Utilizing Timber Harvest Simulation as a Tool for Education

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***Abstract*—Forestry is an important economic field in Germany as well as world wide. In Germany, specially trained forest managers are in charge of silviculture and preservation of forests. An important part of a forest manager's training is the ability to estimate the economical feasibility and ecological impact of timber harvesting operations. In this contribution, we present timber harvest simulation as a tool to enable teachers to better present these estimations in the forestry classroom. We present the simulation as a featured application of the Forest Management System ClusterWIS, including the developments required to implement our educative approach.**

Keywords–Simulation; Geo Information Systems; Forest Information Systems; Education; Timber Industry.

I. INTRODUCTION

An important part of a prospective forest manager's training is economical and ecological planning and calculation of timber harvesting operations. This training is usually done with elementary teaching methods and does not utilize modern, technology-assisted teaching methods. Common calculation methods taught to aspiring forest managers include calculations following official forestry guidelines (e.g,. those of the German state of North-Rhine Westphalia [1]). These guidelines are primarily based on experience, and utilizing them requires only basic knowledge about the areas affected by a harvesting operation.

The usage of limited information is not without drawbacks: It is rarely possible to accurately calculate concrete costs and revenue for a single, custom harvesting operation. The amount of flexibility regarding key process parameters is very limited. Forestry instructors, however, need tools that are more flexible to teach students the influence of different parameters on the outcome of a harvesting operation, and that are customized to the forestry areas used to educate their trainees on site.

Some researchers already approached this problem: Asikainen [2], Bruchner [3], Ziesak et al. [4] and Hemm et al. [5] used simulation to estimate costs and revenues for harvesting operations. However, their approaches were largely limited to a small set of predefined geographic locations, and were still not very flexible regarding different process parameters (e.g., they could only simulate a single mechanized harvester and forwarder). Therefore, we already developed a hybrid discrete-event and quasi-continuous timber harvest simulation system presented in [6] as a more flexible alternative. It offers a grater flexibility than the classical, table-based approaches or the other simulative approaches. It is able to calculate the economical results of a timber harvest operation, and also offers methods to estimate the ecological impact of those operations.

Hence, we propose our simulation system as the basis for a simulation tool that is fit to be used in education. However, it still does not quite offer the required flexibility. With the integration of our simulation system into ClusterWIS, we were able to extend and adapt the system to meet the requirements of educative use, and were even able to improve its' usability for non-simulation experts. In this contribution, we present our extensions and adaptations in detail.

Even so, a flexible simulation system alone is of limited use to forestry trainers. They also need an didactic concept that is adapted for use with the simulation. Teachers need to properly utilize simulation results in their classes to gain all benefits of such a system. Therefore, we also developed such a concept and present it in this contribution.

The structure of this article is as follows: The next section introduces ClusterWIS as as the underlying infrastructure for our approach. Section III presents the ClusterWIS timber harvest simulation system as well as our novel approaches to extend that simulation system and improve its flexibility and usability. Finally, section IV describes a didactic concept for forest manager trainees based on timber harvest simulation in ClusterWIS.

II. THE GEO AND FOREST INFORMATION SYSTEM CLUSTERWIS

ClusterWIS [7] is a decentralized infrastructure for Geo and Forest Information Systems that originated from the "nD Forest Management System Virtual Forest" [8], [9]. It is implemented using the simulation system VEROSIM® and allows us to readily access several data sources that originated in the Virtual Forest and to develop custom algorithms to process their data for a wide range of applications.

In particular, the following data sources are relevant to timber harvesting and are used by the timber harvesting simulation that is the basis for our didactic concept.

- A land registry that defines forestry sites.
- A high-resolution terrain elevation database (including hill shades).
- A map of forest roads and streets.
- A tree database containing information about location, type, age, and height of trees present in the forestry sites; Because of cost concerns, the entries of this database were not generated by exhaustive forest assessment, but were generated from aerial

Figure 1. 3D view of a simulated mechanized harvester in ClusterWIS.

measurements of tree heights in combination with a pre-existing tree type map, utilizing the methods described in [10].

- A database of forest machinery available for harvest operations.

