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# EvaSylv: A user-friendly software to evaluate forestry scenarii including natural risk

Patrice Loisel\*, Guillaume Duvill  † Denis Barbeau‡ Brigitte Charnomordic§

## Abstract

- **Context** Forest management relies on the evaluation of silviculture practices. The increase in natural risk due to climate change makes it necessary to consider evaluation criteria that take natural risk into account. Risk integration in existing software requires advanced programming skills.
- **Aims** We propose a user-friendly software to simulate even-aged and monospecific forest at the stand level, in order to evaluate and optimize forest management. The software gives the possibility to run management scenarii with or without considering the impact of natural risk. The control variables are the dates and rates of thinning and the cutting age.
- **Methods** The risk model is based on a Poisson processus. The Faustmann approach, including tree damage risk, is used to evaluate future benefits, economic or ecosystem services. It relies on the calculation of expected values, for which a dedicated mathematical development has been done. The optimized criteria used to evaluate the various scenarii are the Faustmann value and the Averaged yield value.
- **Results** We illustrate the approach and the software on two case studies: economic optimization of a beech stand and carbon sequestration optimization of a pine stand.
- **Conclusion** Software interface makes it easy for users to write their own (growth-tree damage-economic) models without advanced programming skills.

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The possibility to run management scenarii with/without considering the impact of natural risk may contribute improving silviculture guidelines and adapting them to climate change. We propose future lines of research and improvement.

Keywords: forest management; simulation; storm risk; natural risk; optimization ; Decision Support System; stand level; Faustmann

## 1 Introduction

Forest managers have always been interested in the evaluation of silviculture practices. Nowadays, they must consider criteria that cover the increase in natural risks (Hanewinkel et al., 2012) due to climate change. Furthermore, in the face of growing societal demand, forest managers must also consider biodiversity, carbon sequestration and more generally ecosystemic services. For all these criteria, risk must be taken into account and silviculture should evolve accordingly.

Focusing on forest management at the stand level, a lot of growth models are now available, which were historically dedicated to one or two given species (Monserud and Sterba, 1996; Coates et al., 2003; Lacerte et al., 2006; Pretzsch et al., 2006). Most of them are implemented in software: we do not give details here, but an extensive review can be found in Dufour-Kowalski et al. (2012). Recent efforts have been made to integrate growth models in software platforms in order to fulfill the growing user demand. However existing software suffers from two main limitations : i) it requires a lot of efforts for users to customize the models used for the simulations ii) it does not integrate natural risks (except ForestGALES for wind risk (Gardiner and Quine, 2000), but ForestGALES is very specific and must be coupled with forest growth software).

The motivation behind the present work is to answer the limitations of forest simulation software cited above. The challenge is to easily evaluate scenarii while eventually taking the natural risks into account. We propose a software, called EvaSylv which constitutes a significant advance regarding both these limitations. This software will facilitate the emerging of new silviculture guidelines.

EvaSylv consists of a chain of interconnected models, including a tree growth model, a

risk model, a tree damage model following risk, and several economic criteria. The chain of models works at stand level, and allows to compute analytical expressions for criteria (Faustmann Value, Averaged Yield Value) linked to a given technical itinerary. This analytical approach has the advantage to yield precise results in a short computing time, compared to a Markov-based approach for computing expected values, which requires a great number of time-consuming simulations.

In EvaSylv, users can easily write their own models through a user-friendly interface. The functions and models are considered as a supplementary kind of data, and can be modified via the interface. Contrary to other forest simulation software, users do not have to get into the complex software code. They are written in basic Python and do not require advanced programming skills.

The paper is organized as follows: the framework is introduced in Section 2, including a recall of the mathematical models used for simulation and optimization. Software design is presented in Section 3. Case studies relative to simulation and optimization of beech and pine stands are given in Section 4. Section 5 gives some conclusions and perspectives.

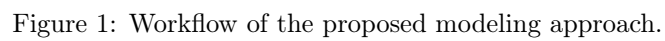
## 2 Framework

The objective of the present work is to provide an operational easy-to-use simulation and optimization framework for testing forest management scenarii at stand level.

EvaSylv has been designed to allow users to easily write their own models through a user-friendly interface: growth functions, damage models (linked to natural risk), economic valorizations. The functions and models are considered as a supplementary kind of data, and can be modified via the interface, without having to get into the complex software code. They are written in basic Python and do not require advanced programming skills.

