



Spatial aspects in the Heureka forest decision support system - an overview

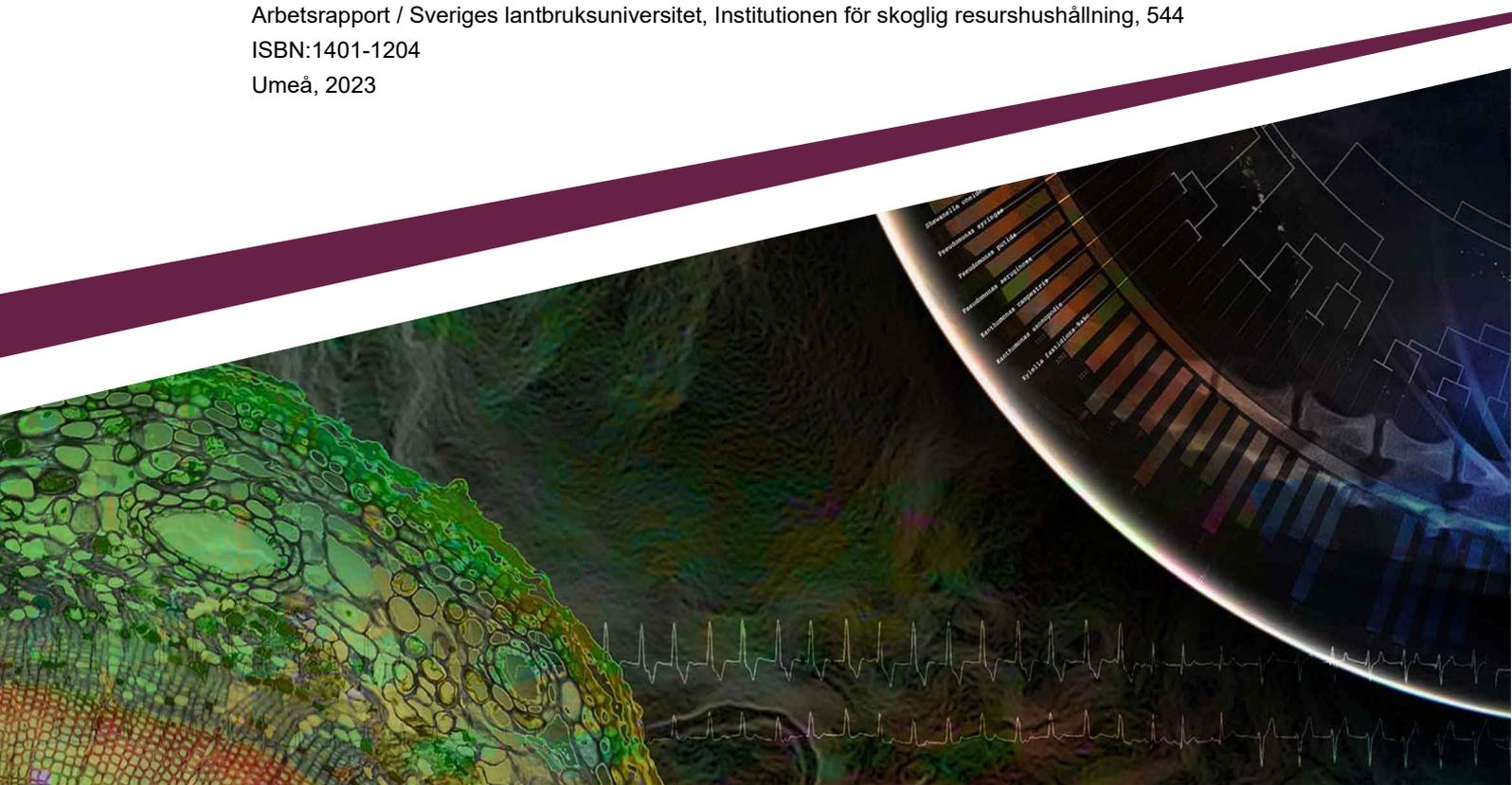
Lars Sängstuvall, Tomas Lämås, Karin Öhman