In addition, ClusterWIS offers the possibility to render clear two-dimensional views of the aforementioned data sources, as well as three-dimensional renderings that intuitively illustrate the nature of the displayed forest areas. Figure 1 displays a simulated mechanized harvester in ClusterWIS. Finally, the service-oriented, distributed nature of the ClusterWIS infrastructure allows for the easy deployment of the simulation system to educational institutions by offering simulation as a service.

III. A CLUSTERWIS-BASED SIMULATION SYSTEM FOR TIMBER HARVESTING OPERATIONS

One of the features that is available in ClusterWIS is a Petri-net based scripting Interface called State Oriented Modelling Language++ [11], [12]. This interface has already been used to prototypically develop a combined discrete-event and quasi-continuous simulation system for timber harvesting in the Virtual Forest [6], [13]. It offers the possibility to simulate and analyse work processes in the field of fully mechanized timber harvesting conducted by harvesters and forwarders. A simulation pass in this system is conducted by completing the following tasks:

1) Select the affected area. This includes an automated import of the forest and skidding roads – also known as logging roads or logging trails – that are used for navigation by mechanized harvest resources.
2) Mark trees in the affected area for felling.
3) Calculate the marked trees' assortments. This includes the process of subdividing felled trees into segments (called *sorts*), usually to optimize the revenue of a felling operation. The relevant parameters in timber assortment are the minimum allowed top diameter of the resulting sorts, and optionally, their lengths.
4) Select harvest resources (i.e., mechanized harvesters and forwarders)
5) Execute the simulation.
6) Review the simulation results.

The behaviour of harvest resources modelled as a multi-agent system by hierarchical, synchronized and timed Petri-net state machines. The synchronized Petri-net components represent the discrete-event portion of the behavioural model and react to events, such as the felling of a tree or the successful unloading of logs at a road. The timed Petri-net components model the quasi-continuous potion of the behaviour and simulate real-time navigation used to determine the position of interacting harvest resources to allow for safety checks (e.g., when a tree is felled by a harvester, all other harvesters have to be at a minimum safety distance). The Petri-nets are executed by the SOML++ scripting interface and interact with the underlying geo information system to execute the models and lead to a simulation of harvesting operations. More details of this simulation approach and the underlying framework can be found in [6].

However, the simulation system included in ClusterWIS is limited with regard to the flexibility of supported process parameters: It only supports simulations of fully mechanized timber harvesting operations and offers a very limited way to calculate timber assortments. It is also confined to a pre-existing database of forest and skidding roads. Those limitations are severe: The definition of assortments is the most important factor in determining the yield and financial revenue of a harvesting operations, and different skidding road spacings may require manual felling of trees, which is an important cost factor.

While discussing our initial concepts for digital timber harvesting education with representatives of a local forestry teaching facility, we realized that we needed to extend the ClusterWIS timber harvest simulation system and add features that address the mentioned shortfalls. The following subsections discuss these adaptations and extensions in detail.

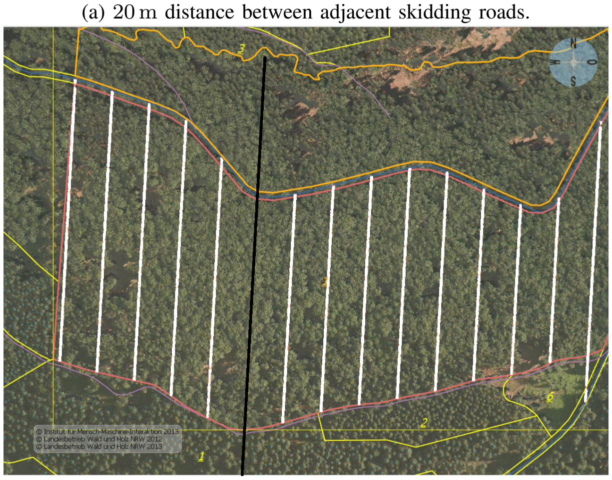
A. Definition of Custom Skidding Roads

The positioning – and particularly the distance – between adjacent skidding roads is an important factor for the total work, and correspondingly costs, associated with a harvest operation. If skidding roads are more than two harvester tool ranges (usually $20\,\mathrm{m}$) apart, some trees are not reachable by mechanized harvesters, and thus cannot be felled by them. Since the German Forest Stewardship Council (FSC) standardizes a skidding road distance of at least $40\,\mathrm{m}$ for ecological reasons [14], this happens quite regularly. In order to enable users to adequately simulate and compare harvest operations with different sets of skidding roads, we added a tool to customize the road network accordingly, and utilize the resulting roads in simulation. In particular, we added the possibility to generate equidistant skidding roads in an area based on a single prototype, shown in Figure 2.

