Evaluation of Growth Simulators for Forest Management in Terms of Functionality and Software Structure Using AHP

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/63925

Abstract

A range of computer models exist for simulating forest growth, with different model functions, spatial resolutions and regional calibration specifications. Choosing a suitable simulator is difficult due to its abundance and complexity. The aim of the project is to evaluate a simulator that could be adapted to conditions in Switzerland and used to support decision-making processes in both forest enterprises and scientific contexts. Fourteen potentially suitable forest growth simulators were identified through a literature review, which was then narrowed down to four: BWINPro, SILVA, MOSES and PrognAus. In the second phase, these were systematically evaluated in terms of functionality and software structure using AHP, in order to identify a suitable simulator. The AHP evaluation entailed: (1) determining the decision criteria and hierarchy, (2) performing pairwise comparisons and calculating the utility values and (3) conducting a sensitivity analysis. AHP was found to provide a transparent, verifiable evaluation process for simulator selection. This enabled a critical argumentation and assessment of the simulators. In the third phase, not covered by this article, the selected simulator will be parametrised for Swiss conditions and incorporated into an overarching decision-support system for forest planning and management.

Keywords: AHP, decision support, forest management, forest growth simulator, evaluation

1. Introduction

With rising demand for timber and the ecological and social services provided by forests, as well as sustainability requirements, there is an increasing need for reliable forecasts concerning the likely impacts of alternative silvicultural treatment strategies on forest growth [1].

To produce such long-term forecasts at forest enterprise level, a computer simulation model for forest growth is essential. In this context, a growth simulator means a computer program used to predict and simulate silvicultural scenarios, consisting of one or more growth models that biometrically and mathematically reproduce the biological growth process [2].

Simulators increasingly play a key role in decision support for forest management, particularly in the context of climate change and the associated adaptation strategies. They provide information on the likely outcomes of different forest-management strategies, allowing users to select the most suitable strategy for achieving their management goals [3].

To meet the broad range of demands associated with forest management, simulators ideally need to be able to support both economic and ecological decisions by simulating management strategies and disturbances and their ecological and economic impacts on different tree species and stand types at different sites. No such 'comprehensive' simulator is currently available in Switzerland.

Figure 1 shows the basic elements of forest growth modelling. A tree's increment depends on its initial state, site factors and stand structure. The stand structure has a crucial impact on competition for water, nutrients and light. It is shaped by anthropogenic interventions, natural mortality processes and tree growth. The increment of an individual tree is described by diameter and height growth functions, which depend on competition, site factors and the tree's initial dimensions.

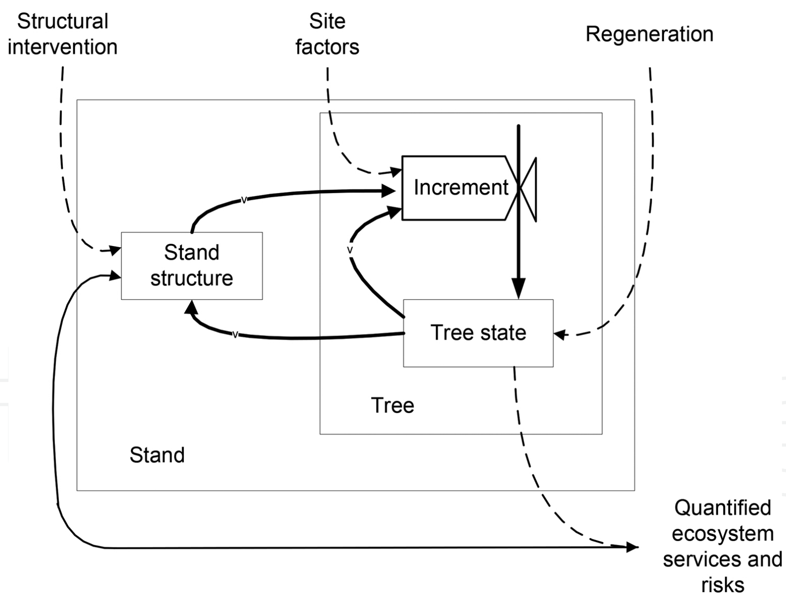

Figure 1. Modelling forest stand dynamics [4].

Stand structure is influenced by anthropogenic thinning and final harvest as well as natural mortality processes. These are modelled by appropriate algorithms. Ingrowth or regeneration models are also required to generate new trees in the system. If one also wishes to produce reliable forecasts of tree-volume (stemwood) and financial-yield development, accurate stem-form and assortment models are essential, as well as specific models for calculating timber-harvesting expenses. The respective state variables of trees can be used to derive other secondary variables such as the biomass of branches, bark, needles and leaves as well as their nutrient content, in order to estimate the nutrient removal that would result from whole tree harvesting. Other types of ecosystem services such as carbon sequestration, biodiversity and the windthrow risk of trees can also be modelled from the tree state variables.

There exists a whole series of simulators with different model functions, spatial resolutions and regional calibration specifications, developed for a wide variety of applications. This makes it difficult to evaluate and select a suitable simulator for one's own purposes.

Different methods exist, which can support the evaluation of software packages. One of the most widely used methods is the analytic hierarchy process (AHP) (e.g. [5–8]). Until now AHP was used only once in forestry for the evaluation of an IT system [9]. Thereby, an IT system which supports the business processes in forest enterprises was evaluated. AHP was not used so far for the assessment and selection of a growth simulator for forest management.

The goal of the project presented here is to evaluate a forest growth simulator that could be adapted to conditions in Switzerland. The simulator needs to not only support stand-level decision processes within a forest enterprise but also be suitable for use in scientific contexts. It should be able to map climate changes or allow climate sensitivity to be integrated at a later stage [10].