The evaluation requires the choice of a technical itinerary describing the authorized actions. For each itinerary, the Faustmann approach is available to evaluate future benefits, economic or not. It necessitates the calculation of their expected values, for which a dedicated mathematical development was written (Loisel, 2011, 2014).

Fig.1 represents the workflow of the simulation and optimization processes within the



software. The elements shaded in gray correspond to the in-depth program structure and the elements within orange-colored containers correspond to the interface. Particular attention has been paid to the choice of the latter in order to free the user from writing complex mathematical calculations whilst ensuring a broad range of possibilities for designing the scenarii.

## 2.1 Software core

The software core consists of the definition of technical itineraries (with their corresponding scenarii), the set of mathematical models and evaluated criteria, used in the simulation or optimization module.

Different technical itineraries are available, each of them corresponding to a management strategy, taking or not taking the natural risks into account. Within the technical itinerary, the scenario parameters provide the settings for the initial forest state and for the thinnings: tree-density, dates and rates, as well as the choice of the criterion to optimize, if optimization is required. The software can be used in three main modes:

- Unconstrained simulation: apply a technical itinerary,
- Constrained simulation : apply an admissible (which satisfies constraints for optimization) technical itinerary,
- Optimization : find the optimized settings according to a given criterion.

The simulation is run over the rotation time  $T$ . It is based on four interconnected models: tree growth model, natural (such as storm) risk model, tree damage model and gain/cost model. The tree growth model output feeds both the tree damage model and the valorization one. The evaluation criteria, based on the Faustmann approach (Faustmann, 1849), are calculated differently whether or not natural risk is taken into account in the technical itinerary. In the no risk case, the criteria are deterministic (Faustmann, 1849), in case of risk (Reed, 1984), they are based on expected values or CVaR.

## 2.2 Technical itineraries

The technical itineraries constitute a simple framework, based on production rules which its own consequences in terms of income.

In the present version, two technical itineraries are available, the first one for the no risk case and the second one for the case of risk. In the no risk case, stand management follows a basic non ambiguous itinerary: a clearcutting and a regeneration of the stand are done at the end of rotation period (or cutting age)  $T$ . In presence of natural risk, different technical itineraries may be used by forest managers. The software implements an adaptation to storm risk (Loisel, 2014) of the itinerary described in Reed (1984), originally designed for forest fire risk and widely used as a reference in presence of natural risk. It handles storm risk by defining a rule base, based on the fact that only when trees reach a certain height, storms cause direct damage but also weaken the trees, increasing future damage. The rule base is as follows:

- If a storm occurs before Threshold time (user-defined)  $t_L$ : no or neglectable impact on trees, then forestry management is unchanged.
- If a storm occurs at time  $\tau$  between  $t_L$  and  $T$ : the ratio of damaged trees is high, then a clearcutting and a regeneration of the stand are performed at time  $\tau$ .
- if no storm occurs before time  $T$ : a clearcutting and a regeneration of the stand are done at time  $T$ .

In the work presented in this paper, the considered natural risks are storms, though our approach remains valid for other natural risks, provided that suited itineraries are elaborated. To each technical itinerary corresponds associated criteria. The criteria are of different kinds, deterministic or expected actualized value of future incomes (Faustmann Value) or expected income (Yield Value), For the expected cases, the expressions of the expectations are hard-coded in the software. In order to evaluate the different criteria, it is necessary to evaluate incomes and costs. To this issue, various models must be given.

## 2.3 A sequence of models

The various model parameters and functions (see Table 1) are of four different kinds, detailed below:

- tree growth model (at stand level). It describes the dynamics of the tree basal area  $s$ : increment growth rate and the function describing the evolution of the dominant  $H$  and average  $H_{moy}$  tree heights. It is a continuous model which is then discretized.
- natural risk model. The natural events occur independently of one another, and randomly in time.
- tree damage model. The proportion of damaged trees depends on the stand state when the event occurs (in case of storm, see Schmidt et al. (2010)). The expected proportion of damaged trees may depend on the time, the tree basal area and the tree height.
- stand valorization model. Two submodels may be considered:
  - economic model. The economic incomes depend on the timber price functions for thinnings and on the final cutting age.
  - sequestered carbon model. The sequestered carbon model is related to the instantaneous income and the decreasing following thinning or final cut.

