EFFORTE –
'Efficient forestry by precision planning and management for sustainable environment and cost-competitive bio-based industry'

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Validation and analyses of expected impacts

Validation of developed tools for operational planning

June 30, 2019

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1. EFFORTE project objectives

EFFORTE is a research and innovation project providing the European forestry sector with new knowledge and knowhow that will significantly improve the possibilities of forest enterprises to assemble and adopt novel technologies and procedures.

The project aims at enhancing the efficiency of silviculture and harvesting operations; increasing wood mobilization and annual forest growth; increasing forest operations' output while minimizing environmental impacts; and reducing fuel consumption in the forest harvesting process by at least 15%.

The project is based on three key elements of technology and knowhow:

1) Basic understanding of fundamentals of **soil mechanics and terrain trafficability** is a crucial starting point to avoid soil disturbances, accelerate machine mobility and assess persistence of soil compaction and rutting. The key findings and recommendations of trafficability related to EFFORTE can immediately be adapted in all European countries.

2) Due to decreasing Cost-competitiveness of manual work and maturity of technology it is now perfect time to realize the potential of **mechanization in silvicultural operations**. EFFORTE pursues for higher productivity and efficiency in silvicultural operations such as tree planting and young stand cleaning operations.

3) 'Big Data' (geospatial as well as data from forestry processes and common information e.g. weather data) provides a huge opportunity to increase the efficiency of forest operations. In addition it adds new possibilities to connect knowledge of basic conditions (e.g. trafficabillity), efficient silviculture and harvesting actions with demand and expectations from forest industries and the society. Accurate spatial information makes it possible for forestry to move from classic stand-wise management to precision forestry, i.e. micro stand level, grid cell level or tree-by-tree management. EFFORTE aims at achieving substantial influence to the **implementation and improved use of Big Data within Forestry** and through this increase Cost-efficiency and boost new business opportunities to small and medium size enterprises (SME) in the bioeconomy.

EFFORTE researchers will develop and pilot precision forestry applications that, according to the industrial project partners, show the greatest potential for getting implemented immediately after the project.

2. Introduction

This document compiles together the methods and tools, which have been developed and/or tested within the Efforte project in work package 3. For each tool, the report provides a short description and the status of the application at the end of the project. Moreover, each application is graded for technical readiness, fit for purpose, complexity, burden for maintenance and validity of the predictions. The grading has been executed by following the grading rules given at table 1. Grading rules were designed specially in Efforte-project for the tool validations. The intellectual property rights (IPR) of each tool have also been described. The technical readiness is graded by the Technical Readiness grading system by the Horizon 2020 (figure 1).

Table 1. Grading rules used in the tool and method validations.

Technical readiness	
+++	The system has been proofed to work in practice and provides logical results
++	Most important parts of the system has been shown to work
+	The concept/idea has been shown to work
Fit for purpose	
+++	The system fits well for the purpose and gives useful decision support to improve operations
++	The system fits reasonably for the purpose and eases operations at some extent
+	The system fits poorly for the purpose
Complexity	
- - -	The system is very complex and requires links to numerous data sources
- -	The system has some features of complexity
-	The system is rather simple
Maintenance	
- - -	The system is laborious/maintenance costs are rather high
- -	The system needs updating frequently and causes some maintenance costs
-	No significant maintenance costs exists
Validity of the predictions	
+++	The system produces trustworthy predictions all year around
++	The system produces non biased predictions but the there exists plenty of variation
+	The system shows tendency/classification but no accurate numbers

TRL	
9	**TRL 9 – actual system proven in operational environment** (competitive manufacturing in the case of key enabling technologies; or in space)
8	**TRL 8 – system complete and qualified**
7	**TRL 7 – system prototype demonstration in operational environment**
6	**TRL 6 – technology demonstrated in relevant environment** (industrially relevant environment in the case of key enabling technologies)
5	**TRL 5 – technology validated in relevant environment** (industrially relevant environment in the case of key enabling technologies)
4	**TRL 4 – technology validated in lab**
3	**TRL 3 – experimental proof of concept**
2	**TRL 2 – technology concept formulated**
1	**TRL 1 – basic principles observed**

Figure 1. Definitions for the technology readiness levels (TRL 1-9) according to the Horizon 2020 – Work Programme 2014-2015 (Horizon 2014)

3. Developed tools

3.1 Depth To Water (DTW) maps

Description

In modern forestry the forest land is trafficked by heavy vehicles repeatedly with 5-30 year intervals, which increases the risk of rutting and damages to soil and water. The most serious damages caused by rutting are connected to the soil close to lakes, ponds and running water. Modelling of water run-off in the landscape as in depth to water maps (DTW) is a method to identify and avoid wet areas prior and during cutting. The model shows where moving soil water is less than 1 m below ground surface. The model and data sources needed are described in more detailed in D3.3 and in D3.4.

In the model wet areas are described by a DTW-index where deeper blue colour indicates that water is closer to the soil surface (Figure 2).

- 0<DTW<25 (cm) ………deep blue, in field mostly open water
- 25<DTW<50 (cm)……..dark blue, mostly wet conditions
- 50<DTW<75 (cm)………blue, potential risk area
- 75<DTW<100 (cm)……..light blue, buffer zone
- DTW>100 (cm)…………no colour

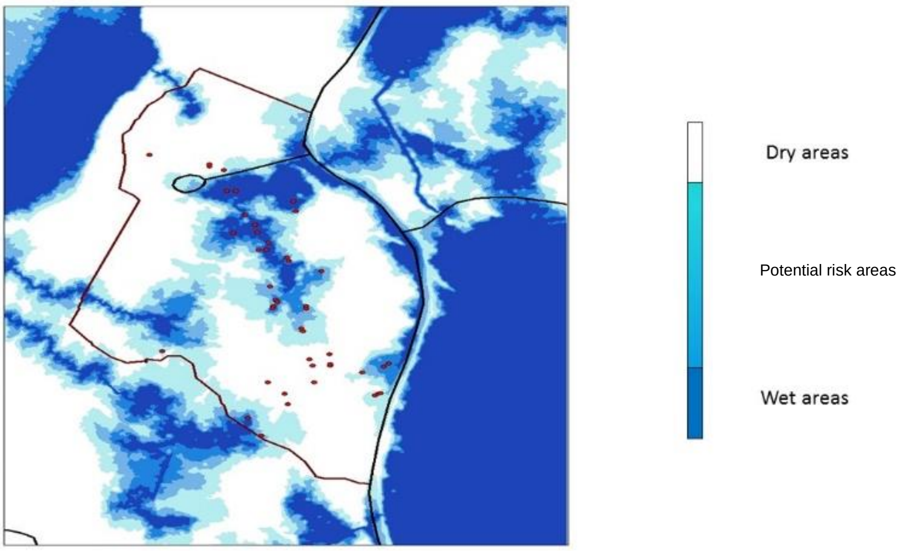

Figure 2. DTW model with rutting marked as red dots.