Swedish University of Agricultural Sciences, SLU
Department of forest resource management)

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Lars Sängstuvall, <https://orcid.org/0000-0002-6444-6234>, Swedish University of Agricultural Sciences, department of forest resource management

Tomas Lämås, <https://orcid.org/0000-0002-2837-4501>, Swedish University of Agricultural Sciences, department of forest resource management

Karin Öhman, <https://orcid.org/0000-0002-0216-6536>, Swedish University of Agricultural Sciences, department of forest resource management

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Sammanfattning

Den här rapporten har skrivits som en del av forskningsprogrammet Mistra Digital Forests första fas (2018-2022), inom ett arbetsområde som rör användning av heltäckande skogliga data inom skoglig planering. Skoglig planering omfattar rumsliga/spatiala aspekter om värdet av en skoglig åtgärd eller egenskaperna hos ett skogsbestånd inte bara beror på egenskaperna hos själva beståndet, utan också påverkas av beståndets grannar och/eller läge i landskapet. I svenskt skogsbruk har spatiala aspekter traditionellt inte hanterats i den strategiska skogliga planeringen, utan i den taktiska skogliga planeringen och/eller den ekologiska landskapsplaneringen.

I rapporten beskriver vi ingående och presenterar tillämpningar av den spatiala funktionalitet som finns tillgänglig i beslutsstödsystemet Heureka, samt identifierar potentiella utvecklingsmöjligheter. Dessa omfattar bland annat att förenkla användargränssnittet för optimeringsverktyget i Heureka, minska byggtiderna för olika optimeringsproblem, stödja effektiva avgiftsfria lösare av optimeringsproblem, förbättra GIS-funktionaliteten, möjliggöra enkel användning av öppna data för olika analysändamål, samt publicera Heureka systemet som öppen källkod.

Nyckelord: Långsiktig planering, rumsliga aspekter, skoglig planering, spatiala aspekter, strategisk planering,

Abstract

This report is part of task 1.4 in work package 1 in the Mistral Digital Forests first phase (2018-2022) research programme. The task concerns the use of information with complete spatial coverage (“wall-to-wall data”) in forest planning. Spatial aspects in forest planning are present if the value of a forest management activity or the character of a specific stand does not rest only on management or attributes of the stand itself but also on stands in the neighborhood. Traditionally in Swedish forestry spatial aspects, e.g. the spatial location of final fellings, has been handled in tactical planning and/or ecological landscape planning and not in the strategic planning.

In this report, we thoroughly describe and present state-of-the art applications of the spatial functionality available in the Heureka forest DSS, and identify potential development tasks. These include to simplify the interface of the optimization model, reduce the build times associated with the formulation of various optimization problems, support efficient free solvers of optimization problems, improve GIS functionality, enable the use of open data in various forms of analysis using the Heureka systems and publish the Heureka system as open source.

Keywords: Forest management planning, long-term planning, spatial aspects, strategic planning.

Preface

This deliverable (1.4.4) is part of task 1.4 in work package 1 in the Mistral Digital Forests first phase (2018-2022) research programme. The task concerns the use of information with complete spatial coverage (“wall-to-wall data”), such as traditional forest maps with associated stand data or high-spatial-resolution forest data from e.g. airborne laser scanning, in order to ensure a sustainable and multifunctional use of the forest resource.

Prior to this deliverable the task has provided five deliverables. The first one (1.4.1; Öhman et al. 2020a) is a short report from two stakeholder workshops on visions for the next generation of forest decision support systems (DSSs). The participants stressed, among others, that future DSSs have to handle climate change effects - especially negative ones, increased number of ecosystem services, being applicable on different forest data sources, and being useful in the communication with the society in general.