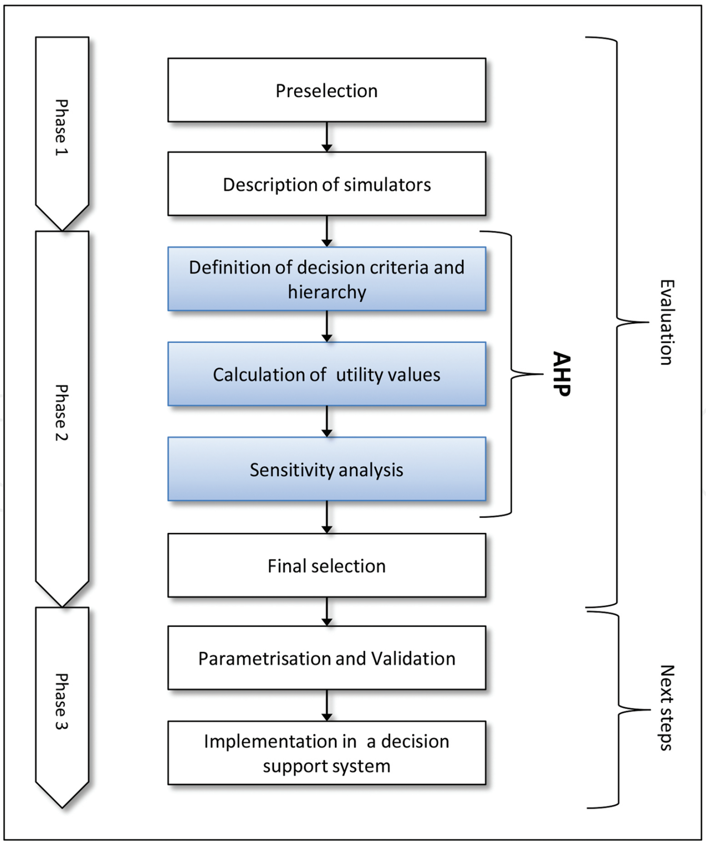

Figure 2. Procedural method of the project (phase 3 is not described by this article).

The process for the evaluation of a suitable growth simulator is divided into three phases (**Figure 2**). The first phase involves a literature review in which 14 potentially suitable simulators are identified. In a preselection phase, the 14 forest growth simulators are narrowed down to a few. In the second phase, an AHP model is created for the systematic comparison and assessment of the remaining simulators [11, 12]. Using AHP, the four simulators are evaluated in greater depth in terms of their functionality and software structure. Based on the AHP results, a suitable forest growth simulator is selected. In the third phase, the chosen simulator is reparametrised using real data from Switzerland and the simulation results are checked for validity. The simulator is also intended to be incorporated into a decision support system (DSS), used to assist forest planning and management processes. However, phase three is not described in this article.

2. Preselection of simulators

In an initial literature review, 14 forest growth simulators were identified and their main characteristics were recorded (**Table 1**). The simulators were selected based on the following key requirements:

- Suitability for forest management: Can it simulate treatment strategies?
- Availability/quality of descriptions: Is there written documentation on the simulator and does it explain its structure and functionality?
- Area of application: Where was the simulator developed (country/region) and could it be adapted to Switzerland?

		FBSM	SiWaWa	MASSIMO	ForClim	SILVA	PrognAus	MOSES	BWINPro	PICUS	STAND	MOTTI	FVS	FORECAST	TASS
Support for forest decision processes		+	+	-	-	+	+	+	+	-	+	+	+	-	+
Treatment and thinning methods		-	-	-	+	+	+	+	+	+	-	-	+	-	+
Ecosystem services	Economic	+				+	+	+	+		+	+		-	+
	Ecological			-	+	+			+	+	+	+	+	+	-
Main tree species found in Switzerland		+	-	+	+	+	+	+	+	+	-	-	?	?	
Forest types	Mixed stands			+	+	+	+	+	+	+	?	+	+	+	
	Uneven-aged stands			+	+	+	+	+	+	+			+	+	
Spatial resolution at individual tree level		+		+	+	+	+	+	+		?	+	+		+
Parametrisation using inventory and experimental -plot data		+	+		+	+	+	+		?	+	+	+	+	

Note: + = represented in the simulator, - = moderately represented, no sign = not represented, ? = no information available.

Table 1. Validation of the simulators during the preselection.

A geographical filter was applied to the selection process. All major simulators developed in Switzerland were considered, provided that they met the key requirements, while from neighbouring countries, Scandinavia and the English-speaking world only the best known and well-documented simulators were examined. The following simulators were included:

- *Switzerland:* FBSM [13, 14], SiWaWa [15], MASSIMO [16, 17], ForClim [18]
- *Austria, Germany:* SILVA [4, 19], PrognAus [20], MOSES [21, 22], BWINPro [23–25], PICUS [26, 27]
- *Scandinavia and English-speaking countries:* STAND [28], MOTTI [29], FVS [30, 31], FORECAST [1, 32], TASS [33, 34]

Based on this review, four simulators were chosen for the AHP evaluation, namely BWINPro, SILVA, MOSES and PrognAus. The preselection was based on positive performance in the following areas (**Table 1**):

- Suitability for supporting forest decision processes
- Simulation of common treatment and thinning methods
- Output of economic and ecological indicators
- Representation of the main tree species found in Switzerland
- Simulation of uneven aged and mixed stands
- Spatial resolution at individual tree level
- Scope for parametrisation using Swiss inventory and experimental-plot data

3. Description of simulators

A uniform and comprehensive description of BWINPro, SILVA, MOSES and PrognAus is a key prerequisite for performing an evaluation. These descriptions provide a basis for decision-making in the pairwise comparison. **Tables 4**–**7** in the appendix describe the sub-models and functionalities for each of the four simulators.

4. AHP analysis

The AHP analysis was the central component of the final selection and involved comparing the selected simulators—BWINPro, MOSES, SILVA and PrognAus—with each other and evaluating them. The AHP analysis comprised the following steps:

- Defining the decision criteria and hierarchy based on a detailed set of requirements (4.1)
- Calculating the utility values by means of pairwise comparisons (4.2) and

- Performing a sensitivity analysis (4.3).

4.1. Decision criteria and hierarchy

Based on the widely accepted recommendations concerning the uniform and standardised description of forest growth simulators [35], decision criteria were defined and structured hierarchically using a decision tree (**Figure 3**). On the one hand, the recommendations enable the requirements for the chosen simulator to be defined. On the other hand, they provide a framework for the decisions based on which of the individual simulators can be thoroughly scrutinised, particularly in terms of their model and software structure and functionalities.