Within the EFFORTE-project the model has been tested in operational forestry together with our forestry collaborators in Sweden and the project has also made it possible to test the model in other countries. According to the interviews with persons making logging plans and operators in logging machines, the feedback of the use of DTW-map can be summarized as follows:

- The DTW-map can be used to identify moist and potentially wet areas and thereby strip-roads etc. can be planned to go around those areas
- Narrow passages over wet areas can be identified which facilitates were to place bridges or other accessories to protect soil and water.
- Base-roads and strip-roads, where many loads have to be transported, can be planned to locate in higher altitudes of the terrain which has better bearing capacity and is less sensitive to high soil pressure.
- Wet areas in the map can be used as indicator for high value forest and riparian-zones which should be protected as nature conservation areas.
- There is a potential to develop the DTW-model further, if it could correspond to different soil-types and variation in weather and rain flow.
- The model is also less reliable in areas with ditches.

In collaboration with our partners in EFFORTE a field inventory over approx. 40 logging objects was carried out to evaluate how the DTW model is used and how it identifies risk areas concerning were damages to soil and water appears. According to the validation of the DTW model in operational forestry:

- The DTW-model identified more than 90% of the actual wet areas in the forest.
- Serious damages to soil and water decreased to less than 0.1% of the total strip road lengths when using the model as a base map in the logging machines.
- In cases where serious damages did occur more than 80% of them could be explained by the DTW model.

Status of the application at the end of the project

All forest Swedish partner companies in EFFORTE have used DTW-maps or similar models in planning of the logging site and in logging operation (used as a map layer in the harvester/forwarder computer) since 2014. The DTW model as in-data for different decision tools has been tested in EFFORTE.

Technical readiness (TRL 5) (+++)

The depth to water (DTW) model has been implemented in the Swedish forestry during the EFFORTE project. The model was not created during the project (it was created 2001 in UNB Canada) but we have validated the use and accuracy in operational forestry.

Fit for purpose (+++)

The validation of the model shows that:

- The DTW model gives good information about wet and sensitive areas in both planning and performing of logging operations
- The DTW model could also be used as in-data for different decision tools, also tested within EFFORTE

Complexity (-)

All data used in the model can be extracted from a digital terrain model created from light detection and ranging (LIDAR) system. The model is easy to use and easy to understand but the simplicity also means low resolution and misleading values in some conditions. There is a great potential in development of the model if soil type, ditches and weather could be added to the model.

Maintenance (-)

The model uses DTM as in-data, which doesn´t need maintenance.

Validity of the predictions (+)

The DTW model is built on in Data describing topography e.g DTM from LIDAR. The DTW model shows that wet and moist conditions mostly occur in lowlands and, usually terrain transport can be done safely on higher parts of the object. This, of course is only half truth, since bearing capacity is influenced by a combination of several factors e.g. soil type, weather, climate, ditches etc. The use in operational forestry has thus shown that the DTW-model gives a good indication about potential risk areas concerning damages to soil and water.

IPR

The model is free in some map-programs, for example in ESRIs program Arc-map.

3.2 The static trafficability map

Description

The static trafficability map presents the classification of forests in 4 different trafficability classes. The trafficability classes are based on seasonal changes in bearing capacity of forest floor in Finland. The map provides information about the season when harvesting operations may take place with standard logging machinery (i.e. a harvester and a forwarder) without causing substantial damages on forest soil. The mapping unit is a pixel of 16m size compatible with the forest resource information provided by the Finnish Forest Centre. Each pixel is classified in one of the following classes:

1. Operations possible in all seasons

2. Operations possible in summer, mineral soils
3. Operations possible in summer during dry season, mineral soils
4. Operations possible in summer, peatlands
5. Operations possible in summer during dry season, peatlands
6. Operations possible only during frost or thick layer of snow
7. Open water
8. No data (missing airborne laser scanning (ALS) data)

The model and data sources needed are described in more detailed in D3.3 and in D3.4.

The applicability of the application is tested in two separate studies. Metsäteho carried out a survey for their shareholders in January 2019. In total, 100 answers from forest machine operators and officials both in wood procurement organizations and harvesting companies were received. The main findings of the survey were that the application has been taken into operative use by the shareholders of Metsäteho quite well; about 40% of persons, who have access to the data (data was available in their operative area prior to the survey), used the application actively. The use of the application has been concentrated on pre-harvest planning and actual harvesting operation. In addition, tool has been used in planning of wood purchase. Half of the answers indicated that the application is useful or very useful. Further developments were requested for the user guidance and improving the classification accuracy. Interesting finding was that the overall rating given to the application was highest among those answers which had been used the application for the longest. The results of the scientific evaluation carried out by University of Helsinki have not been published yet. The initial findings indicate that the classification is consistent. Although, it seems to have a tendency to have a slight bias towards the worst classes, i.e. it results a bit pessimistic, or conservative, output.

Status of the application at the end of the project

The application has been in operative use in Finland from 2017. The first year was practicing, piloting and testing. The data is distributed as open access data by The Finnish Forest Centre. The data can be accessed via a map application and a web map service WMS . Also, the raster maps can be downloaded from The Finnish Forest Centre’s www-site (www.metsakeskus.fi/korjuukelpoisuuskartat) as tif-files. In addition, forest owners can access the data in www.metsaan.fi service portal. Metsaan.fi is a service for forest owner to easily access the information of their own forest and to use digital forest services. The current data coverage is presented in figure 3. The data coverage increases annually following the national ALS program and ALS-based forest inventories.

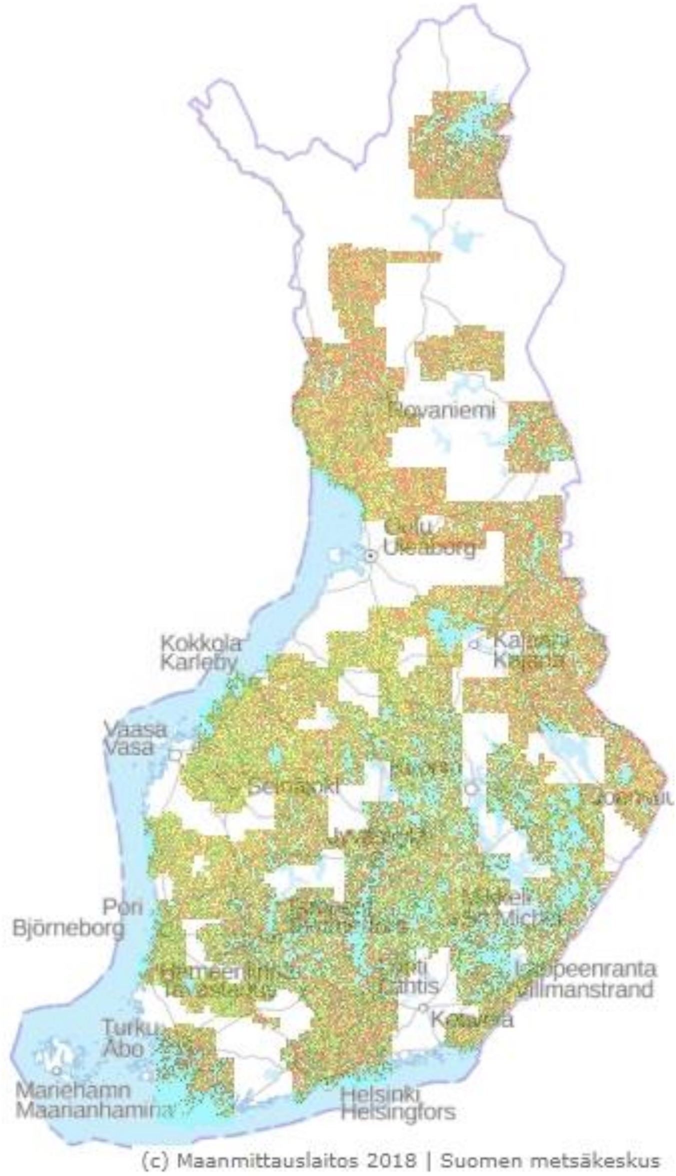

Figure 3. Data coverage of static trafficability maps on 15th May 2019 (a screenshot from The Finnish Forest Centre's map application).