Long-term forest planning can either be based on a strata-based or an area-based approach. In Sweden a strata-based approach - based on a stratified and field surveyed sample of stands - has for several decades been used on large forest holdings. As an alternative, the area-based planning approach is based on information on all stands within a holding. The second deliverable (1.4.2, Öhman et al. 2020b) compares (pros and cons) these two approaches. A major advantage for the strata-based approach is the known certainty of the forest information obtained. A major disadvantage, on the other hand, is that the planning cannot be geographically explicit and spatial aspects cannot be handled. An area-based approach, on the other hand, enables spatial analyses, but the typical unknown accuracy of the information used (stand registers (forest inventories)) have so far made it less appropriate for long-term planning. Furthermore, suitable planning DSSs were missing until the release of the Heureka system (Wikström et al. 2011), restraining the development and usage of spatial analyses in Swedish forestry.

High-spatial-resolution forest information typically presents the information for raster map elements (e.g., 10x10 m²). In forest planning, traditional stands have so far been similar to treatment units, i.e., the unit to be thinned or clear felled at a certain time point. High-spatial-resolution forest information - typically raster elements - enables another approach; a dynamic treatment unit (DTU) approach. In the latter approach, raster elements are temporarily aggregated into treatment units

to be harvested at a specific point of time. Deliverable 1.4.3 (Wilhelmsson et al. 2021) presents a case study applying the DTU approach on a ca. 1200 ha forest landscape and 50 years planning horizon. A comparison between the DTU approach and the traditional stand-based approach is made on a 4 480 ha landscape in deliverable 1.4.5 (Wilhelmsson et al. (in prep.)). Deliverable 1.4.6 (Öhman et al. 2021) applies a traditional area-based approach but concerns a multi-objective planning problem. Timber production objectives are integrated with the objective to reduce the fragmentation of voluntarily set asides (in terms of total circumference of voluntarily set asides and nature reserves). Fragmentation is shown to be noticeably reduced to a modest reduction of economic outcome of timber production. Moreover, the study applies habitat models for Siberian jay and for a fictive species to illustrate the effects of reduced fragmentation. The present deliverable (1.4.4) compiles and describes the different spatial aspects that are handled by the Heureka DSS and pin points potential further development.

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Abbreviations

ARM	Area Restriction Model
DSS	Decision Support System
GUI	Graphical User Interface
LP	Linear Programming
HSI	Habitat Suitability Index
MIP	Mixed Integer Programming
NPV	Net Present Value
TPG	Treatment Program Generator
URM	Unit Restriction Model

Spatial functionality in Heureka – current models, tools and their application

1.1 Introduction

Sustainable forestry means that both ecological, economic and social values are to be taken into account. For many of the aspects behind these values, it is not enough to do something on an arbitrary location in the landscape. You also have to know where in the landscape, how an action is carried out, and how the action depends on and affects surrounding areas. Thus, spatial relationships are prominent within a sustainable forestry and concerns ecological (e.g., suitable habitat for species), economical (e.g., spatial concentration of harvests) as well as social aspects (e.g., maximum area of clear felling). Forest planning must therefore handle also such spatial aspects (Baskent and Keles 2005, De Pellegrin Llorente et al. 2017).

Spatial aspects in forest planning are present if the value of a forest management activity or the character of a specific stand does not rest only on management or attributes of the stand itself but also on stands in the neighborhood. For example, the cost of harvesting a stand depends on whether or not fixed costs (entry costs for roads, etc.) can be shared with harvesting of other stands in the neighborhood. Another example is how whether or not a stand makes up a suitable habitat for a specific species depends, besides on the stand itself, also on the composition of the surrounding landscape.