The decision tree comprises eight main criteria (model approach, range of application, calibration specification, input, sub-models for growth, output, environmental influence and

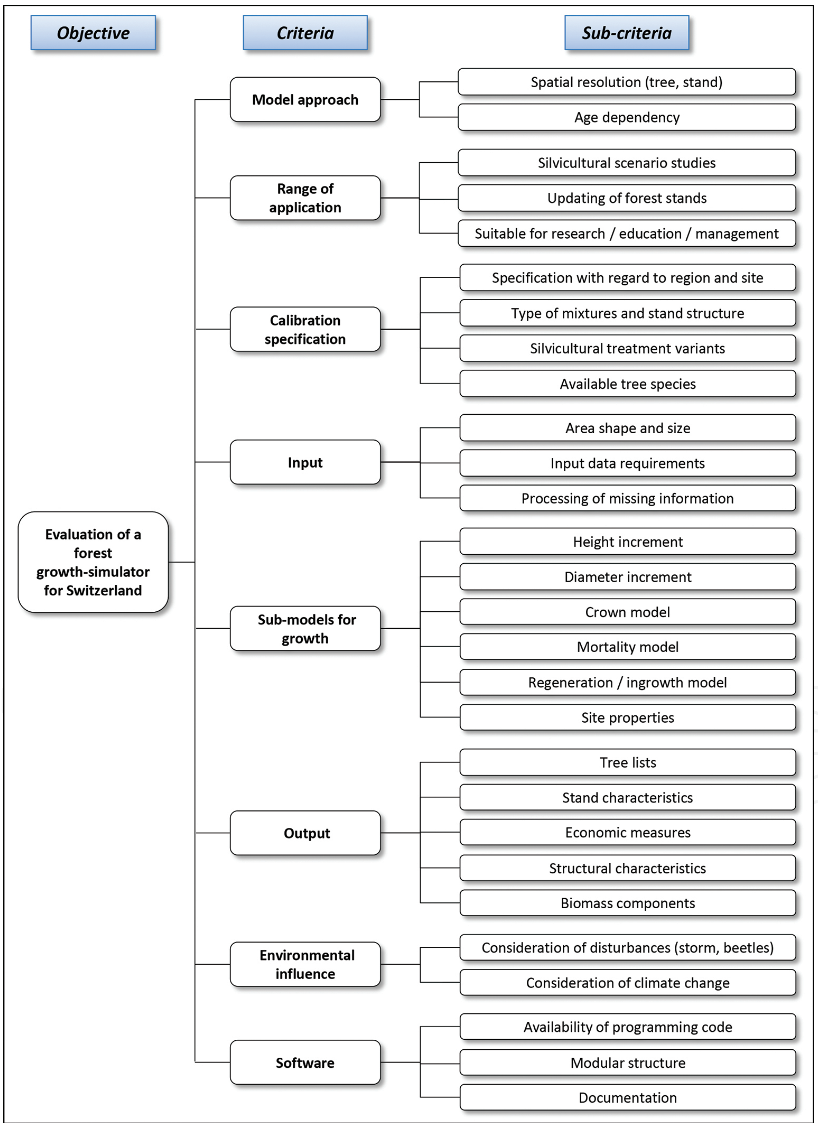

Figure 3. Decision-making hierarchy.

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software), which in turn are divided into 28 sub-criteria. The decision criteria supplement the basic requirements presented in **Table 1**. The simulator that best fulfils all the criteria represents the ideal simulator for the purposes of the evaluation. The main criteria are explained below.

4.1.1. Model approach

- **Spatial resolution:** The simulator should apply an individual-tree approach to stand description, either considering the tree position using coordinates (distance dependent) or without individual-tree coordinates (distance independent). This enables the simulation of individual tree-oriented harvesting strategies, which are especially important in continuous cover forestry. In addition, more detailed conclusions can be drawn concerning the structural development of stands; these are mainly relevant for ecological assessments.
- **Age dependency:** The site index (based on top height) at a particular age is often used to assess the quality of the site (at the age of 50 or 100 years). It must, therefore, be possible to determine the age of the stand. This is not a problem with even-aged single-layer stands. However, in the case of uneven-aged and mixed stands, estimating the age is difficult, if not impossible. A model approach that does not depend on age is therefore an advantage.

4.1.2. Range of application

- **Silvicultural scenario studies:** Simulating silvicultural scenario studies serves to determine the quantitative, financial and structural effects of different treatment strategies on thinnings and surviving growing stock. Based on the results, the silvicultural scenario best suited to meet the specified goal can be identified.
- **Updating of forest stands:** It should be possible to simulate individual stands over a period of 40–50 years in management cycles of 5–10 years.
- **Suitable for research/education/management:** Initially, the simulator will be used primarily for research purposes. However, it should also be suitable for use in forest management and education in the future.

4.1.3. Calibration specification

- **Specification with regard to region and site:** It must be possible to transfer the simulator to Switzerland and use it for the different regions and sites within Switzerland. The model can also be optimally adapted to Switzerland by parametrising it using data from long-term experimental plots and the National Forest Inventory (NFI).
- **Type of mixtures and stand structure:** In addition to modelling even-aged high forest systems, the simulator must also be able to model mixed and uneven-aged stands.
- **Silvicultural treatment variants:** The simulator must be able to model the main treatment variants such as final crop tree thinning, target diameter harvesting, thinning from the top and thinning from below, and planting.

- **Available tree species:** The simulator must be able to represent the main tree species in Switzerland, including spruce, fir, pine and larch as well as beech, maple, ash and oak.

4.1.4. Input

- **Area shape and size:** It should be able to generate user-defined polygonal areas as well as present stands as a standardised square area.
- **Input data requirements:** It should be possible to initialise simulation runs using input data that is easy to collect in forestry practice (random sampling unit, inventory).
- **Processing of missing information:** There should be a routine for adding missing input data (e.g. tree positions, tree heights, dbh distributions), so that a simulation can be performed even with incomplete information.

4.1.5. Sub-models for growth

The following sub-models are summarised in this section:

- **Height increment**
- **Diameter increment**
- **Crown model**
- **Mortality model**
- **Regeneration/ingrowth model**
- **Site properties**

The simulator should include these algorithms so that it can model stand growth in its structural development. The individual growth algorithms can be implemented using a variety of approaches. It is also necessary to record site properties so that different local growing conditions can be taken into account. Aside from the widely used site index (based on top height), there are also approaches that describe the site effects on tree growth with respect to soil properties as well as prevailing temperatures and precipitations. These are often not age dependent and therefore offer a clear advantage over the site index in the case of uneven-aged stands. The corresponding database, equations and parameters for the individual algorithms must be accessible.

4.1.6. Output

In addition to analysing different treatment strategies purely from a forest management perspective, the simulator should also enable an assessment of ecological and social aspects. This requires not only common forestry parameters such as individual-tree data, stand characteristics and economic measures but also outputs relating to stand structure and biomass components.