Each model is known with a different accuracy. Growth models are accurate and usually well validated by forestry researchers, while the risk and tree damage models are much more difficult to assess and generally have a low degree of fiability. The economic criteria are usually easy to compute, contrary to the sequestered carbon criteria. It is important to underline that, in a model sequence, the overall accuracy is governed by the less precise model. This justifies the choice made in this first version of EvaSylv to consider tree average-based growth models, instead of modeling basal area structured tree growth which describes more precisely the tree growth.



Scope	Variable/Parameter	Description
Growth	$n$	tree density ( <i>stems/ha</i> )
	$s$	average tree basal area ( $m^2$ )
	$H_0$	potential height (linked to fertility) ( $m$ )
Risk	$\lambda$	risk rate ( $year^{-1}$ )
Tree damage	$t_L$	limit time for tree damage ( $year$ )
	$H_L$	limit height for tree damage ( $m$ )
	$L_s$	damage rate ( $year^{-1}$ )
Economic parameters	$\delta$	discount rate ( $year^{-1}$ )
	$C_n$	clearing costs after a destructive event (€)
	$C_1$	regeneration cost (€)
	$c_w$	silvicultural cost (€)
Carbon	$c_a$	annual cost (€)
	$\gamma$	carbon discount rate ( $year^{-1}$ )
	$Cb$	sequestered carbon ( $ton$ )

Table 1: Variables and parameters used for simulation.

## 2.4 Silviculture

Two phases are to be considered in silviculture. The first phase consists in respacing. It is user defined by a set of two dates and the corresponding respacing rates (Table 2). The second phase is relative to thinnings. It is also user defined first by the maximum number of thinning dates  $N$ , then by the thinning dates  $(u_k)_{k=1..N}$  and the corresponding rates of thinnings  $(h_k)_{k=1..N}$ . Users must also specify the cutting age  $T$ .

Scope	Variable/Parameter	Description
Respacing	$h_0, h_1$	fixed respacing rates ( $year^{-1}$ )
	$td_0, td_1$	fixed respacing dates ( $year$ )
Control variables	$N$	maximum number of thinning dates
	$h_k$	$k$ th thinning rate ( $year^{-1}$ )
	$u_k$	$k$ th thinning date ( $year$ )
	$T$	cutting age (free or imposed) ( $year$ )
Constraints	$n_f$	final tree density (constrained or imposed) ( $stem/ha$ )
	$\Delta$	minimum elapsed time between thinnings ( $year$ )
	$t_0$	reference time for thinning date ( $year$ )

Table 2: Variables and parameters used in silviculture and optimization.

## 2.5 The criteria used for evaluation

We distinguish the no risk case and the storm risk case.

(i) *In absence of storm risk:* For a cutting age  $T$ , a discount rate  $\delta$ , the Faustmann Value  $J$  taking into account thinning incomes of a stand is the discounted value of cutting incomes minus cost of regeneration  $C_1(n_0)$  and actualized annual costs  $c_a$ :

$$J = -\frac{c_a}{\delta} - C_1(n_0) + \frac{W_e(T) - C_1(n_0)}{e^{\delta T} - 1} \quad (1)$$

where  $W_e(T)$  is the total economic income on  $[0, T]$  composed of the sum of thinning incomes  $R_k$  at time  $u_k$  actualized at time  $T$  and the final income  $V(T)$ :

$$W_e(T) = \sum_{k=1}^N R_k \cdot h_k \cdot e^{\delta(T-u_k)} + V(T) \quad (2)$$

For a simplified carbon sequestration model,  $J_C = \frac{W_e(T)}{e^{\delta T} - 1}$  where:

$$W_c(T) = \frac{\delta}{\gamma + \delta} \left[ \sum_{k=1}^N Cb(u_k) \cdot h_k \cdot e^{\delta(T-u_k)} + Cb(T) \right] + \delta \int_0^T Cb(u) e^{\delta(T-u)} du \quad (3)$$