Traditionally, spatial aspects, e.g. the spatial location of final felling, has been handled in tactical planning and/or ecological landscape planning and not in the strategic planning. Instead, spatial aspects have been addressed at the strategic level by including a planning reserve in the problem formulation (Ulvdal et al. 2022). However, by not explicitly taking spatial considerations into account also at the strategic level, there is a risk that the strategic analyses will reach harvesting levels that will be impossible to meet in the subsequent tactical planning, or that the area of available habitat at a certain harvest level will be overestimated. The reason to why spatial aspects have not been handled at the strategic level is, among other things, that when the process of strategic planning was established, the computing capacity was very limited and the DSSs of the time were mainly developed to

handle a strata-based approach not able to cope with spatial consideration. It was also expensive and difficult to obtain spatially comprehensive data of sufficiently high quality. Today the situation is different. First, there are new possibilities to describe the forest with geographically comprehensive data, e.g. with help of remote sensing, and such data are freely available for the whole of Sweden (Skogsstyrelsen 2022). Second, the computational capacity of computers is steadily increasing, and there are new DSSs with new functionality. One such is the Swedish Heureka DSS, which can handle a larger palette of spatial aspects compared to previous systems.

The aim of this report, being the last deliverable from task 1.4 within the first phase of the Mistra Digital Forest research programme, is to give a general overview – and some in-depth descriptions – of spatial aspects handled by the Heureka software (Wikström et al. 2011). Another aim is to pin point necessary as well as potential further development of the system. In all, this report serves both as a state-of-the-art description, and as a first mean to increase knowledge and usability of the spatial functionality in Heureka PlanWise, i.e. the Heureka software used for strategical planning at large Swedish forest companies. The scope of spatial aspects in forest management planning is, however, much larger than covered by this report and the Heureka system. For an overview, see e.g., Baskent and Keles (2005) and De Pellegrin Llorente et al. (2017).

1.2 What spatial aspects are handled by Heureka PlanWise?

The Heureka decision support system consists of a suite of software for forest analysis and planning. Three of the software (named StandWise, PlanWise and RegWise) concern forest dynamics having a common kernel made up of, among others, growth and yield models. Simulation and optimization are respectively used to project the consequences of different management alternatives or to find preferred solutions. Simulation as a consequence projection method (answering “what if” questions) as applied in Heureka RegWise means that a set of different forest management and forest owner behaviour rules are specified to generate one single treatment programme for each treatment unit (stand) in the analysis area. On the other hand, an optimization approach (answering “how to” questions) means, first, by simulation generating a large set of potential management alternatives for each treatment unit (stand). Then the best alternative for each treatment unit is selected using an optimizing algorithm based on the goals and constraints stated for the planning problem. Heureka PlanWise is based on the latter and follows the general planning model consisting of using simulation in combination with optimization (Öhman et al. 2020b).

In PlanWise the Treatment Programme Generator (TPG) is a core component that generates the set of potential management alternatives for each treatment unit. The user defines the frame for generating the set of potential management alternatives for each unit by stating the maximum number of thinnings, shortest allowable rotation age, etc. An example of a TPG result is given in Figure 1.

After running the TPG the stated planning problem is built and solved by Linear Programming (LP) or Mixed Integer Programming (MIP). Building the optimization problem in Heureka is done using ZIMPL, and as solvers freeware as well as commercial solvers can be used. For a more detailed description of PlanWise we refer to the report “Overview of the PlanWise application and examples of its use” by Eggers and Öhman (2020). Heureka PlanWise has the most comprehensive spatial functionality out of the three software, and is therefore used as reference in this report.

The spatial aspects handled by PlanWise can be categorized by their relation to the optimization procedure:

1. Spatial aspects are handled prior to and independent of the optimization – a (spatially) exogenous pre-optimization approach: Prior to the optimization, units (stands) are allocated to certain domains or zones. A domain is defined by stand attributes (e.g. stand age or tree species) or by spatial location, such as stands adjacent to water courses.
2. Spatial aspects are handled by the optimization procedure – a (spatial) endogenous optimization approach: Here two sub-cases can be distinguished:
 - a. Spatial pre-calculation tools as well as optimization models available in PlanWise are used to solve the spatial problem.
 - b. Spatial pre-calculation tools are used but the optimization model must be formulated by the user to solve the spatial problem.
3. Spatial aspects are handled when a solution of a planning problem is found, i.e., after running the optimization routine – a post-optimization approach.