B. Simulation of Manual, Mechanized and Mixed Timber Harvesting

Trees that are outside the range of mechanized harvesters have to be felled manually by lumberjacks. Lumberjacks are not bound to a road network, but can walk up to any tree and fell it utilizing a chainsaw. However, utilizing manual labour in harvesting operations is more expensive and time-consuming than utilizing mechanized harvesters. To profit from the unlimited range and mobility of lumberjacks as well as the efficiency of mechanized harvest, lumberjacks must fell the trees toward the skidding roads, where mechanized harvesters may pick the felled trees up and process them. This includes

(a) 20 m distance between adjacent skidding roads.



(b) 40 m distance between adjacent skidding roads.

Figure 2. 2D top down view of an exemplary forest area with customized, equidistant skidding roads (white). The black line is the prototypical skidding road used to generate the others.

the de-branching and splitting of the felled trees into sorts. If no harvesters are assigned to a harvest operation, lumberjacks have to conduct the processing as well. Figure 3 shows the simulated behavioural work flow of a lumberjack.

We added the functionality to utilize lumberjacks into our simulation system as a type of harvesting agent by modelling their behaviours as Petri-nets that resemble those nets that model the harvesters' behaviour.

We also added skidders as a new type of harvesting resource. Skidders are manually operated tractors outfitted with tongs or cable winches that can be used to manually transport logs from the wood to the nearest street. In this case, skidders act as the manual counterpart to mechanized wood forwarders. Furthermore, skidders can be used to pull felled trees to skidding roads if they cannot be felled into the harvesters' range.

With the inclusion of manually working harvest resources, the simulation system now offers the following harvest scenarios:

- Fully mechanized harvest with harvesters and forwarders.
- Fully manual harvest with lumberjacks and skidders.

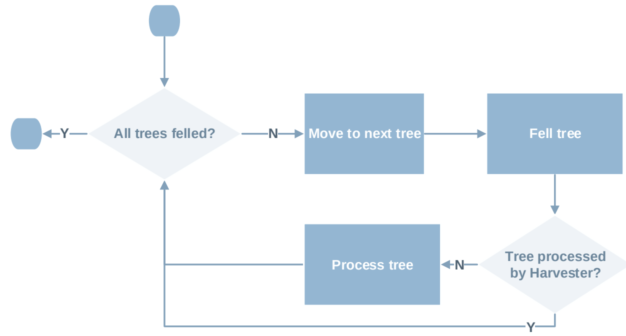


Figure 3. Schematic work flow of a manually harvesting lumberjack.

- Mixed harvest with lumberjacks felling trees that are far away from skidding roads, and harvesters and forwarders conducting all further work steps. Optionally, skidders may be used to pull felled trees toward skidding roads.

C. Improved Interoperability with Timber Assortment Tools

When adding the possibility to simulate lumberjacks, we realized that manual and mechanized harvest utilizes different approaches for timber assortment: While mechanized harvesters predominantly produce fixed-length log segments, the process of repeated manual bucking by lumberjacks is quite labour-intensive and therefore expensive. Consequently, manual harvest is usually used to fell whole logs. However, the pre-existing interface from the simulation system to the timber assortment tool BDAT [15] could only execute fixed-length sortimentation. We extended this interface to support the calculation of whole-log sortimentations. We also added the commonly used parameter of minimum top diameter to the interface. This parameter defines a minimum diameter for each harvested log or log segment. Smaller segments are regarded as industrial-grade wood and are valued less.

After discussions with domain experts, we realized that BDAT, while enabling a fast and easy-to-configure calculation of assortments, lacks flexibility that is desired in practice. Therefore, we decided to add a new interface to the HOLZERNTE (German for "timber harvesting") software package [16] that is developed at the Forest Research Institute Baden-Württemberg and allows for arbitrary, highly customized assortments. However, this software is only used with an extensive forestry background and lacks performance when calculating sorts. To overcome the second limitation, our software interface generates a limited number of representative, virtual trees that are sorted by HOLZERNTE. The resulting assortments are re-used for multiple trees that are most similar to the respective virtual one.