(ii) *In presence of storm risk:*

Let  $E_V(\tau)$  the expected final income and  $E_{C_n}(\tau)$  the expected clearing costs in case of a storm at time  $\tau$ .  $E_{R_k}$  is the expected potential thinning income at time  $u_k$ . The expected Faustmann Value with storm risk becomes:

$$J_R = E[\mathcal{F}] = -\frac{c_a}{\delta} - C_1(n_0) + \frac{E_W(T) - C_1(n_0) - C_1(n_0)a(T)}{b(T)} \quad (4)$$

where  $(\delta + \lambda)a(T) = \lambda(e^{(\delta+\lambda)(T-t_L)} - 1)$ ,  $b(T) = e^{(\delta+\lambda)T - \lambda t_L} - a(T) - 1$  and  $E_{W_e}(T)$  is an expected income, with

$$E_{W_e}(T) = \sum_{k=1}^N \beta_{\delta, \lambda}^k E_{R_k} \cdot h_k + \lambda \int_{t_L}^T [E_V(\tau) - E_{C_n}(\tau)] e^{(\delta+\lambda)(T-\tau)} d\tau + V(T) \quad (5)$$

where  $\beta_{\delta, \lambda}^k = \beta_{\delta, \lambda}(u_k)$  and  $\beta_{\delta, \lambda}(u) = e^{(\delta+\lambda)(T-u) + \lambda(u-t_L)} -$ .

The expressions of the expected values of criteria are hard-coded in the software. So, the optimization procedure for expected values does not require simulation of the technical itineraries.

For a simplified Carbon sequestration model, we can express a Faustmann Value  $\mathcal{F}_C$ , the corresponding expected Faustmann value with storm risk  $J_{RC} = E[\mathcal{F}_C] = \frac{E_{Wc}(T)}{b(T)}$  where:

$$E_{Wc}(T) = \frac{\delta}{\gamma + \delta} \left[ \sum_{k=1}^N \beta_{\delta,\lambda}^k Cb(u_k) \cdot h_k + \lambda \int_{t_L}^T E_{Cb}(\tau) e^{(\delta+\lambda)(T-\tau)} d\tau + Cb(T) \right] + \delta \int_0^T \beta_{\delta,\lambda}(u) Cb(u) du \quad (6)$$

In the case of an economic evaluation, the software gives both the Faustmann criteria and the Long Run Average Yield, with or without risk. With risk,  $CVaR(p)$  is also available.

## 2.6 Optimization

Forest management depends on several control variables (Table 2), some of them being scalars, the others being vectors. The scalar ones include the cutting age  $T$  and the final  $n_f$  tree density at time  $T$ . The user has the possibility to optimize the different criteria with the cutting age  $T$  imposed or not, the final tree density  $n(T)$  set to  $n_f$  or only constrained:  $n(T) \geq n_f$ . The respacing dates and rates are control variables. The vector of control variables is organized in two sets. The first set is composed of the thinning dates  $(u_k)_{k=1..N}$  such that  $0 < u_1 < u_2 < .. < u_N < T$  and the second set is composed of the thinning rates  $(h_k)_{k=1..N}$ . A minimum time lag  $\Delta$  between two thinnings (starting no sooner than  $t_0$ ) is imposed in the constrained and optimization modes (see Section 2.1).

The results are obtained using algorithms to optimize the different considered criteria. User selects the choosen algorithm. The provided algorithms do not manage constraints on control variables. In order to satisfy constraints, some artificial variables are introduced (see Appendix A). These artificial variables are required in both the constrained simulation and optimization modes, but are not used in the unconstrained simulation

mode.

### 3 Software design

EvaSylv is designed to let the user set up the runtime behaviour by modifying scalar values and defining custom functions to be used by the mathematical models. Parameters are organized in a hierarchical tree with nodes. A key point is that custom functions are treated exactly as parameters, giving a great flexibility to the models.

In its present version, the program is a stand alone program, distributed in open source license. The software architecture is schematically composed of three layers. At the deepest level, the *core layer* contains all components of the simulation: model structures and communication between them, technical itineraries and analytical expressions for the criteria. At the most external level, the *interface layer* handles the (graphical or command line) interface that allows to enter a model and its parameters and to build a scenario. In between, the *Build layer* fills in the model structures and scenario parameters for transmission to the *core layer*. The software is entirely written in Python. Python version 3.0 has been used, with the main following Python libraries:

- `numpy`([www.numpy.org](http://www.numpy.org)) provides tools and data structures for high precision scientific computation,
- `scipy`([www.scipy.org](http://www.scipy.org)), based on `numpy` provides, among other scientific programming tools, a toolbox for optimization,
- `sympy`([www.sympy.org](http://www.sympy.org)) provides symbolic computation tools.
- `matplotlib`([www.matplotlib.org](http://www.matplotlib.org)) is used for plotting functionalities.

The software can be run in script mode with a configuration file or using a graphical user interface (see screenshot in Fig.2). Parameterizing a simulation/optimization is done by double-clicking an item belonging to this tree and editing it. Customizable functions are compiled before the execution of the simulation/optimization functions.