The data and application are constantly developed. The data is improved by defining exceptions in various cases that occur as the application is extended from piloting to operative use. The exceptions have included the following cases:

1. Masking of rivers with width threshold of 20 meters (narrower rivers are not masked).
2. Handling of no data areas (areas with no ALS observations are classified as no data or as selected static trafficability class based on background data).
3. Processing border areas of ALS coverage (buffering or using background data to prevent mis-classification between ALS flight blocks).

The static trafficability model has been improved by introducing open access soil maps provided by Geological Survey of Finland as input data. According to test results this improves the classification accuracy. However, the improvement is not included in operative model because lack of operative level testing. In application, the data distribution is developed so that the static trafficability classification can be accessed as vector format in addition to raster layer.

Technical readiness (TRL 5) (+++)

The static trafficability model for Finland is ready and the application is in operative use. The model can be improved by adding soil class maps as input data, but it requires further testing. The transferability of the model outside Finland is not tested. It is assumed that it requires adjustment for local conditions and data accessible as well as field observations for model development and validation.

Fit for purpose (+++)

The trustworthiness of the model is investigated but the scientific results are not published yet. According to the end user survey the fit for purpose is high.

Complexity (--)

The application is simple to use, and data can be integrated in operative systems easily. Transferability of the model outside Finland can be complex.

Maintenance (--)

The maintenance costs depend on input data accessibility. If ALS data is available as archive data or acquired for other purposes the maintenance costs are low after establishment. Updating the information requires new ALS data or updating the vegetation information from some other source.

Validity of the predictions (++)

The application classifies forest trafficability on the basis of remotely sensed data, map data and quite limited number of reference observations. The accuracy of predictions is therefore dependent on how well the reference data represents the variation of the area of interest and how much of the variation can be explained by ALS derived layers and map data. Also, spatial and temporal resolution of ALS and map data affects the validity of the predictions. Based on user feedback and analysis the validity is adequate as the application is now for operative use at forest stand level.

IPR

The model is developed and owned by Arbonaut Ltd that continuously develop and update the model. Arbonaut Ltd is globally operating company in developing information gathering and GIS solutions for forest inventory and natural resource management (www.arbonaut.com).

3.3 The dynamic trafficability map

Description

The dynamic trafficability map is based on the SpatHy model developed at Luke. The model is a hydrological and ground water model that combines topography with information on trees, soil data and weather data. It can predict soil moisture content at certain point and moment if provided accurate weather data is available (Figure 4).

Status of the application at the end of the project

The model and data sources needed are described in D3.3 and the basic principle in D3.4. The model has been developed and tested in EFFORTE project. The first demos of the application have been introduced in the beginning of 2019. Demo of the model is running at https://wetness.luke.fi/wetnessdemo . The trustworthiness of the system is rather poorly investigated.

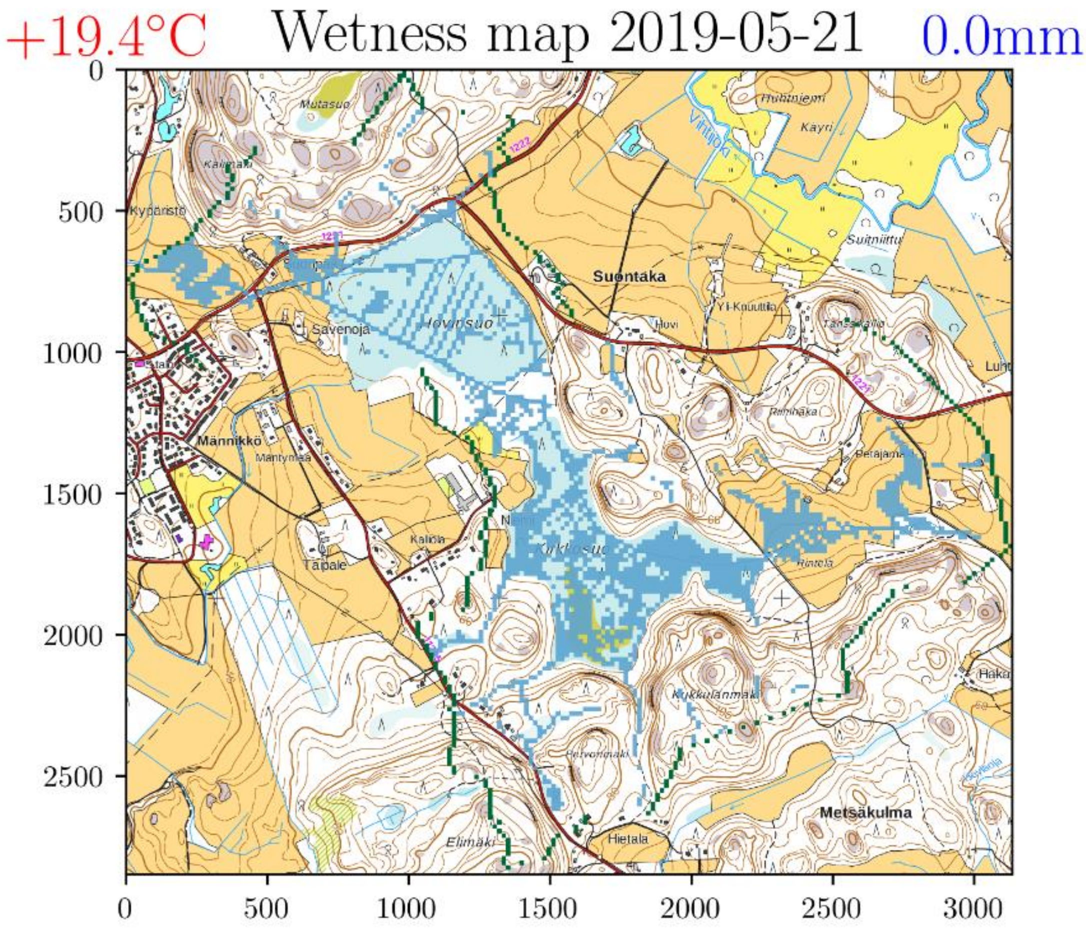

Figure 4. Demo of the Spathy-model.