With the extension of the BDAT interface and the addition of the HOLZERNTE interface, users are now able to choose between two easy to use and fast, yet simple methods to calculate assortments and one that is highly flexible, but more difficult to use.

D. Support For Wood Quality Classes in Revenue Calculation

Wood prices—and therefore the potential revenue from a completed timber harvest operation—are dependent not only

Results

During this harvest operation, 407 trees with an average diameter breast height of 28,44 cm were felled. A total volume of 261,21 m³ was harvested.

Revenue and Costs

Calculation	Amount Value (€)	Wood Volume (m³)	Amount Value per Wood Volume (€/m³)
Lumberjack	204,51		
Lumberjack	160,68		
Lumberjack	167,60		
Harvester	2 375,69		
Forwarder	1 683,00		
Total Costs for Felling and Processing	2 908,48	261,21	11,13
Total Costs for Skidding	1 683,00	261,21	6,44
Total Costs	4 591,48	261,21	17,58
Gross Revenue	19 953,95	261,21	76,39
Net Revenue	15 362,47	261,21	58,81
Lost Revenue	206,60	2,85	72,42

Figure 4. Screen shot of economic results generated by a simulation run, as displayed in our custom HTML template (translated to English).

on the previously mentioned assortment, but also on the quality of the wood itself. In Germany, wood quality is measured in quality classes, which abstract from quality factors as irregular growth, cracks or insect damage [17]. Since we were able to obtain wood price tables that are differentiated into these quality classes, we added the possibility to assign quality classes to the harvested assortments to the BDAT interface, and to extract the corresponding data from the calculation results of the HOLZERNTE software.

With these changes, users can choose to set the harvested woods' quality and calculate felling revenues dependant on this parameter, regardless of the chosen assortment algorithm.

E. Analysis and Presentation of Simulation Results

During discussions with domain experts, we realized that we needed to rework the results statistics previously displayed by the simulation system: The statistics were incomplete, unclear, and displaying them on high-resolution and high-DPI monitors was not possible. Therefore, we completely replaced the statistics display of the ClusterWIS wood harvest simulation system. In order to reach compatibility with arbitrary display sizes and resolutions, we designed a HTML-based template as the foundation for our results display, thereby shifting the responsibility for correct rendering of our results to the web browser used to display them.

The first part of our results page (see Figure 4) displays the economical outcome of an exemplary simulation run of a mixed harvest scenario that does not utilize skidders. The economical outcome table contains a breakdown of all simulated felling costs and the expected total revenue of the harvested logs. It also contains a row displaying potential revenue that was lost, because not all trees could be felled due to their distance to the skidding roads.

Our results page also contains a set of detailed statistics tables of all harvested sorts (grouped by tree type and sort class and sort quality class) and their corresponding values. For comparison, we also display a similar table for all assortments that could not be harvested (e.g., because they were out of range of the harvesters in a fully mechanized harvesting operation).

Harvester

Work Breakdown:

Action	Time (total)	Time (per Wood Volume)
Driving	01:21:19	00:00:19
Positioning	01:38:42	00:00:23
Felling	00:59:44	00:00:14
Processing	07:11:10	00:01:39
Total (RAZ)	11:10:54	00:02:34
Total (MAS)	13:25:05	00:03:05
Total (GAZ)	16:06:06	00:03:42

Statistics:

Criterium	Value	
Felled Trees	231	
Processed Trees	407	
Processed Wood Volume	261,21 m³	
Efficiency	16,22 m³/h	
Distance Driven	5 212,79 m	19,96 m/m³
Fuel Consumption	187,85 l	0,72 l/m³
Average Driving Speed	3,85 km/h	
Houly Costs (including Fuel)	177,05 €/MAS	

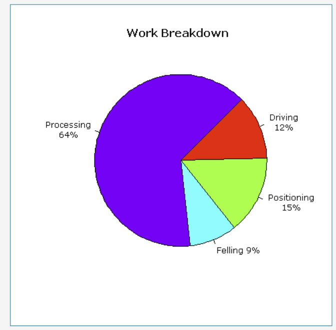


Figure 5. Screenshot of work statistics calculated from a simulation run, as displayed in our custom HTML template (translated to English).