Treatment program	Period															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1				FF					CI							Th
2			FF					CI						Th		
3			SF			SF			SF			SF				SF
4		SF			SF			SF			SF			SF		

FF – final felling, CI – cleaning, Th – thinning, SF – selection felling

Figure 1. Potential treatment programs for an arbitrary treatment unit over 16 five-year periods. (cf. Eggers and Öhman, 2020).

The three cases are described further below. Cases 1 and 3 are handled also by the simulation based RegWise software but RegWise is not referred to in the following text. A fourth case can be distinguished where the outcome of PlanWise (spatial pre-calculation tools) and the TPG (the set of potential treatment programmes) are used. The spatial problem is then formulated externally and solved with an external solver. It is then possible to import that solution back to PlanWise, for example to use the report tool to build charts. Such cases are not included in the following case descriptions.

1.3 Case 1: The pre-optimization approach

In the pre-optimization approach, the user defines the spatial pattern of management activities before the optimization procedure, e.g. that certain stands (forming a domain) are exempted from management and set aside for free development or that the stands closest to watercourses may not be clear-cut. A drawback with the approach is that it does not take into account the dynamics over time. For example, making one domain for stands that are set aside for free development meets the spatial requirements of today, but does not take into account the fact that the forest develops over time. On the other hand, the approach is straightforward and does not in most cases affect the choice of optimization method.

In Heureka there are three tools for handling spatial aspects with a pre-optimization approach: a tool for creating spatial domains, a buffer zone tool and a tool for creating spatial explicit retention patches, each of them presented in more detail below.

1.3.1 Spatial domains

The stands imported into Heureka PlanWise and RegWise can interactively via map functionality be divided into different domains (a domain is a group of stands, almost like a zone even if the stands does not have to be contiguous) and then different settings for treatment programme generation can be specified for each domain. For example, for one domain only treatment programmes for continuous cover forestry are generated while for another domain schedules belonging to even aged forestry are generated. Spatial domains can be created by first selecting areas in the map in the Initial state tab, see Figure 2 and then in next step connecting one or more control categories specifying potential management to that domain.

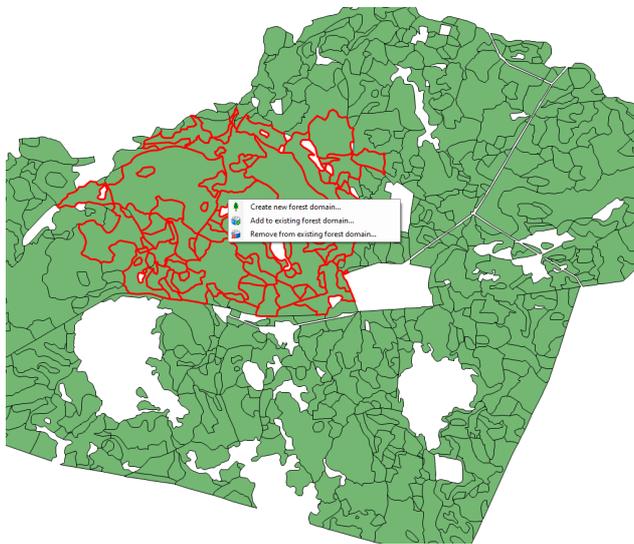


Figure 2. Example of a spatial domain, interactively defined in the Heureka map tool (in red).

1.3.2 Buffer zones

A tool is available for defining buffer zones around, e.g., water courses based on one or more map layers. It splits stands (polygons) into a main stand (parent stand) and a “buffer stand”, the latter being the part of the original stand intersecting any on the map layers defining the buffer zone (Figure 3). As for retention patches zones made up of buffer stands can be unmanaged or managed, in the latter case potentially coordinated with management of the parent stand, see below. The buffer zone tool is available on the tab Initial state / Map / .