The simulator should generate results for the following criteria:

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- **Tree lists/individual-tree data:** Tree species, age, height, diameter at breast height (dbh), increment, volume, slenderness (ratio of tree height and dbh), crown base, crown width, crown percent and coordinates (tree position)
- **Stand characteristics per hectare:** Mean basal area tree, height of mean basal area tree, top height of the stand (H100; H50), number of trees, basal area, volume, number of trees in thinnings, basal area of thinnings, volume of thinnings as well as stocking degree and tree species composition
- **Economic measures per hectare:** Volume of timber harvested (in cubic metres without bark), assortments, timber harvesting revenues and timber-harvesting expenses
- **Structural characteristics at stand and enterprise level:** Described by various structures and species indices
- **Biomass components per hectare:** Biomass of stemwood, branches, bark, needles, leaves and roots

4.1.7. Environmental influence

Forest ecosystems are open systems, in other words, they are dependent on and can be influenced by external factors. A forest growth simulator should be able to take account of the effect of such factors on tree and stand growth.

- **Consideration of disturbances:** For example, windthrow/wind breakage, snow breakage or beetles
- **Climate change:** It is very important to be able to simulate the effect of a temperature rise on growth as well as the impact of changes in precipitation (drought). The simulator should ideally already include such a feature or at least have scope to incorporate it.

4.1.8. Software

- **Availability of programming code:** The programming code must be freely available so that the simulator can be used for the required research purposes. This means that the processes inside the simulator are clearly understandable and the derivation of the results can be traced. It must also be possible to alter the simulator or remove sub-models from it.
- **Modular structure:** A modular structure has the advantage that when changes need to be made, it is not necessary to overhaul the entire simulator but only the module concerned, as the individual components interact with one another via precisely defined interfaces. It also means that individual modules can easily be replaced or supplemented by models developed in-house.
- **Documentation:** Comprehensive documentation on the simulator, explaining the underlying functionalities, model equations and parameters, and a user guide are important to provide a detailed insight into the simulator. This is the key to understanding how it works.

4.2. Results of the pairwise comparisons

Once the criteria and hierarchy have been established, the individual criteria are compared pairwise with each other. This pairwise comparison method allows the decision maker to extract a highly accurate evaluation from the numerous competing criteria.

The pairwise comparisons were supported by the software 'CelsiEval', which also calculated the normalised weights for the respective criteria. In this case, the criterion software receives the highest weighting (0.306) in relation to the overarching goal of the evaluation. The second-level criteria are model approach, range of application, calibration specification, growth and environmental influence (0.121), with the input and output criteria (0.046) coming last (**Table 2**).

Criteria (normalised weights)		**Sub-criteria (normalised weights)**		**(Relative priorities)**			
				BWINPro	**SILVA**	**MOSES**	**PrognAus**
C1 Model approach	0.121	Spatial resolution	0.800	0.125	0.375	0.375	0.125
		Age dependency	0.200	0.125	0.125	0.125	0.625
C2 Range of application	0.121	Silvicultural scenario studies	0.429	0.250	0.250	0.250	0.250
		Updating of forest stands	0.429	0.250	0.250	0.250	0.250
		Suitable for research/education /management	0.143	0.250	0.250	0.250	0.250
C3 Calibration specification	0.121	Specification with regard to region and site	0.068	0.068	0.390	0.390	0.152
		Type of mixtures and stand structure	0.152	0.250	0.250	0.250	0.250
		Silvicultural treatment variants	0.390	0.500	0.167	0.167	0.167
		Available tree species	0.390	0.375	0.125	0.125	0.375
C4 Input data	0.046	Area shape and size	0.143	0.250	0.250	0.250	0.250
		Input data requirements	0.429	0.250	0.250	0.250	0.250
		Processing of missing information	0.429	0.313	0.313	0.313	0.063
C5 Sub-models for growth	0.121	Height increment	0.143	0.167	0.167	0.167	0.500
		Diameter increment	0.143	0.375	0.125	0.125	0.375
		Crown model	0.143	0.250	0.250	0.250	0.250
		Mortality model	0.143	0.400	0.200	0.200	0.200
		Regeneration/ingrowth model	0.143	0.300	0.100	0.300	0.300
		Site properties	0.286	0.083	0.417	0.083	0.417
C6 Output	0.046	Tree lists	0.344	0.250	0.250	0.250	0.250
		Stand characteristics	0.344	0.250	0.250	0.250	0.250

Criteria (normalised weights)		Sub-criteria (normalised weights)		(Relative priorities)			
				BWINPro	SILVA	MOSES	PrognAus
		Economic measures	0.129	0.152	0.390	0.390	0.068
		Structural characteristics	0.129	0.375	0.375	0.125	0.125
		Biomass components	0.055	0.313	0.313	0.313	0.063
C7 Environmental Influence	0.121	Consideration of disturbances	0.125	0.100	0.100	0.400	0.400
		Consideration of climate change	0.875	0.083	0.417	0.083	0.417
C8 Software	0.306	Availability of programming code	0.400	0.625	0.125	0.125	0.125
		Modular structure	0.400	0.523	0.200	0.200	0.078
		Documentation	0.200	0.390	0.152	0.390	0.068
		Utility value of the alternatives		**0.319**	**0.240**	**0.214**	**0.227**

Note: The utility values of the alternatives are shown at the end of the table.

Table 2. AHP-calculated normalised weights for the criteria and sub-criteria as well as the relative priorities of the different alternatives in respect to the sub-criteria.

The next step was to compare the model alternatives with each other in pairs. Therefore, the information in the appendix (**Tables 4–7**) was used as a basis for the decision-making process. The pairwise comparisons were performed in group discussions by three scientists from the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), who have a sound knowledge of forestry science and management.