Technical readiness (TRL 3) (+++)

The Spathy model is ready but the system will continuously be improved by Luke researchers. The model can be linked with external input and output sources but it requires additional resources.

Fit for purpose (+++)

The trustworthiness of the model is rather poorly investigated. Though after calibration the model should give more accurate predictions on soil moisture content that the static systems.

Complexity (---)

The model can work as a standalone component that can be integrated in complicated or simply data structures. Establishment of the system for a given areas is rather laborious, since the model needs to be linked with data sources on trees, topography and meteorological data.

Maintenance (-)

After establishment the maintenance cost should be rather low. Tree information has to be updated annually.

IPR

The model is developed and owned by Luke that continuously develop and update the model. Use of the model is free.

3.4 Optimal routing during forest operations

Description

During forest operations the forwarding of forest products (mainly timber and pulpwood) from the forest to roadside have a large impact on the economy of the forest operations. Each forwarder may load up to 20m³ of timber and in final felling the removal can sometimes exceed 2,000m³ in timber volume and thus, there will be about 100 forwarding rounds to extract all the wood. Transportation distance will have a large impact on the economy, but there is also a great need to avoid damage on water and soils to reduce nutrient leakage into streams, lakes and rivers.

In the Efforte project two calculation models have been developed, *Bestway* and *Ajourakone* (Figure 5 and Figure 6). Both models produce route networks from the cutting area to the landing at roadside. Both models utilise detailed digital elevation model and may also consider depth to water models and detailed distribution of timber volume. Based on the Bestway model, further developed application, *Timbertrail*, was used during the validation. Ajourakone is a web-based application.

Status of the application at the end of the project

The model and data sources needed are described in D3.5 The models have been developed and tested in EFFORTE project. The validation of the Timbertrail application is described in a separate validation report (Willén et al. 2019).

Figure 5. Demonstration of the layout of the main extraction routes created by the Bestway-model.

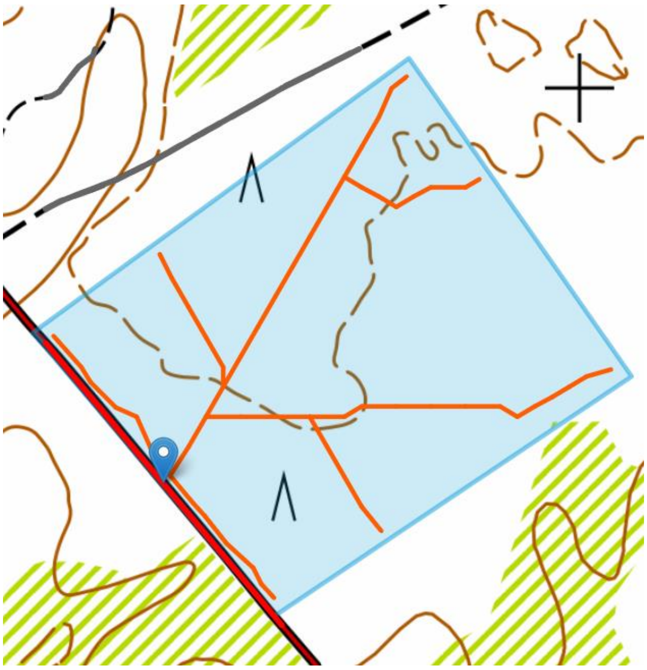

Figure 6. Demonstration of the layout of the main extraction routes created by the Ajourakone-model.

Technical readiness (TRL 5) (+++)

The Timbertrail application is ready to be further demonstrated in a prototype system fully integrated in the forest planning systems. The model is linked with external input and output sources. During the Efforte project one forest company (SCA in Sweden) has implemented a similar model based on the results from the Efforte project. The technical principles of the Ajourakone are functional and appropriate, but the visualization of the result, taking into account the fine tuning of the parameters, still requires work.

Fit for purpose (+++)

The Bestway model has been validated in several forest companies and proven to fit for purpose. The Ajourakone has been tested in three periods in the field during the Efforte project with forest companies Metsä Group, UPM and Stora Enso. The last test period ended at the end of September 2018. The feedback was that in this form Ajourakone works quite well on difficult sites, but it is not totally ready for the field use. The route visualization principles will be regenerated and the objects on the harvesting area that have influence on the route alignment will be added to the model.

Complexity (-)

The models use several data sources, but they are commonly available in forested countries although the models may be complex, they are rather easy to use and implement.

Maintenance (-)

After establishment the maintenance cost is low. There is no urgent need for updates of the data sources required and the models are robust. Updating of the forest information may be needed on a 10-year interval.

Validity of the predictions (++)

Bestway and Ajourakone propose forwarding routes based on the details of the terrain and standing forest prior to cutting. They produce valid routes, however dependent on the input data, such as landing sites and no-go areas. In Bestway, a coming more robust model will also include proposition of landing sites and, therefore, it improves the predictions. In both models the variations in soil content may also influence the predictions as more soft soils are more sensitive to rutting. However, detailed soil maps are missing.

IPR

The Bestway model is developed and owned by Skogforsk that continuously develop and update the model. Use of the model is possible through co-operation with Skogforsk. The Timbertrail application is developed and owned by Creative Optimization AB and use of the application is possible through co-operation. The Ajourakone is designed and programmed by CGI company on the basis of Metsäteho's and its shareholders definitions. Ajourakone is financed by Metsäteho and its shareholders. CGI owns the product rights.

3.5 Sequencing in operational planning

Description

Scheduling of harvesting resources (i.e. logging fleet) and planning which areas are to be harvested, and in what order, is an important part of the forestry planning process. Scheduling is complex, because many different decisions must be made, and a large amount of detailed information must be processed.

Skogforsk has developed a planning model that generates proposals about which stands are to be harvested, when, and by which harvest team (Figure 7). Costs of harvesting, transport to industry, movement of machines between areas, and work team movements to and from the area are minimised, while maximising the value of the harvested forest. The yield from the harvested stands is matched against the company's specific delivery requirements for different recipient points.

The result is a schedule for a harvesting plan that can be incorporated in existing decision-support systems. The model generates detailed information about use of resources in the forthcoming month, and a more long-term tactical plan for up to a year ahead.

The model has been tested and evaluated with good results in case studies involving two Swedish forest companies. The tests were based on authentic data for actual planning on five occasions. Evaluation showed that many of the scheduling proposals generated by the optimization model were feasible and formed a good basis for an operative plan. In those cases where the model's proposals were not feasible in practice, possible reasons included incorrect definition of when the harvest areas would be accessible.

Status of the application at the end of the project

The model and data sources needed are described in a separate Efforte report (Flisberg et al. 2017) that summarise the methods and testing performed. The testing of the models has been performed in the EFFORTE project. Further testing and implementation are discussed with the forest companies, but no concrete plans exist currently. Figure 7 present results from the model. Harvesting teams are numbered in the list on top and then the planned cuttings are shown daily for the first month and more generalized later. The image in the figure presents the routing for one of the harvesting teams.

