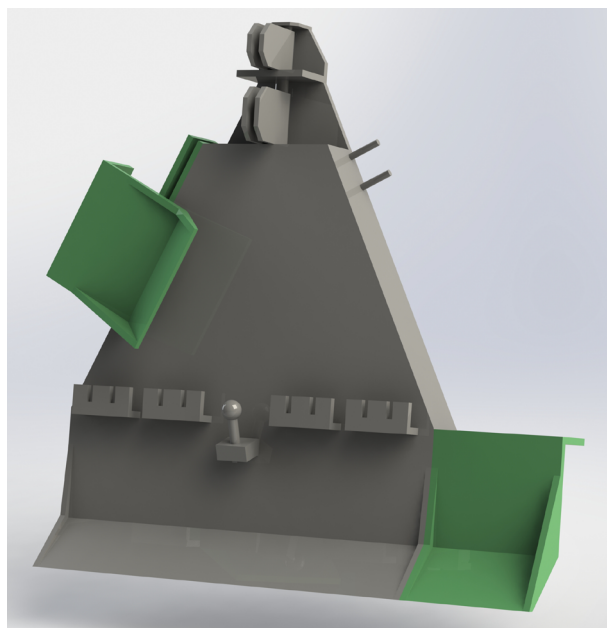
Figure 3. Removable extensions (concept 1).

The advantage of this system is that it is unnecessary to bring the additional parts when there is no need. A disadvantage is that the parts occupy some volume when stored in their supports on the upper side of the frame, increasing the equipment size.

(2) The second concept has rotating additional blades (Figure 4). The additional parts are connected to the main frame by hinges situated down on the backside. This system makes it possible to store the additional parts in the back of the main frame when they are not required, while, when they are in use, they can be rotated and positioned laterally. The advantage of this second proposal is that the additional blades disappear behind the skidding winch when they are not used. A disadvantage is that to extract the additional parts a minimum space is required to guarantee that the blades do not collide with the back tires of the tractor.
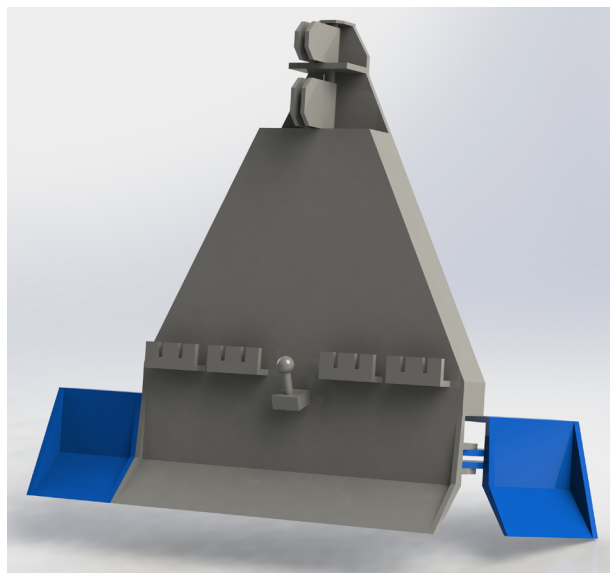
Figure 4. Rotating extensions (concept 2).

This limit has the consequence of increasing the distance between the skidding winch and the back of the tractor.

(3) Additional extractable blades characterize the third concept (Figure 5). The additional blades slide in a subframe situated in the lower part of the skidding winch; in this way, they totally disappear in the equipment's main frame. This system guarantees that the additional blades do not occupy more space when
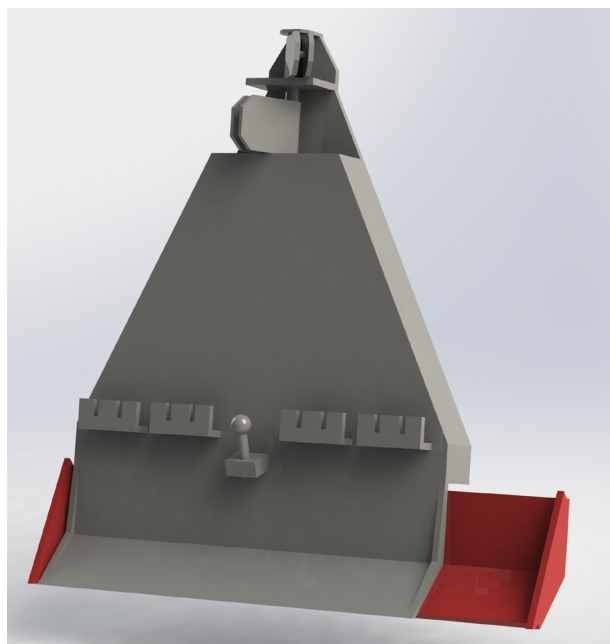
they are stored. Moreover, there is no need of a greater distance from the back tires, as seen in the previous solution. A disadvantage of this concept is that it requires the presence of a subframe, a more complex structure than the previous ones.

Figure 6 shows the final skidding winch concept with tractor and trailer.

In this study, we considered a typical process of timber harvesting adopted in the northwestern Black Sea region of Turkey. In particular, we introduced new skidding winch equipment, aimed to increase productivity in timber harvesting operations. To model and simulate the real harvesting system that was adopted in the western Black Sea region of Turkey, we used DES. The simulation provided information about queues resulting from bottlenecks in the process, mainly related to the skidding phase. An alternative system characterized by forwarding in place of skidding was also modeled and simulated. The results coming from the software showed that with the second system, it should be possible to achieve substantial increases in productivity. Moreover, the simulation gave the opportunity to design a new skidding winch concept. The main requirements for the new equipment were evaluated using a customer-centered approach by interviewing several people involved in forestry operations and building the House of Quality to translate customer requirements into engineering characteristics of the product. However, we identified three conflicts between engineering parameters and three physical contradictions. We solved the conflicts between the engineering parameters with the TRIZ Inventive Principles, using the Matrix of Contradictions. The physical contradictions were solved with the TRIZ Separation Principles. Three concepts were generated using Catia V5. Future studies could cover the simulation of manual operation and worker postures in virtual reality sessions to carry out ergonomics analyses. Moreover, the evaluation of costs in terms of fuel consumption, manpower, and equipment could be useful in order to see how the increase in productivity given by the adoption of the tractor-trailer system affects the capital expenditure and operating expenses.
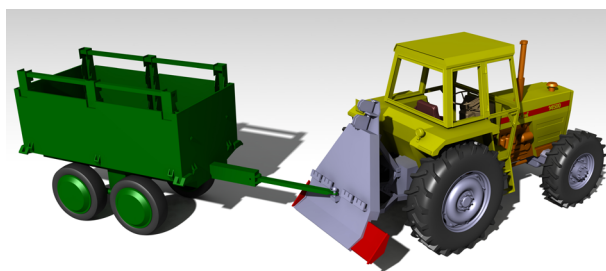

Figure 5. Extractable extensions (concept 3).

Figure 6. Final concept of skidder and trailer.

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