Afterwards, the relative priorities of the model alternatives in relation to the sub-criteria and the utility value for the different alternatives were calculated (**Table 2**). In the AHP analysis performed here, BWINPro achieves the highest utility value of 0.319. In other words, it is likely

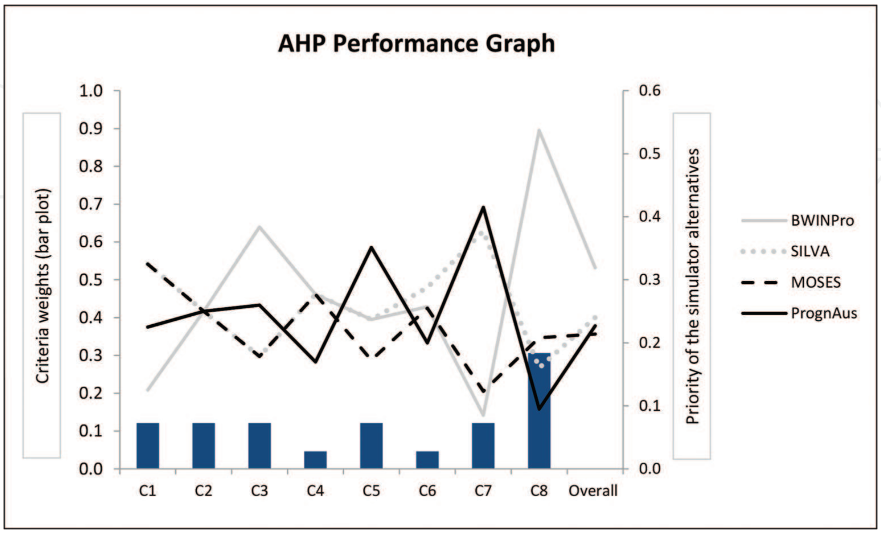

Figure 4. AHP performance graph.

to be the most suitable simulator for the goals specified in the AHP. The AHP performance graph shows how the individual simulators perform in relation to the main criteria (**Figure 4**). It can be seen that BWINPro is not the best-performing simulator in all criteria. The contents of the performance graph are explained in the following sections.

Model approach: SILVA and MOSES use a distance-dependent approach based on individual-tree coordinates, which the decision makers consider important for the simulation of a continuous cover forestry system. They, therefore, receive the highest priority on the first criterion. PrognAus is rated higher than BWINPro because its approach is not age dependent. However, because the 'age-dependency' criterion has a lower weighting than 'spatial resolution', this rating has less of an impact on the ranking (**Table 2**).

Range of application: The simulators scored equally in the three sub-criteria 'silvicultural scenario studies', 'updating of forest stands' and 'suitable for research/education/management'.

Calibration specification: Although MOSES and SILVA (site performance model) have been partially parametrised with Swiss data from long-term forest experimental plots, BWINPro receives a higher priority than the other models on this criterion. This is partly attributable to the 'silvicultural treatment variants' criterion: BWINPro offers treatment concepts geared towards nature conservation and promoting biodiversity, such as protecting trees with a dbh above a certain value or the possibility of selecting habitat trees. In addition, the model has been parametrised for a whole range of tree species. Only the PrognAus model offers a similarly extensive selection of tree species.

Input: The four simulators scored equally on the 'area shape and size' and 'input data requirements' sub-criteria. However, PrognAus receives a lower priority than the other simulators due to its lack of a structure/stand generator.

Sub-models for growth: PrognAus receives the highest priority in this criterion, mainly owing to its potential-independent approach for describing height and diameter increment. The decision makers rated this higher than a potential-dependent approach. Furthermore, PrognAus describes the site potential in terms of multiple site factors. On the 'crown model' sub-criterion, the four simulators were ranked equally as no direct conclusion can be made without comparing model results with real data. The decision makers feel that this aspect is not so important in the context of the AHP comparison because the selected simulator is to be adapted to Swiss conditions in phase 3. In the 'mortality' sub-criterion, BWINPro receives a higher priority than the other simulators as it considers age-related as well as simply density-related mortality. In the 'regeneration/ingrowth' criterion, SILVA was rated lower due to its lack of a corresponding sub-model (cf. [10]).

Output: SILVA receives the highest priority in this area as it provides a variety of economic and ecological indicators needed for the planning and management of forest stands. BWINPro and MOSES receive the second-highest priority. In BWINPro's case, this is due to its inability to calculate timber-harvesting expenses, while for MOSES the lower ranking is owing to its limited output on stand structure. PrognAus receives the lowest priority of all the simulators

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as it delivers limited output on economic indicators and stand structure and none at all on biomass.

Environmental influence: PrognAus features a calamity model to simulate random harvesting as a result of windthrow/wind breakage, snow breakage and beetle infestation. The height and basal area increment model has also been expanded to include climatic variables. As a result, this simulator receives the highest priority, followed by SILVA in second place. SILVA does not consider disturbances but is able to simulate climatic influences, which are covered by the empirical database. MOSES comes third. It is not climate sensitive, but does enable an estimate of windthrow and snow breakage based on slenderness. BWINPro receives the lowest priority as it cannot currently simulate either disturbances or climatic influence.

Software: In the 'software' criterion, which has the heaviest weighting of all the main criteria, BWINPro receives the highest priority by some distance. This simulator has the advantage of being freely available online. It was programmed in the Java programming language as part of the TreeGrOSS (Tree Growth Open Source Software) project, using open-source software packages. The advantage of this is that the software is free of charge, the program code is clearly identifiable and users can easily adapt the program to their specific needs. Another advantage of BWINPro is its object-oriented software structure consisting of multiple Java packages. SILVA and MOSES also feature sub-modules and components, but because less information was available about these, they were both rated below BWINPro. SILVA receives a slightly lower priority than MOSES because it did not have a user manual, although in other respects this simulator is well documented. PrognAus receives the lowest priority as it performed badly in all three sub-criteria, although the main reason was its patchy documentation.

4.3. Sensitivity analysis

The utility values of the simulator alternatives are heavily dependent on the normalised weights of the main criteria. Consequently, small changes in the weights could alter the ranking of the alternatives. Because the weightings are based on subjective decisions, the stability of the alternative ranking must be verified using different normalised weights. A sensitivity analysis was therefore conducted to determine how stable the utility values would remain if the criteria weightings were to be subsequently changed. Should the change in weightings cause a variation in the utility value ranking, a review/revision would be needed. To this end, nine additional scenarios were simulated with different normalised weights for the main criteria:

- Same weighting of each criteria (0.125)
- Different weighting, with one criterion in each case being considered as very important (0.500) and the rest as equally 'unimportant' (0.071) (e.g. C1 = 0.5 and C2–C8 = 0.071).

The results are presented in **Table 3**. By comparing the total number of position points it can be seen that BWINPro, SILVA and PrognAus come very close together in the various sensitivity scenarios. However, BWINPro is still the best simulator in five of the nine scenarios, slightly outperforming SILVA in terms of the total number of position points.