Users write their own functions using the software interface, which checks syntax validity. These user data are automatically interpreted by the software to build the full

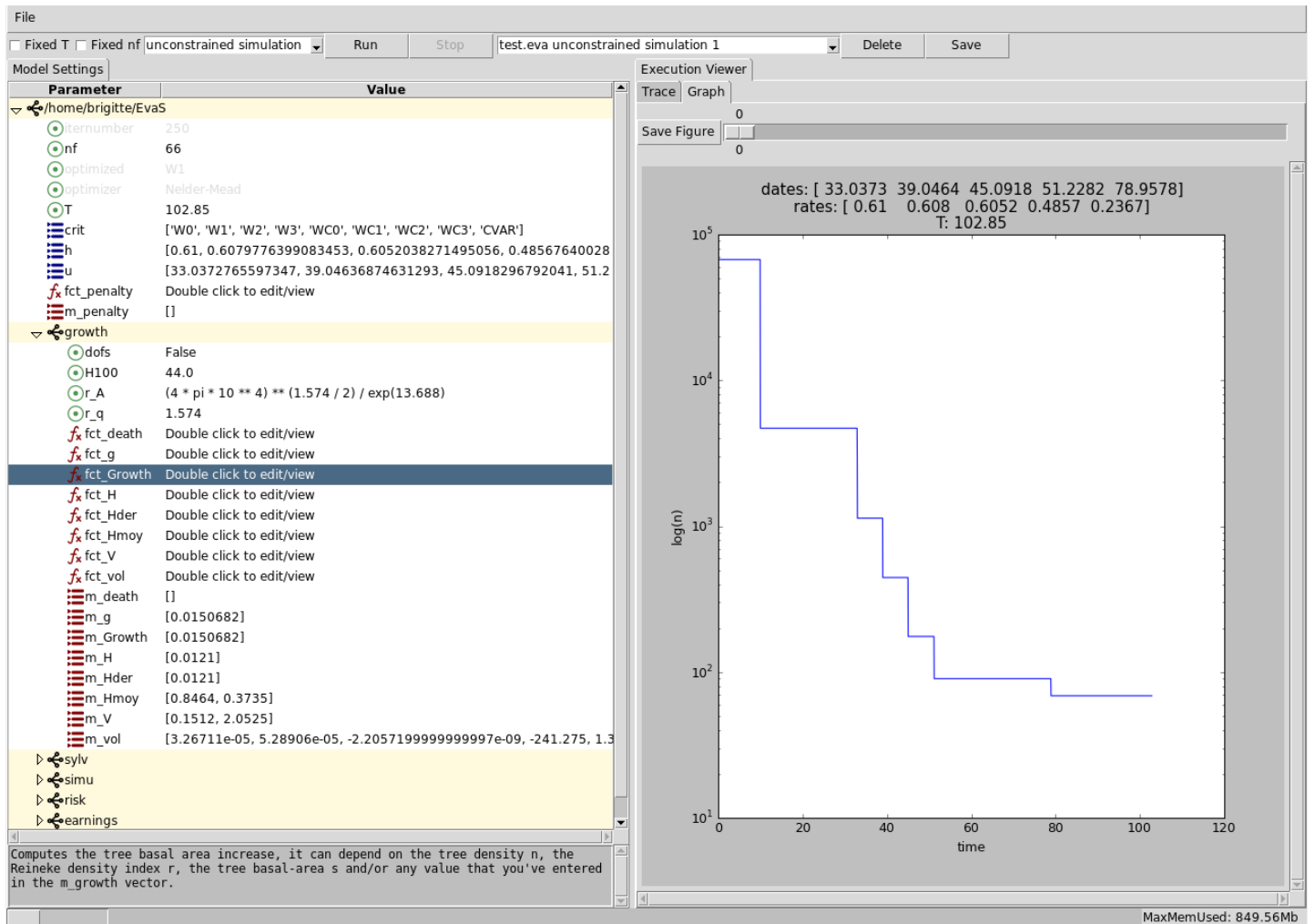


Figure 2: EvaSylv graphical user interface.

model. Default configurations are provided for beech and pine forests. Users can adapt them to describe other species. The most important functions are summarized in Table 3. The function arguments are limited to the ones given in Table 3, with an extra parameter vector, as illustrated in 4.1.1 (named  $m$  or  $p$  in respective functions).