Results Comparison

Comparing results for a table-based calculation and a simulation-based calculation.

Results Overview

Name	Harvested Trees	Wood Volume (m³)	Gross Revenue (€)	Total Costs (€)	Net Revenue (€)
Table-Based Calculation	Ø	108,90	8.875,35	3.913,87	4.961,48
Simulation-Based Calculation	130	128,75	10.857,78	3.834,06	7.023,73

Figure 6. Screen shot of an exemplary results comparison table (translated to English).

The last part of our results page consists of work statistics tables for each simulated harvest resource. These tables show the allocation of work time to the different work steps (e.g., driving, felling, debranching or log loading), and some efficiency statistics such as total fuel consumption and work efficiency (i.e., harvested wood volume per hour). We also added a pie chart to offer a quick overview of the work time allocation for each resource. Figure 5 shows an exemplary statistics table. For forwarders, the statistics include a calculation of the minimum, maximum, and average forwarding distance. These statistics are similar to the statistics generated in the former version of the simulation system, and are not described in detail.

In order to be able to compare different harvesting scenarios, we also added a HTML template that combines the economical results of multiple harvest operations. That template can be used to navigate to the previously described in-depth simulation statistics. An example is given in Figure 6. The felling names are links to detailed result pages containing the information described above. The table-based approach (as described in [1]) is not able to calculate a number of harvested trees, since this approach is solely based on wood volume.

IV. EDUCATIONAL USE OF TIMBER HARVESTING SIMULATION

We propose the use of timber harvesting simulation with an interactive, discussion-based didactic approach. Depending on the availability of simulation system instances in the classroom, there are different ways to integrate our extended simulation system into such a concept.

If there is only one simulation system instance available, teachers may want to discuss the relevant simulation parameters (as described in Sections III and III) with their students and display simulation results on a frontal display. The selection of parameters can be done in form of a interactive discussion based on the information displayed by the Geo Information System components of our simulation system. When focussing on a specific aspect of timber harvesting, teachers can set up different simulation runs that differ in only one or two parameters that fit the topic of the lesson. Students can compare the different simulation runs' results to analyse the economical or ecological impact of the changed parameters.

If there are multiple simulation system instances available, students can work in groups to explore the impact of different parameters themselves and try to optimize simulation parameters (selected by the teacher in accordance to the lessons' topic) with regard to financial profit, work efficiency or ecological impact. The students may then present their results to the class and discuss their discoveries.

In both scenarios, teachers may want to restrict the simulation to geographical areas located in the vicinity of the class room. That enables them to take their students to a field trip to that area where the students can try to transfer their simulation-based results to the real world. Teachers can discuss the discrepancies between the (potentially inaccurate, incomplete or out-of-date) data present in the simulation system and the actual area and present restrictions on the simulation parameters that follow from these discrepancies. These restrictions can be taken into consideration when conducting simulation in a later lesson.

When teachers employ our simulation system in their classes as described above, they can deepen their students' knowledge and understanding of the different aspects of timber harvesting. They can focus on any aspect their curriculum requires and can discuss and compare a wide range of possible statistical results that are relevant to real-world use.

A. Exemplary Lesson Plan

We present an exemplary lesson plan that focusses on the difference between fully mechanized and mixed harvest (as described in Section III-B). The lesson plan assumes the availability of our simulation system for the teacher only. It requires a fundamental theoretic understanding of the presented topics by the students, and assumes the teacher to be a certified forestry management educator with corresponding background knowledge about timber harvesting processes, and with an introductory training in the simulation system.