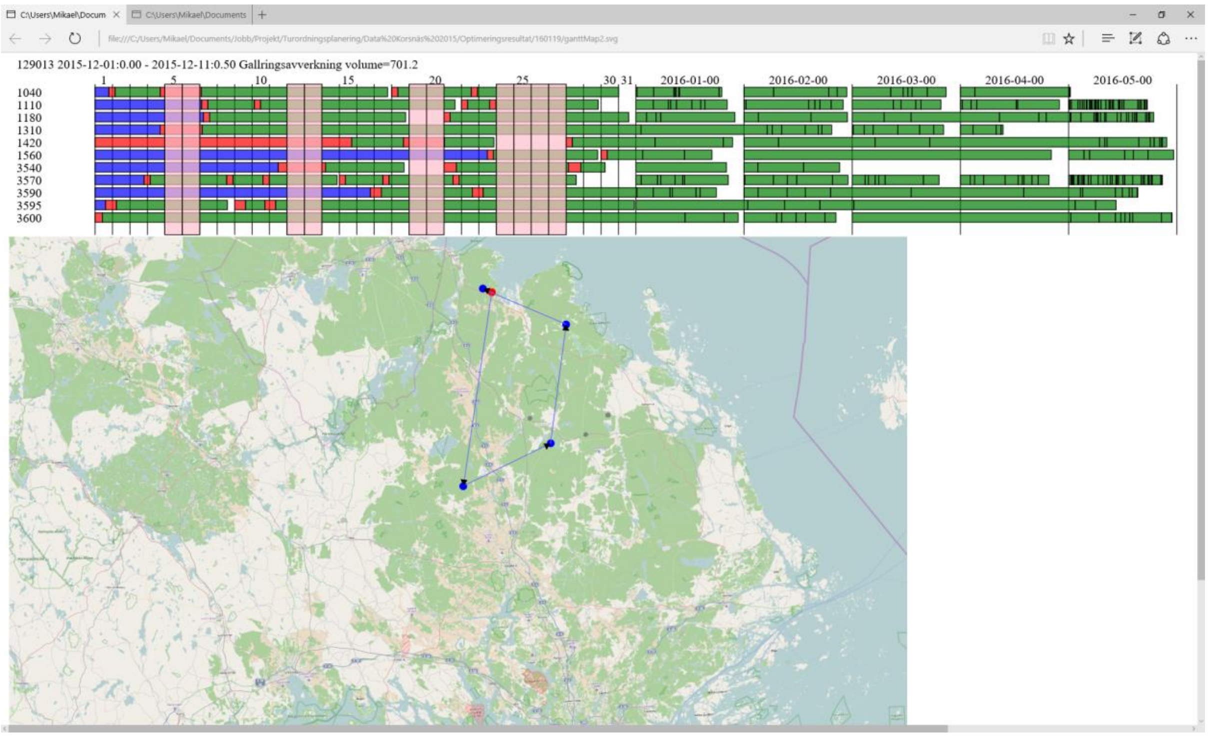

Figure 7. Model for scheduling of harvesters. The monthly schedule of cuttings is presented above the map.

Technical readiness (TRL 5) (+++)

The model for scheduling of harvesters is ready for further demonstration and implementation.

Fit for purpose (+++)

The validation of the model shows a result that is highly useful and may support the production managers with a reliable selection of cuttings. It provides an excellent starting point for the planning of resources that easily may be modified when necessary.

Complexity (--)

The model uses many data sources, but they are commonly available in forest companies. The challenge lies within the continuous data collection in order to be able to re-run the model when necessary.

Maintenance (--)

The model needs to be adjusted for each company according to their data collection. The parameter setting may also vary a bit along forest companies and how they organise their production. Besides this the maintenance costs should be rather small.

Validity of the predictions (++)

The model that proposes scheduling of harvesters produces trustworthy predictions all year around and is also of special interest in the thawing period. However, there is lots of variation caused by the number of input data to the model that constantly is improving.

IPR

The model for scheduling of harvesters is developed and owned by Skogforsk that continuously develop and update the model. Use of the model is possible through co-operation with Skogforsk.

3.6 CAN-bus trafficability mapping - Continuous site trafficability mapping by measuring harvester rolling resistance

Description

Modern forest machines with hydrostatic transmission and CAN-bus engine and transmission management can be used to continuously measure power expended in travelling. At constant speed on level ground the power is expended in overcoming motion resistance, directly related to wheel sinkage and hence vehicle mobility or site trafficability. The harvester always precedes the forwarder on the site, making it feasible to utilize the harvester to collect data on site trafficability to produce a mobility map for the forwarder. The measuring to mapping process can be made fully automated and comprehensive trafficability data collected at low cost.

CAN-bus trafficability mapping was tested with 8-wheeled harvesters and 8-wheeled forwarders in three field tests. The harvesters and in the first test also the forwarder were instrumented for collecting transmission power expenditure in addition to appropriate available CAN-bus information. Trafficability mapping was also tested solely based on momentary diesel engine power in order to eliminate the need for additional pressure transducers.

CAN-bus data based mapping of site trafficability showed good results when compared to soil penetration resistance and harvesting machinery wheel rut depth measurements. Assessing harvester rolling resistance by CAN-bus data offers an interesting possibility to map site trafficability by measuring mobility variables during machine work also in Big Data scale. The proposed solution for collecting rolling resistance data as part of standard operative forestry is ready for piloting. Since modern harvesters are in practice ready for indirect power recording the additional cost of trafficability mapping is negligible.

Status of the application at the end of the project

The application is ready for standardisation work aimed at adoption in serial forest machine production.

Technical readiness (TRL 3) (+++)

Being based on physics, the basic concept is fail proof. The CAN-bus mapping principle has also proved to work in organized field tests and in practical harvesting.

Fit for purpose (+++)

The demand by the forest harvesting industry on getting the CAN-bus mapping as part of standard equipment is high. It is producing information much needed by the practitioners.

Complexity (-)

The minimum instrumentation needed for the application already exists in latest machinery and future development is most likely to bring more. Needed software can be embedded to existing fleet management systems.

Maintenance (-)

The application does not require extra maintenance.

Validity of the predictions (++)

The application classifies site trafficability on the basis of power expenditure. The validity is therefore dependent on the accuracy of the corrections needed in the calculus. The introduction of built-in clinometer and accelerometer will improve the accuracy of momentary corrections. On Big Data scale the validity is adequate as the application is now.

IPR

The method is owned by Luke.

3.7 Post-harvest quality control - Continuous rut depth monitoring by forest machine-mounted LiDAR sensor

Description

The continuous rut depth monitoring by forest machine-mounted 2D-LiDAR sensor system was developed by Argone Ltd and Luke. The system can measure rut depths continuously and provides real-time rut depth estimations. The system can be used in post-harvest quality control, in validating and creating of trafficability estimations as well as in machine operator tutoring.

Status of the application at the end of the project

The method is described in D3.5. The method has been developed and tested in EFFORTE project. Two versions of the method have been tested in field studies in Vihti and Kuru.