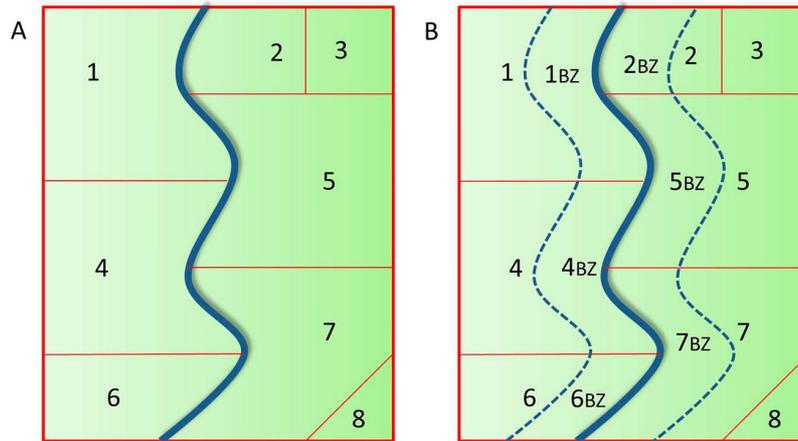


Figure 3. The principles of the buffer zone tool. (A) The original stands (1-8) along a watercourse and (B) the parent stands (1 - 2, 4 - 7) and buffer stands (1BZ - 2BZ, 4BZ - 7BZ). From Lundström et al. (2018).

1.3.3 Tree retention patches

Typically, retention patches are not explicitly mapped in forest maps but only given as an area or proportion of each stand within the analysis area. If so, these areas can not be taken into account e.g., in spatial habitat models. A tool in PlanWise can, however, in a schematic manner make such non-mapped retention patches spatial explicit.

The tool for spatial explicit retention patches is available on the menu bar Data management / Clone Area and Split NC Units. It clones (makes a copy of) an already imported analysis area and splits treatment units (stands) into parent stands and tree retention patches. The area of each retention patch is controlled by the Nature conservation settings in the TPG for each domain involved; either the information is read from the input data (stand register) or stated in the Nature conservation settings as a proportion (%) of each stand to be set aside as a retention patch. Spatial retention patches are formed around the centroid of each stand as rectangle, the spread in north - south and east - west relative to spread of the original stand in those directions (Figure 4). The created copy of the analysis area is found under the list of analysis areas given the extension NC to the original name, all retention patches are given the name (number) of the original stand plus the extension NC as well.

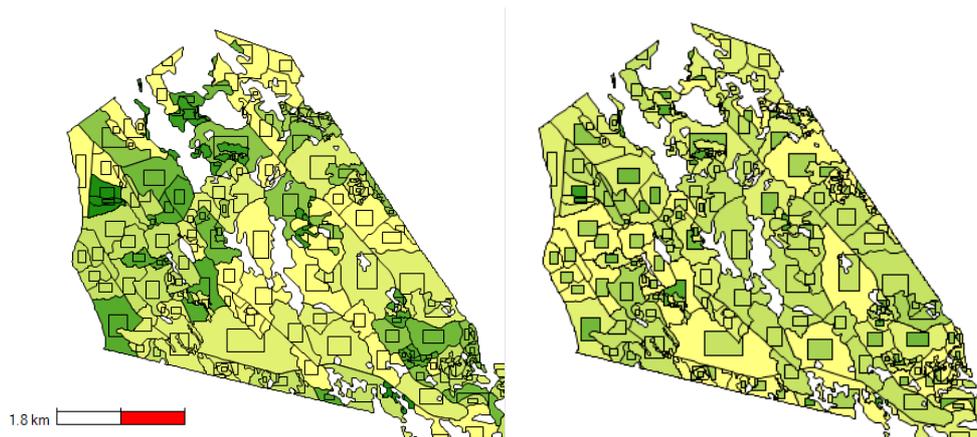


Figure 4. Non-mapped retention patches made spatial explicit by the tool “Clone Area and Split NC Units” (the rectangles in each stand). In this example, the area of retention patches is set to 20% of stand area. Stand age is shown; the darker green the higher age. The initial state to the left and the state in period 10 (5 year periods) to the right.