Criteria weights			Utility value and Simulator position							
			BWINPro		SILVA		MOSES		PrognAus	
i)	C1–C8	=0.125	0.269	1	0.262	2	0.224	4	0.246	3
ii)	C1 Model approach	=0.5	0.207	4	0.289	1	0.267	2	0.237	3
	C2 Range of application	=0.5	0.261	1	0.257	2	0.235	4	0.248	3
	C3 Calibration specification	=0.5	0.318	1	0.226	3	0.204	4	0.252	2
	C4 Simulator input	=0.5	0.272	1	0.268	2	0.246	3	0.213	4
	C5 Sub-models for growth	=0.5	0.255	2	0.252	3	0.202	4	0.291	1
	C6 Simulator output	=0.5	0.264	2	0.273	1	0.237	3	0.226	4
	C7 Environmental influence	=0.5	0.190	3	0.311	2	0.181	4	0.318	1
	C8 Software	=0.5	0.384	1	0.218	2	0.217	3	0.181	4
Sum of position points (lowest = best)				16		18		31		25

Note: Calculated utility values if the normalised criteria weights are changed, (i) same weighting of each criteria (0.125), (ii) with one criterion in each case being considered as very important (0.500) and the rest as equally 'unimportant' (0.071). The last row contains the sum of the position points.

Table 3. Results of the sensitivity analysis.

5. Future steps

The next phase involves parametrising the chosen simulator using data from Switzerland and then checking its validity, that is, how accurately it reflects reality [36]. During the parametrisation process, the simulator's key sub-models, such as diameter and height increment, mortality and ingrowth, will be described climate-sensitively and optimally adapted to the available data using appropriate functions. Consequently, it only makes sense to validate the simulator results once the reparametrisation has taken place. Furthermore, the individual-tree simulators in question consist of multiple sub-models. Pre-validating the sub-models would be highly resource intensive and not justified for the purposes at hand.

At a later stage, the chosen simulator will be integrated into an overarching DSS covering forest planning and management processes.

DSSs are crucial because the management of a forest is a challenging task as all the major ecosystem services, such as timber production, recreation, biodiversity conservation and carbon storage, occur side by side on a small scale and are highly demanded by society. Wrong management decisions can have huge consequences, ranging from a loss of ecological and social values up to a loss of economic income. This situation underlines the urgent need for appropriate concepts and tools for decision support that consider all ecosystemservices and can help forest managers to find an optimal management strategy to fulfil the diverse societal and political demanded services [3]. Climate change additionally exacerbates the problems [37].

For decision support systems, it is vital that the forest growth simulator links and interacts with multi-criteria decision analysis (MCDA) [3, 38, 39]. Only the combined use of simulators and MCDA will cover all the phases involved in the forest-planning process. This includes recognising a decision-making problem, developing management alternatives and, ultimately, selecting an alternative and authorisation to implement it [39].

6. Conclusion

AHP analysis provides a structured evaluation process to support simulator comparison. Using the pairwise comparison matrix, AHP-enabled quantitative ratios were obtained based on the individual qualitative assessments. This made comparison of the simulators much easier by providing a transparent and traceable basis for:

1. the process of selecting comparison criteria
2. the pairwise comparisons of criteria and
3. the pairwise evaluations of the alternatives with respect to each criterion [9].

The comparison criteria were established based on the recommendations concerning the uniform and standardised description of forest growth simulators [35]. On the one hand, these enabled the requirements for the chosen simulator to be defined. On the other hand, they provided a framework for the decisions based on which the individual simulators could be thoroughly scrutinised, particularly in terms of their model and software structure and functionalities and which enabled a critical argumentation and assessment. Particularly when comparing such complex instruments, AHP provides a sound basis for ensuring that all key factors are taken simultaneously into account in the decision. Thanks to quantitative representations, the results are rendered transparent and comparable and 'gut decisions' are significantly reduced.

The main weakness of the AHP method is that it becomes very complicated when a large number of criteria are involved. In such cases, evaluation of all the pairwise comparisons is much more time consuming than when the number of pairwise comparisons is kept to a strict minimum. Furthermore, a comprehensive assessment often results in 'unnecessary evaluations' and this overdetermination can lead to inconsistencies [9].

In general, AHP has proved well suited in evaluating a forest growth simulator. However, it should be noted that AHP itself only provides a subjective basis for decision-making, although the margin of subjectivity can be controlled by means of a sensitivity analysis. This shows whether the result would be significantly different if the criteria weightings were slightly changed. In this case, the ranking of the alternatives proved relatively robust, even with the sensitivity analysis. However, the sensitivity analysis also revealed that, with different criteria weights, SILVA and PrognAus receive higher utility values than BWINPro in some cases. In addition to the sensitivity analysis, therefore, several different decision makers could potentially be involved in performing the AHP analysis. This could generate alternative results, enabling a 'final' end comparison.

The AHP model presented here found BWINPro to be a suitable simulator for the defined objectives. The main reasons for this choice were BWINPro's free availability as open-source software and its modular structure in the Java programming language. On the one hand, this enables the parametrisation of sub-models for Swiss conditions or the replacement of individual components with components developed in-house. In addition, the transparent model structure provides the basis for further development into a climate-sensitive version. The model also offers a broad range of treatment variants commonly found in forestry practice, including those aimed at nature conservation and promoting biodiversity.

Using AHP, a simulator was evaluated which will go on to be parametrised for Swiss conditions with data from long-term forest experimental plots and the National Forest Inventory. Furthermore, the detailed analysis of the different functionalities of the four simulators found that the simulator in question lends itself particularly well to implementation in a DSS. This DSS could support forest planning and management processes in the future.

Acknowledgements

The authors would like to thank the Swiss Federal Office for the Environment (FOEN) (Fund to support forest and timber research), who supported the project.

Nomenclatures

Assortment: The breakdown of a stand of timber/trees into different products.

Basal area: The total area of the stem cross-sections of all living trees.

Biomass: All organic matter in an ecosystem. It includes both living and dead material.

Continuous cover forestry: Continuous cover is defined as the use of silvicultural systems whereby the forest canopy is maintained at one or more levels without clear felling.

Crown: Branches and upper part of the stem of tree. Tree crown can be measured by crown base (stem height where the branches begin), crown height (from crown base to the top of the tree) and crown per cent (ratio of crown length and tree height).

Diameter at breast height (dbh): Diameter of a tree stem 1.3 m above ground (convention on standardised measurement of stem thickness).

Ecosystem Service: Function of an ecosystem that contributes to human well-being, for example, timber production or carbon storage.

Final Harvest: Harvest (clearance) of a forest stand that has reached the planned harvesting age.