1) The students discuss guidelines for skidding road placement in tandem with the teacher. One important guideline to consider is the German FSC that requires a distance of $40\,\mathrm{m}$ between skidding roads.
2) The students utilize hill shades maps, aerial photographs and a 3D view of the terrain to develop concrete skidding road placements according to the guidelines. The teacher adds them to the simulation system.
3) The teacher adds a new set of parameters to the timber harvest simulation system.
4) The teacher presents different methods to select trees for felling and utilizes one method to mark trees for felling in the simulation system.
5) The students discuss different possible timber assortments. The teacher adds a corresponding assortment to the simulation parameters.
6) The students develop different possible resource configurations in tandem with the teacher. They discuss each configurations' advantages and disadvantages (e.g., regarding felling costs or tree reachability from the skidding roads).
7) The teacher chooses a fully mechanized harvesting configuration (i.e., one mechanized harvester and one forwarder) and adds it to the parameter set.
8) The teacher starts the simulation. After the simulation is finished, they open the results page.
9) The students analyse the results with the teacher. They are expected to realize that soil stress concentrates on paths leading up to the landing site (Figure 7a) and that some trees are out of range of the harvesters and remain unharvested (Figure 7b).
10) The teacher adds a set of lumberjacks to the simulation parameters and repeats the simulation.
11) The students analyse the new results and compare them with the previous ones. They are expected to realize that more (possibly all) trees were harvested in the second simulation, and accordingly, the gross revenue has increased. The cost per harvested wood volume has gone up due to the utilisation of (relatively expensive) lumberjacks.

During step 2, the students may rely on physical maps of the area, map views offered by the Geo Information System, or a mix of both. Steps 4 and 5 are not in the focus of the presented lesson and should be discussed only briefly. They may be discussed in detail in another lesson.

Another topic that may be presented in a different lesson is the environmental impact of harvest operations. In such a lesson, the teacher may compare soil stress (see Figure 7a) and fuel consumption resulting from the use of smaller/larger forwarders or different (or multiple) landing sites. Such a comparison can be found in [6].

V. Conclusion

In this contribution, we presented extensions and usability improvements to the ClusterWIS-based system for timber harvest simulation. We aimed for the improvement of the users' flexibility when configuring the simulation parameters. In order to do so, we completely reworked the assortment interface and enabled users to utilize a professional external program to finely tune the assortments to their requirements. We also allowed users to create their own skidding road networks and consequently simulate manual felling of trees. We finally replaced the former results display by a navigable, HTML-based results document.

In the end, all these improvements allowed us to develop a concept for educational use of timber harvesting simulations in training forestry managers, included in the decentralized forest information infrastructure ClusterWIS. We presented this didactic concept and illustrated it with a corresponding exemplary lesson plan.

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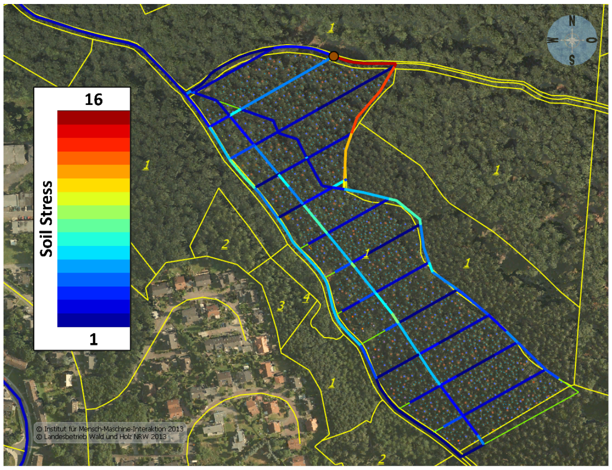
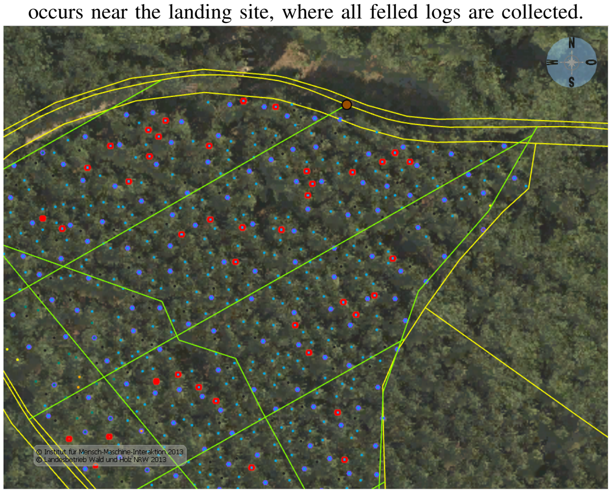


(a) Number of passages of mechanized harvest resources over skidding roads as an indicator of resulting soil stress [18]. Maximum soil stress occurs near the landing site, where all felled logs are collected.



(b) Trees that could not be felled due to their distance to skidding roads are marked red.

Figure 7. Results of a fully mechanized timber harvesting operation with a skidding road distance of 40 m

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