Technical readiness (TRL 2) (+)

Basic concept of 2d-LiDAR seems to work in rut depth estimation. The system is purely experimental and for production applications it would have to be incorporated into the forest machine structure.

Fit for purpose (++)

The applicability of the method has not been tested in stand level operations or operational conditions.

Complexity (---)

The method requires quite expensive and sensitive equipment to be installed in machine working in rough conditions.

Maintenance (---)

The visibility of the sensor must be kept clear in varying and often harsh conditions.

Validity of the predictions (++)

Predictions of the system are valid, but vegetation and logging residues can cause biased estimations of rut bottom or reference level.

IPR

The method is owned by Luke.

3.8 Detailed forest yield prediction previous and during harvesting

Description

Single forest objects harvested by Cut-To-Length (CTL) harvesters are often directed to 5-10 different wood assortments aimed for many different products and delivered to more than one, sometimes several different industries. Improved characterization of log assortments, dimensional distributions as well as wood and fibre properties has several potential and partly different values for different industrial customers. This enables precision delivery plans by improved control of the standing wood, sharper bucking instructions in combination with trafficability, efficient utilization of the harvesting machine fleet and optimized logistics including reduced need for “uncertainty stockpiling”.

Short description of system components facilitating

Detailed forest yield prediction starts with assortments by distributions of log dimensions by methods and programme modules (hprCM, hprYield, hprImputation and hprDemo) described in Söderberg et al. (2018). Technically, standard harvester production files StanForD 2010 (hpr-files) must be processed by hprCM (Siljebo et al 2018) to get complete, valid stems including i) estimated tops above the last cross-cut, ii) branch volumes (Marklund 1988), iii) filtration/completion of registration errors and false input. Wood and fibre properties of logs can be run to get the detailed property prediction module hprProp (Arlinger & Wilhelmsson 2019), which also requests at least one per object average of tree age. At the current stage hprCM can be run integrated with either hprYield or by hprAnalys (Möller et al 2011). The hprCM module will also produce estimated amounts of delimbed branches and needles (spruce and pine), and remaining tree top section above smallest merchandised log in the stem. The software modules have been developed in other projects in connection to EFFORTE. However, as a part of EFFORTE, imputation of suitable stands, including realistic frequencies of downgrading and prediction of wood properties by hprProp have been validated and further analysed with respect of possible gain in output from forest operations by improved characterization of raw material properties.

Validation in two cases

Validation of detailed predictions of wood properties of Scots pine sawlogs from 64 harvesting objects (SCA Forest) by hprProp for predicting demarcation of specific property based sawlog assortments in comparison with similar demarcation by the sawmills X-ray frame at SCA Bollsta sawmill (Figure 8) (Möller et al, manuscript). A specific study of the possibilities to predict heartwood diameter in sawlogs from 58 harvesting objects by real and imputed hpr-files and the heartwood prediction model (Wilhelmsson et al. 2002) in the hprProp program module was performed in cooperation with SCA forestry and Bollsta sawmill (Holappa-Jonsson et al. Manuscript) (Table 2). As a scientifically developed proof of concept (without possibilities to validate by control measurements in this case study), hprProp was also used to predict and compare object averages of basic density (Wilhelmsson et al 2002) and fibre length (Ekenstedt et al. 2003) of the flow of kraft pulpwood from the same 64 harvesting objects as was included in the SCA sawlog validation (Figure 9). Finally, also as a proof of concept, detailed log properties of some Norway spruce sawlog and pulpwood assortments are shown in figures 10 and 11.

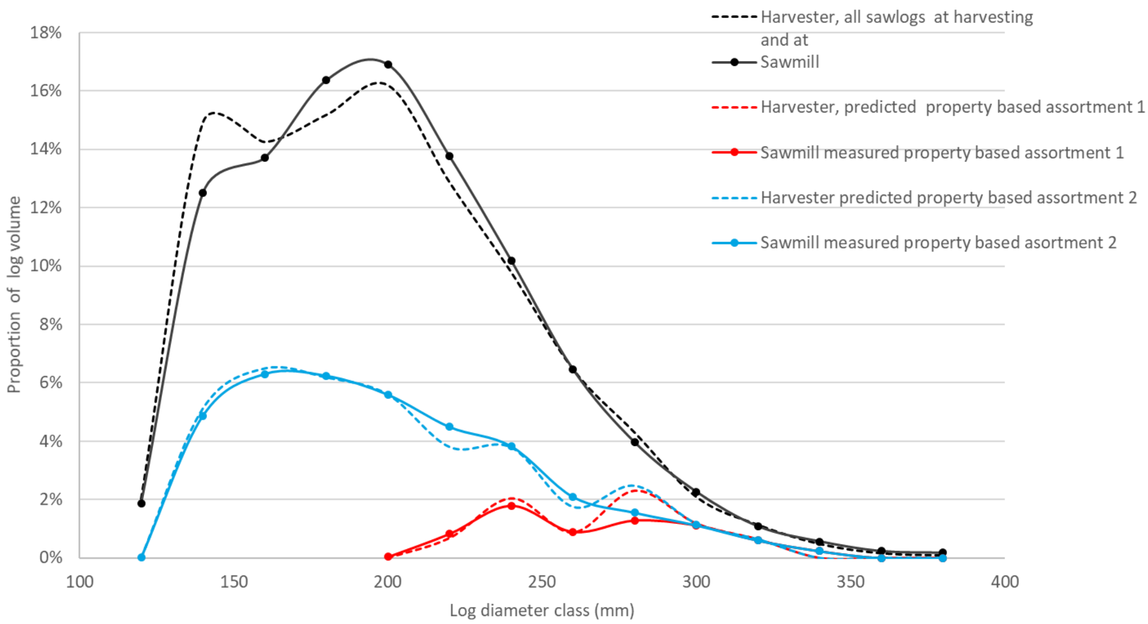

Figure 8. Frequencies of pine sawlogs sorted by different dimensions, and by two assortment based predicted properties (from hprProp) compared with the same measured properties by the sawmill X-ray frame (SCA Bollsta), (Möller et al, manuscript).