Forest enterprise: Organisational unit, which, as a public or private legal entity or natural person, manages forests strategically and operatively.

http://dx.doi.org/10.5772/63925

Crop tree (Future tree): Trees which will be selected in an early stage of stand development and which are expected to become a component of a future commercial harvest. Through periodical thinnings competing trees are removed.

Growing stock: This is the volume of stem wood with bark of all living trees and shrubs in a stand of area. The growing stock is usually given in cubic metres of wood per hectare forest.

High forest: A high forest is a type of forest originated from seed or from planted seedlings. It usually consists of large, tall mature trees with a closed canopy.

Ingrowth: The volume, basal area or number of those trees in a stand that were smaller than a prescribed minimum diameter or height limit at the beginning of any growth-determining period and, during that period, attained the prescribed size.

Increment: Increase in diameter, height, circumference, basal area, volume or value of a stand or individual tree within a defined time interval.

NFI: Sampling inventory for a whole country. It periodically records the condition of the forests and any changes that have taken place. On the basis of these data, statistically reliable conclusions can be drawn for a whole country. The primary source of data are aerial images, data collected in forests and surveys of the forest service.

Planting: Planting of young trees in a forest to regenerate it.

Regeneration: Establishment and growth of young trees. Regeneration that takes place without human involvement is called natural regeneration (opposite planting)

Silviculture: Silviculture is the practice of controlling the establishment, growth, composition, health and quality of forests to meet diverse needs and values.

Site: Entirety of all the environmental factors that affect plant communities.

Site factors: Environmental factors influencing plants, either > biotic (e.g. vegetation competition and harmful organisms) or abiotic (e.g. geology and weathering).

Site index (based on top height): A species-specific measure of actual or potential forest productivity (site quality), expressed in terms of the average height of trees included in a specified stand component at a specified base age.

Stand: Tree collective with homogeneous structure and tree species composition. It represents the smallest spatial unit for silvicultural activities.

Stocking: Collective of trees or shrubs in a forest.

Target diameter: Diameter at breast height at which trees will be harvested.

Thinning: A silvicultural treatment made to reduce stand density of trees primarily to improve growth, enhance forest health, or recover potential mortality.

Timber-harvesting expenses: Cost and effort involved in preparing the wood (timber harvest)

Timber-harvesting revenues: Through the sale of wood earned money.

Top height: The average height of the 100 trees/ha of the largest diameter.

Tree volume (or stemwood): Aboveground wood of the tree stem (without branches, but with bark), unit of measure is solid cubic meter standing wood.

Appendix

Tables 4–7 describe the sub-models and functionalities for each of the four simulators.

1.1	Spatial resolution	Semi-distance-dependent individual-tree model
1.2	Age dependency	Age dependent
2.1	Silvicultural scenario studies	*ForestSimulator:* simulation and analysis of individual stands; *WaldPlaner:* simulation, analysis and optimisation of multiple stands in a forest enterprise
2.2	Updating of forest stands	In 5-year steps, a simulation of more than 30–40 years is not recommended
2.3	Suitable for research/education/ management	Yes
3.1	Specification with regard to region and site	Parametrised for northwest Germany, southern Germany [40, 41], Saxony [42]
3.2	Type of mixtures and stand structure	Even-aged as well as uneven-aged and mixed stands
3.3	Silvicultural treatment variants	Final crop tree selection (interactive and automatic), protection of trees above a specified dbh (for nature conservation), protection of minority species (biodiversity), selection of habitat trees, target diameter harvesting, shelterwood cutting, clear cutting, thinning from below, planting
3.4	Available tree species	A total of 19 tree species; the following are fully parametrised: oak, beech, spruce, Douglas fir, pine
4.1	Area shape and size	Model stands based on a square or circular sample plot
4.2	Input data requirements	Sample plots from forest inventory can be analysed
4.3	Processing of missing information	Data addition routine for diameter distributions, missing height values, estimated age, crown bases, crown widths, tree positions
5.1	Height increment	Potential-dependent estimate using yield tables, distance-independent; model and coefficients: [25]
5.2	Diameter increment	Potential-independent, distance-independent; model and coefficients: [25]
5.3	Crown model	Crown base, crown width; model and coefficients: [25]
5.4	Mortality model	*Density-related mortality:* model and coefficients: [25]; *Age-related mortality:* activated above a specified maximum age
5.5	Regeneration/ingrowth model	Ingrowth is regulated via regeneration layers (manually or automatically); automatic routine: sub-model determines whether and how much of which species is set as regeneration and how much is attributed to ingrowth (dbh > 7 cm)

5.6	Site properties	Regional site index, site index (based on top height) at age 100
6.1	Tree lists	Yes
6.2	Stand characteristics	Yes
6.3	Economic measures	Assortment, calculation of timber-harvesting revenues
6.4	Structural characteristics	Number of species, Shannon index, species profile index, percentage of height mixing, percentage of diameter mixing, percentage of species mixing, quantity of deadwood
6.5	Biomass components	Done as part of the assortment + key nutrients per assortment
7.1	Consideration of disturbances	No
7.2	Consideration of climate change	In progress
8.1	Availability of programming code	BWINPro is available online as TreeGrOSS (Tree Growth Open Source Software).
8.2	Modular structure	Yes
8.3	Documentation	Good to very good

Table 4. Characteristics of BWINPro.

1.1	Spatial resolution	Distance-dependent individual-tree model
1.2	Age dependency	Not age dependent
2.1	Silvicultural scenario studies	Enables the development and optimisation of silvicultural treatment strategies
2.2	Updating of forest stands	Possible, interactive and in batch operation, in 5-year steps
2.3	Suitable for research/education/ management	Yes
3.1	Specification with regard to region and site	*Site performance model:* parametrised with data from long-term experimental plots in Bavaria, Lower Saxony and Switzerland; *Increment, crown development, mortality:* parametrised with data from long-term experimental plots at TU München
3.2	Type of mixtures and stand structure	Even-aged as well as uneven-aged and mixed stands
3.3	Silvicultural treatment variants	Thinning from below, thinning from top, selective thinning, final crop tree technique, target diameter harvesting, combination of individual techniques in relation to strength and intervention time
3.4	Available tree species	Spruce, fir, pine, beech and oak
4.1	Area shape and size	Stand is simulated as a rectangular area, the size depends on the stand density and the number of trees
4.2	Input data requirements	Interface for processing inventory data