Models	Purpose	Function
Tree growth	stand basal area (increase)	$Growth(t, n, s, H_0)$
	tree height	$H(t, H_0), Hder(t, H_0), Hmoy(t, H_0)$
	tree volume	$vol(t, s, H)$
	tree mortality rate	$death(t, n, s)$
Tree damage	tree damage rate	$Loss(t, H_L)$
Economic	thinnings, final timber price	$Pse(t, s, H), Ps(t, s, H)$
	fertilization, clearing costs	$C_f(t), C_n(n, Loss, Vol)$
	regeneration, silvicultural costs	$C_1(n), wc(t, k, n, s, H, Vol)$
Carbon	sequestered carbon	$Cb(t, s, H)$

Table 3: Functions used in models.

## 4 Results and discussion

EvaSylv offers the possibility to implement many models, depending on the species and on the taking into account of storm risk, or not. The software functionalities are illustrated with two examples. The first example aims to optimize the economic valorization of a beech stand. The second one is related to the carbon evaluation of a pine stand. In the first case, silviculture is evaluated for the four types of criteria: Faustmann and Average value with risk and without risk. In the second one, the Faustmann criteria are given.

To enter the sub-models, the user can either use the interface or a configuration file, starting from a default file.

### 4.1 Economic evaluation of silviculture for a beech stand

We consider a beech stand. We are interested in the financial incomes obtained from the timber sales.

#### 4.1.1 Growth model

This sub-model is the one that requires the greatest number of functions. The model core is related to the tree basal area. The tree basal area is governed by a dynamic model, following a differential equation. The user must provide the second member of that equation. Let us take as example a growth function (Le Moguedec and Dhote, 2012) with one parameter  $m_1$  and the following mathematical expression:

$$(1 - e^{-m_1 n(t) \sqrt{4\pi s(t)}}) V(t, H_0) / n(t)$$

where  $V(t, H_0)$  is the potential total basal area increase.

The software interface (see Fig. 2) displays a help text with the growth function purpose and its possible dependencies with other model components, in that case the tree density  $n$ , the basal area  $s$ , the potential height  $H_0$ . The expression of the growth function is given below, written in Python code, very close to the mathematical formulation.

```
def fct_Growth(self, t, n, s, m, H0):
    g=((1-exp(-m[1]*n*sqrt(4*pi*s)))*self.fct_V(t,H0))/n
    return g
```

The growth function definition is prefilled with a default expression. The first line must not be edited. The function takes as argument the  $m$  parameter, which is a vector of any length, whose elements will be accessed by using  $m[1], m[2] \dots$  in the function body, which can be edited to fulfill the user needs. The components of the  $m$  vector are specified by the user in a predefined box located above the corresponding function. The  $m$  vector being of variable length, there is a lot of flexibility, as the user can add any parameter of interest. The reference to a pre-defined function must be preceded by the *self.* prefix.

The potential total basal area increase is for instance equal to:

$V(t, H_0) = p_1 + p_2 H_{der}(t, H_0)$ , where  $H_{der}(t, H_0)$  is the derivative of  $H(t, H_0)$ , the dominant height with respect to time  $t$ .

```
def fct_V(self, t, p, H0):
```

```
return p[1]+p[2]*self.fct_Hder(t,H0)
```

Here is an example of a  $H$  function.

```
def fct_H(self, t, p, H0):
    return H0 * ( 1 - exp(-p[1] * t))
```

The derivative is automatically generated (using the symbolic computation tools of sympy).  $Hder$  is given by:

```
def fct_Hder(self, t, p, H0):
    return p[1] * H0 * exp(-p[1] * t)
```

The user may check it and modify it, if necessary.

#### 4.1.2 Optimization

Results given in Table 4 are obtained with the classical Nelder Mead algorithm. The Faustmann value is calculated with a discount rate  $\delta = 0.025$  per year. Whatever the chosen criterion, Faustmann value with actualization or Average value, the presence of storm risk reduces the optimal cutting age and therefore the optimal thinning dates occur earlier. This is in agreement with the commonly admitted management strategy. By changing the timber price function  $P_s$  (see Table 3), the user can evaluate the criterion behaviour with respect to the market price.

The introduction of risk in the scenarii has a much greater impact onto the Average value. This is due to the fact that the loss is increasing with respect to stand age.

The evolution of  $n$ , the tree density, is plotted in logarithmic scale at the right side in Fig.2.