Table 2. Validation of predicted heartwood diameters in sawlogs of Scots pine (SCA-Bollsta). Accuracy of predicted mean heartwood diameters by heartwood model predictions (in hprProp) based on imputed ALS data, when validated against means measured by 3D/X-ray scanner on real logs (Holoppa-Jonsson et al. Manuscript)

Diameter class	Mean, Measured mm	Mean, Predicted mm	Standwise RMSE mm	All stands Bias mm	N Stands	N Measured 3D/X-ray logs	N Predicted logs by simulated harvesting of imputed stems
140-159	69.59	75.18	8.10	-5.59	52	45 182	23 026
160-179	87.47	91.34	7.64	-3.88	52	37 323	17 108
180-199	103.64	105.69	7.74	-2.06	52	35 718	14 886
200-219	120.78	121.37	8.41	-0.59	56	33 878	13 115
220-239	137.86	137.63	8.79	0.23	52	23 697	8 742
240-259	156.06	155.80	10.11	0.57	43	15 261	5 722
260-279	173.08	171.44	10.19	1.63	41	9 094	2 941
280-299	190.82	187.47	10.87	3.35	38	5 094	1 608
300-319	207.93	204.55	13.53	3.38	27	2 527	585
320-339	226.05	223.01	12.86	3.74	15	1 156	167
340-359	*247.10*	*232.11*	*31.14*	*14.97*	*3*	*358*	*21*
360-379	*249.92*	*255.67*	*6.10*	*-5.74*	*2*	*163*	*6*
Total	136.15	136.34	9.76	-0.49	58	209 451	87 927

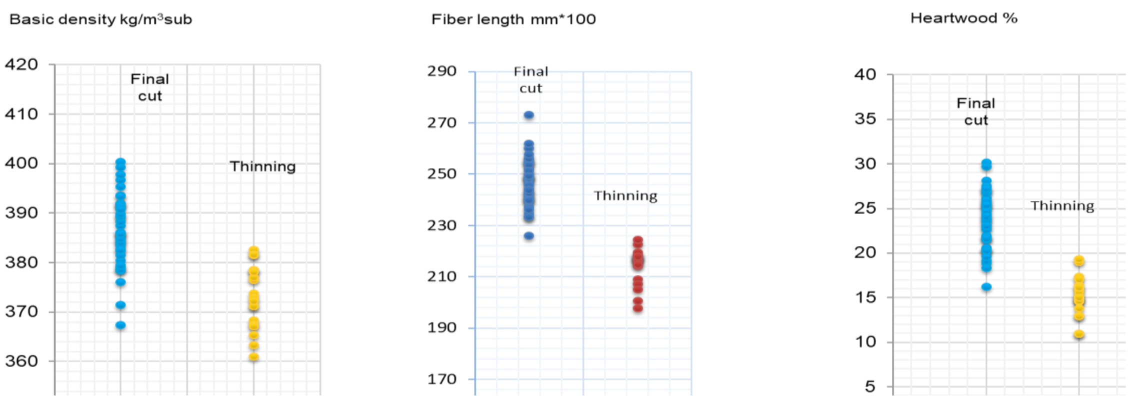

Figure 9. Predicted pulpwood properties by hprProp (one dot per object average) as stand averages in final cut and thinning, SCA Forest (Möller et al. Manuscript)

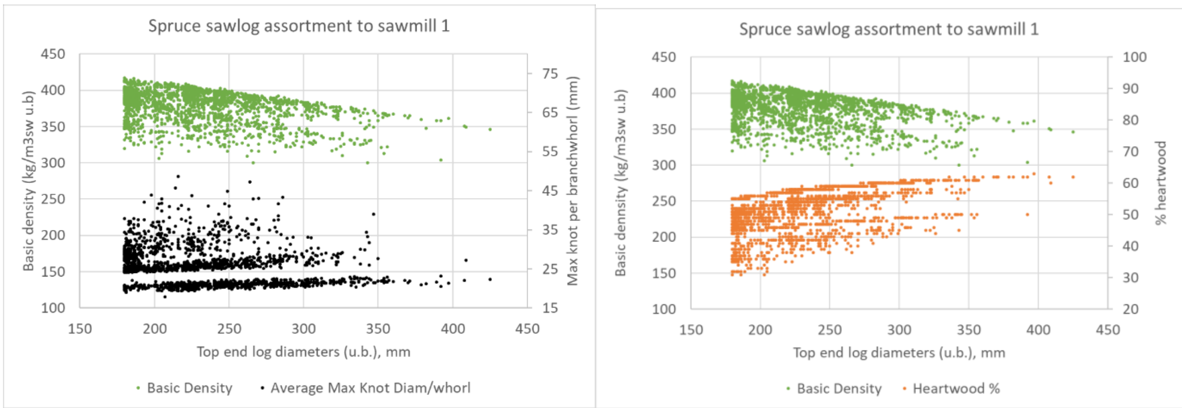

Figure 10. Output from hprProp applied to real production reported for one of four produced spruce sawlog assortments. HprProp operates on each log included in the ordinary hpr-file at harvesting and average tree age (from forest plan), latitude and altitude. This example shows predicted basic wood density & maximum knot diameters/whorl (left figure) and basic density & heartwood content (right figure) over log diameters from a 30 hectare harvesting object (Labbo, Uppland).

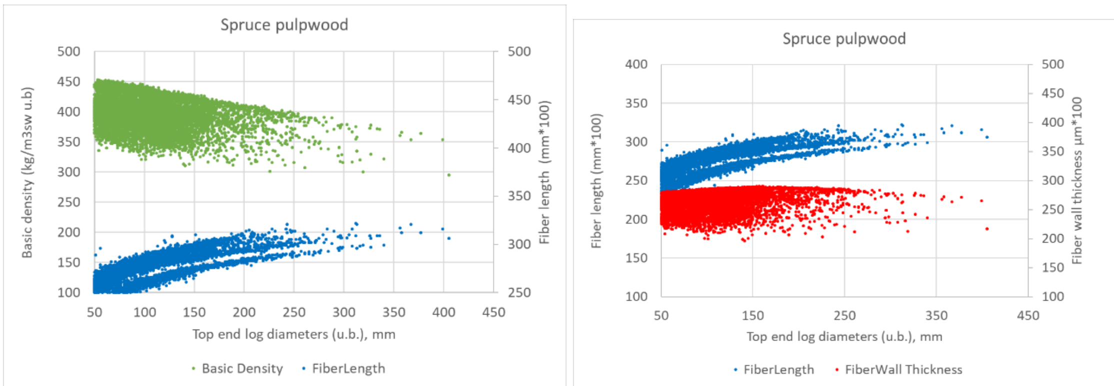

Figure 11. Output from hprProp applied to real production reported for one of four produced spruce pulpwood assortments. HprProp operates on each log included in the ordinary hpr-file at harvesting, + average tree age (from forest plan), latitude and altitude. This example shows predicted basic wood density & fiber length (left figure) and fiber length & fiber width (right figure) over log diameters from the Labbo object.

More about hprProp and detailed yield predictions for integration forestry-industry

At the current stage of development the hprProp module includes models for predicting individual log values on basic wood density, green density at felling, heartwood diameter and percentage, bark thickness, number of annual rings (given known number of rings at breast height), mean annual ring width, knot type (Sound/loose), average maximum knot diameter/whorl, fibre length, fibre width and fibre wall thickness.

From the measured (log dimensions and height in stem) and predicted log properties for sawn board properties (MOE, MOR), durability, knot free blanks between branch whorls, different surface properties can also be predicted at different levels of accuracy. Property distributions related to sawing patterns are now becoming possible to use by developed information systems. Moisture content and predicted heartwood/sapwood diameters of sawlogs makes it possible to reduce energy and improve quality in kiln drying by controlling variations. Combinations of harvesting and pre-harvesting predictions and sawmill e.g. X-ray frame measurements are of great interest for the further integration of industry and forestry. When combinations of preferred log lengths, diameters and wood properties are requested by different customers, the in-forest predictability in CTL-harvesting becomes increasingly important. Pulp, paper and other fibre product properties as pulp yield, tear and tensile index, porosity, brightness, fibre flexibility etc. can also be characterised by predicted properties of pulp wood and sawmill chips. For energy utilization the energy content of stemwood, branches, tops, needles and bark can be predicted (hprCM). Finally, wood processability properties such as moisture content at harvesting, and weather based drying out (processability, discoloration, decay etc.) after harvesting/forwarding/stockpiling can be predicted. By this actual raw weights can be predicted for transport optimisation including valuable input to terrain and forest road net trafficability.