4.3	Processing of missing information	Spatial stand structure is added via SILVA-STRUGEN structure generator [43], missing tree and stand indicators via tariff and model functions
5.1	Height increment	Chapman-Richards function, potential derived from site factors, distance dependent; model: [4], coefficients: [19]
5.2	Diameter increment	Potential dependent, distance dependent; model: [4], coefficients: [19]
5.3	Crown model	crown base, crown width; model: [4], coefficients: [19]
5.4	Mortality model	LOGIT function, mortality is determined by a random number (if Pm > random number --> mortality); model: [44], coefficients: [19]
5.5	Regeneration/ingrowth model	Not available
5.6	Site properties	Species-specific unimodal dose-response functions: aggregate nine site factors which describe the effect of the site on the potential height increment [45]
6.1	Tree lists	Yes
6.2	Stand characteristics	Yes
6.3	Economic measures	Assortment [46], timber-harvesting expenses, timber-harvesting revenues
6.4	Structural characteristics	Characteristic values of stand structure, stand stability and diversity (Clark–Evans index, Pielou index, species profile index, species mixing and diameter differentiation)
6.5	Biomass components	Derived by estimators from tree dimensions
7.1	Consideration of disturbances	No
7.2	Consideration of climate change	Simulation of reactions to changed environmental conditions is possible within the scope specified by the empirical database (see site model)
8.1	Availability of programming code	Not freely available, not open source
8.2	Modular structure	Structured into various sub-modules
8.3	Documentation	Good

Table 5. Characteristics of SILVA.

1.1	Spatial resolution	Distance-dependent individual-tree model
1.2	Age dependency	Age dependent
2.1	Silvicultural scenario studies	Possible
2.2	Updating of forest stands	In 5-year steps, the maximum simulation length is 40 growth periods
2.3	Suitable for research/education/ management	Yes
3.1	Specification with regard to region and site	Parametrised with data from long-term experimental plots in Austria and Switzerland

3.2	Type of mixtures and stand structure	Even-aged as well as uneven-aged and mixed stands
3.3	Silvicultural treatment variants	Clear cutting, thinning from top, thinning from below, random thinning, target diameter harvesting, planting
3.4	Available tree species	beech, oak, other hardwood, spruce, pine, fir, Swiss stone pine, larch, other softwood
4.1	Area shape and size	Stand is simulated as a rectangular area, size can be freely selected
4.2	Input data requirements	Stands can be generated based on a survey or angle count sampling
4.3	Processing of missing information	STANDGEN: stand generation program, from even-aged monospecific (monoculture in even-aged forest) to uneven-aged mixed (selection forest)
5.1	Height increment	Potential dependent, determined by top height curves from different yield tables, distance dependent; model: [21, 47], coefficients: [48], MOSES 3.0
5.2	Diameter increment	Potential dependent, based on dbh/height ratio, distance dependent; model: [21, 47], coefficients: [48], MOSES 3.0
5.3	Crown model	Periodic adjustment of crown base; model: [47], coefficients: [48], MOSES 3.0
5.4	Mortality model	LOGIT function, mortality is determined by a random number (if P < random number --> mortality); model: [21], coefficients: MOSES 3.0
5.5	Regeneration/ingrowth model	Regeneration sub-model: the algorithm predicts the probability, species composition and density of regeneration. From a height of 1.4 m, trees are simulated using the standard growth functions
5.6	Site properties	Regional site index, site index (based on top height) at age 100
6.1	Tree lists	Yes
6.2	Stand characteristics	Yes
6.3	Economic measures	Assortment, timber-harvesting expenses
6.4	Structural characteristics	Aggregation index, mixing index
6.5	Biomass components	Biomass of wood over 7 cm in dbh, biomass from the bark, branches and needles and total biomass
7.1	Consideration of disturbances	Estimate of windthrow and snow breakage based on h/d ratio
7.2	Consideration of climate change	No
8.1	Availability of programming code	Not freely available, not open source
8.2	Modular structure	Consists of multiple components: MOSES 3.0 (C++), MOSESbatch (Perl), STANDGEN (Delphi), MOSESFramework (C#), Graphical User Interface (C#)
8.3	Documentation	Good to very good

Table 6. Characteristics of MOSES.

1.1	Spatial resolution	Distance-independent individual-tree model
1.2	Age dependency	Not age dependent
2.1	Silvicultural scenario studies	Possible to a limited degree (see 3.3)
2.2	Updating of forest stands	In 5-year steps
2.3	Suitable for research/education/ management	Primarily for research and education
3.1	Specification with regard to region and site	Parametrised with data from the Austrian forest inventory
3.2	Type of mixtures and stand structure	Even-aged as well as uneven-aged and mixed stands
3.3	Silvicultural treatment variants	Percentage removal from defined dbh classes, target diameter harvesting, removal along an equilibrium curve, LOGIT model for tree removal, defined number of trees; harvesting interventions can be performed interactively or automated [49]
3.4	Available tree species	All common Austrian species
4.1	Area shape and size	Possible to define area size
4.2	Input data requirements	Processing of routine inventory data
4.3	Processing of missing information	No
5.1	Height increment	Potential independent, according to the Evolon model type; model and coefficients: [50]
5.2	Diameter increment	Potential independent, distance independent; model: [51], coefficients: [48]
5.3	Crown model	Crown ratio (CR); model: [52], coefficients: [48]
5.4	Mortality model	LOGIT function; model: [53], coefficients: [48]
5.5	Regeneration/ingrowth model	Ingrowth determination involves five sub-models: (i) calculation of ingrowth probability, (ii) probability of species occurrence, (iii) its number, (iv) diameter and v) height of the trees [54]
5.6	Site properties	Description based on the following factors: elevation, slope, exposure, relief, soil depth, humus thickness, soil type, soil moisture content, vegetation type and growing space
6.1	Tree lists	Yes
6.2	Stand characteristics	Yes
6.3	Economic measures	Assortment including ABC classification [55]
6.4	Structural characteristics	Dbh distribution, species distribution and various individual-tree attributes
6.5	Biomass components	No
7.1	Consideration of disturbances	Calamity model for windthrow/wind breakage, snow breakage and beetle infestation [56]

http://dx.doi.org/10.5772/63925

7.2	Consideration of climate change	Height increment model [57] and basal area increment model [58] have been expanded to include climatic variables (total precipitation and temperature per year and growing period, average totals for a 30-year period).
8.1	Availability of programming code	Not freely available, not open source
8.2	Modular structure	?
8.3	Documentation	Satisfactory

Table 7. Characteristics of PrognAus.

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