## 4.2 Evaluation of silviculture for Carbon sequestration of a pine stand

We now consider a pine stand and the impact of silviculture on aerial carbon sequestration. The carbon model is currently an open research topic in itself. Many models exist in the literature (Price and Willis, 2011); (Susaeta et al., 2014) with various complexity



Criterion	Itinerary	Optimal Thinnings				Cutting age	Value
Faustmann Value	without risk	$u_k$	47	55	63	77.5	2808
		$h_k$	.249	.249	.167		
	with risk	$u_k$	44	52	60	68	2591
		$h_k$	.240	.199	.219		
Averaged Yield Value	without risk	$u_k$	138	146	154	163	313
		$h_k$	.167	.250	.250		
	with risk	$u_k$	72	80	88	96	220
		$h_k$	.167	.250	.250		

Table 4: Optimal Value (€/ha) with respect to thinning rates  $h_k$ , dates  $u_k$  and cutting age  $T$  (years).

levels. We chose a simple model, where the carbon function is assumed to be proportional to the tree volume, in order to illustrate the interest of the simulation. With or without risk, the criterion to optimize has an integral form (see Eq.3 and Eq.6), so the optimization must be performed with a minimum tree density target.

The software is run with a constraint on the final tree density  $n(T)$ , that must be  $\geq n_f = 200$  stems/ha. Due to the fact that the chosen model for carbon sequestration is an increasing function of time, the optimization will always try to reach the minimum tree density value. The optimal cutting age is found to be 116.4 years, in both cases, with or without risk. The Faustmann criterion value, calculated with a discount rate of 0.03 per year, is found to be equal to 293 tons of  $CO_2$  for the unrisky case, and 273 tons of  $CO_2$  for the risky case. We arbitrarily assumed that a cubic meter of wood stores a ton of  $CO_2$ , according to generally admitted values, that range between half a ton and a ton.

## 5 Conclusion

The EvaSylv software presented in this paper hopes to fill a gap in the available softwares for forest management. Even though a lot of forest models are available on tree growth at the stand level, and are included in modeling platforms, they are hard-coded and not user-editable. EvaSylv gives the users an easy way to simulate their own models at stand level, without needing to have a deep knowledge of computer science languages and of the program structure. This is the main strength of the software. EvaSylv

functionalities include simulation and optimization tools. Moreover, it allows to take into account natural risks, which is not the case with other forestry simulation platforms. The software relies upon a sequence of integrated models: growth, risk, tree damage and valorization.

In the present version, limited to storm risk, the software provides two kinds of technical itineraries: a deterministic one (without risk) and a basic one in presence of risk. The modeling in presence of risk requires the calculation of expected values for criteria, which change depending on the technical itinerary. Implementing more complex itineraries requires an interaction with software designers, in order to establish the corresponding evaluation criteria.

The software is likely to participate in the improvement of silviculture guidelines, by taking into account available field data and updated storm risk information.

The approach is flexible enough to open several perspectives. First the elaboration of more complex technical itineraries together with forest managers, which implies mathematical developments to obtain the corresponding analytical criteria. Second the extension to more realistic growth models (structured into classes of basal area). Third the building of ecosystemic service forest-related models.

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## A Optimization using artificial variables

The constraints on thinnings dates ( $u_k - u_{k-1} \geq \Delta$  years) and, if necessary, the final tree density constraint ( $n(T) = n_f$ ) are managed using artificial variables  $x_k$  and  $y_k$ . For example, in the case without mortality:

$$\begin{aligned}
u_k &= u_{k-1} + \Delta + \frac{x_k^2}{\sum_{j=1}^N x_j^2 + 1} |x_{N+1}|, & k &= 1..N \\
T &= t_0 + \Delta \cdot N + |x_{N+1}|, \\
h_k &= 1 - \left( \frac{n_f}{n_0(1-h_0)(1-h_1)} \right)^{\frac{y_k^2}{\sum_{j=1}^N y_j^2}}, & k &= 1..N
\end{aligned}$$

Although the Nelder Mead algorithm has a better behavior than the steepest descent method, it is likely to get stuck in local minima (maxima in our work). The implemented algorithm does not ensure to obtain the solution corresponding to the global maximum. To avoid this problem, it is recommended to run the optimization with several initial conditions.

The automatic transformation back and forth between artificial and real control variables is implemented in the software workflow, as represented in Fig.1.

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