Generally, the degree of explained variation of the individual log properties predicted, by models in hprProp, out of total observed variation varies between 20 and over 90 % depending on property, species, assortment (part of stem) etc. The lower degrees of explanation can still be utilized at aggregated levels (diameter class per assortment and object, per log class and object, per assortment and day can be predicted). The highest degrees of fixed effect explanations can also be used into bucking optimisation of individual stems at harvesting. Finally, also Life Cycle Assessments (LCA) can take advantage of the material property information as well as the collection of data from the harvesting and logistic operations.

Technical readiness (TRL 4-5) (+++)

The infrastructure for transferring, processing and storage of harvester production files, laser scanning and other data sources is of decisive importance for planning and control of precision harvesting. Thehpr-file structure (StanForD 2010) and the file transfer system developed by BIOMETRIA in Sweden are already fulfilled prerequisites for detailed forest yield predictions. So far, validations of some wood properties have been performed with the promising results. Further validation and system development is needed to reach operational large scale level.

Fit for purpose (+++)

Most of the operative models have been scientifically developed and many are published in scientific publications described in detail by Arlinger and Wilhelmsson (Manuscript). Validation of the quality of input data and the trustworthiness of the different models/components are scientifically developed and poorly investigated. Though after calibration the model should give more accurate predictions on soil moisture content that the static systems.

Complexity (---)

All new system components in forest yield predictions and reporting are based on StanForD 2010, the CTL-harvesting bucking instructions and the production report file (.hpr). These and developed harvesting quality control routines have already reached TRL 7-9 StanForD standardisation work is a continuing activity outside EFFORTE. The standardisation work and a developed infrastructure is a prerequisite for efficient and future utilization of detailed forest yield predictions. Secure, reliable long time storage of data is also an important issue to consider.

Maintenance (-)

This standardisation work for communication with forest machines is coordinated by Skogforsk and Metsäteho, and continuously developed together with experts from practical forestry, machine manufacturers, system developers and international representatives as e.g. France, Germany, Latvia and Australia. In Sweden (and Latvia) Biometria acts as a hub for harvester information, wood measurements for payment and administration. Other system service providers and software developers are also active within this field. National laser scanning data, new satellite data, meteorological data, road data base and the National Forest Inventories (e.g. in Sweden and Finland) are also important source of information. Larger forest companies will also build their own harvester production and forest inventory data-bases for many different purposes.

Validity of the predictions (+++)

Validation of the predictions varies between the properties so that the system produces trustworthy and non-biased predictions all year round, but there exist plenty of variation at the individual log level.

IPR

The package of hpr-file based program modules of which hprProp, hprCM (hprAnalys) and hpr-imputation have been utilized in EFFORTE are all originally developed and owned by Skogforsk of which some in connection with Skogforsk's partner companies. They are originally developed outside EFFORTE, however, to described extents utilized and validated within EFFORTE. Further development, tests and some extensions have been performed by contribution from EFFORTE and programme modules, like hprAnalys and hprProp have been tested by project partners without cost. The different software modules can also be further utilized by the EFFORTE project partners after "fair and reasonable compensation" to Skogforsk.

4. Summary of the developed tools

According to the tool validation evaluations, most of the tools tested and demonstrated in Efforte have fairly high level of technical readiness and fit for purpose. This is partly due to the close co-operation and connection with the users and practical operations during the tool development. As the development process of systems is usually relatively slow, some of the tools tested and developed in Efforte have had already TRL levels of 1-2 at the start of Efforte. Efforte project has been a demonstration, testing and validation environment for most of the tools. However, some concept-versions of tools, such as *dynamic trafficability map,* have been developed from the scratch during the Efforte. Moreover, with the help of the project, tool development has been restructured and focused better to improve the suitability and validity of the predictions in regards to the requirements and demand of the practical operations. The evaluation summary of system validations is presented in table 3.

Table 3. Tool validation summary. Tools and systems, which are developed and /or tested within the Efforte-project.

Tool	Description	Technical readiness	Fit for purpose	Complexity	Mainte-nance	Validity of the predictions
Depth to water map (DTW)	Soil wetness predictions based on the topography	+++	+++	-	-	+
The static trafficability map	The static trafficability model based on TWI, vegetation, soil class and ditch analysis provides static prediction on forest trafficability	+++	+++	--	--	++
The dynamic trafficability map	SpatHy model linked with tree data, topography and meteorological data provides daily predictions on soil moisture content	+++	+++	---	-	++
Bestway/ Timbertrail	Model and application to produce main extraction routes for forest operations to reduce environmental impact and improve economy with more efficient forwarding	+++	+++	-	-	++
Ajourakone	Model and application to produce main extraction routes for forest operations to reduce environmental impact and improve economy with more efficient forwarding	++	++	--	--	++
Scheduling of harvesters	Model to schedule harvesters to cuttings	+++	+++	--	--	++
CAN-bus trafficability mapping	Continuous site trafficability mapping by measuring harvester rolling resistance	+++	+++	--	-	++
Post harvest quality control	Continuous rut depth monitoring by forest machine-mounted LiDAR sensor	+	++	--	---	++
hprProp	Predicts internal wood and fiber properties of real or simulated log products based on (.hpr) harvester production files and average tree age information	++	+++, ++, +	---	--	+++

5. Discussion

To introduce and develop applications (i.e. tools, models and methods) for supporting the planning and working in forest operations within Efforte-project, the timing of the project has been really good. This is mainly due to the enhanced possibilities in utilizing Big data (i.e. data mining, computing, data fusion, mapping systems etc.) and increased availability of open access data, especially in Finland and in Sweden within the last few years. As this report states, tested and further developed applications and tools for forest operations and operations planning have proved their importance and necessity. However, the tools presented in here are in continuous development process, thus even greater benefits can be expected to gain with the forthcoming tool versions. In particular, the development steps to model soil moisture, soil behaviour during trafficking and soil rutting have been notable in Efforte, thus the introduction of new understanding of the soil behaviour into the forestry applications will increase the prediction accuracy and usability of tools as a whole.

According to the Efforte practical tests, map based decision support tools, such as DTW-map and static trafficability map, have helped the planning of operation and operation itself. Moreover, the more the users have tested the map based systems, the more positive the feedback of the system has been received. This resembles a typical learning curve while using and experiencing new systems. Development work is continuing after Efforte-project, thus the prediction accuracy, user friendliness and applicability will be improved. Open data, improved accessibility to utilize Big data in a new way (i.e. machine data) and novel knowledge of soil-machine-weather interaction are easing the way.

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