1.3.4 Potential management of buffer zones and retention patches

Buffer stands and retention patches can either be left unmanaged or managed; if treatment should occur, the treatments can be either dependent or independent of management activities in the parent stand. If independent, the areas are treated as regular stands and a set of potential treatment programmes including thinnings (if any) and final felling (i.e., ordinary even-aged management) are generated. In this case (independent), what management alternative of the potential ones to be chosen is decided later in the optimization (e.g., based on a maximum net present value (NPV) goal function). If dependent, the set of potential treatments are coordinated (same time points) with potential activities (thinning, final felling or selection felling) of the parent stands. However, the only activity options for buffer stands and retention patches in this case (dependent) is no management or selection felling. If set to selection felling, the timing of activities in buffer zones or retention patches is coordinated with activities in the parent stand when running the TPG, but the activities have also to be controlled by a restriction in the optimization model, see as an example Lundström et al. (2018).

1.4 Case 2: The spatial endogenous optimization approach

In the endogenous optimization approach, consideration to spatial aspects are integrated into the optimization model, and the resulting spatial pattern becomes a result of the optimization procedure. A drawback with this approach is that the optimization problem can be very complicated and the solution times for solving

the optimization problem increases. This is largely due to the fact that in these cases PlanWise cannot use traditional LP to solve the optimization problem. Instead, MIP is used. However, although the endogenous optimization approach can give rise to complicated optimization problems, the approach provides the opportunity to evaluate a very large number of combinations of treatment programmes. This increases the possibilities to investigate the consequences of many spatial alternatives and to find the most cost-effective solutions. In PlanWise there are three pre-calculation tools available for producing information that could be used in different optimization problems for including considerations to spatial aspects: the tool for computing common border lengths, the tool for calculating cliques and harvest clusters and the tool for calculating stand neighborhood. These tools are further described below.

1.4.1 PlanWise spatial pre-calculation tools

In PlanWise there are three pre-calculation tools available for producing information that could be used in different optimization problems for including considerations to spatial aspects as listed in the following section. Resulting calculated spatial relations are stored in the forest database and can be referred to via optimization model parameters, either in the optimization models that already are available in Heureka (case 2a) or in models that are created by the user in the optimization tool (case 2b).

Tools / Compute Common Border Lengths

This tool calculates the common border length (m) between adjacent stands. The information on common border length is e.g. needed when applying *Opening size constraints*. In case two stands connects in a point only the common border length is set to 0 (zero). In the Opening size constraint case the user has in a latter stage to decide how the case of common border length = 0 should be considered.

Tools / Compute Cliques and Harvest Clusters

This tool is needed for applying *Opening size constraint* using the Area Restriction Model (ARM) in the optimization. Cliques and Harvest clusters are two sets of collections of treatment units spatially related to each other: *Cliques* form all arbitrary combinations of treatment units that share a direct spatial adjacency with at least one common treatment unit, whereas *Harvest clusters* are made up of all arbitrary combinations of adjacent treatment units limited by parameters 1-3 below. This is further illustrated in Figure 5.

Harvest Clusters are calculated in order to reduce the extent of calculations in latter stages. For Harvest Clusters the user must provide three parameters (from the Heureka Wiki):

1. "Min Border Length" defines the minimum length of a common border (in meters) if the both of two adjacent stands can be included in the same cluster.
2. "Max Nb Polygons" defines the maximum number of stands (if the stand correspond to one polygon, else substands = polygons) in a cluster.
3. "Max Cluster Area" defines the maximum size (in hectares) of a cluster.

For Cliques the user must state whether a minimum common border length is needed (> 0 m), otherwise, a common point is sufficient for two units being considered adjacent.

Before applying this tool, Compute Common Border Length (see above) shall be performed.

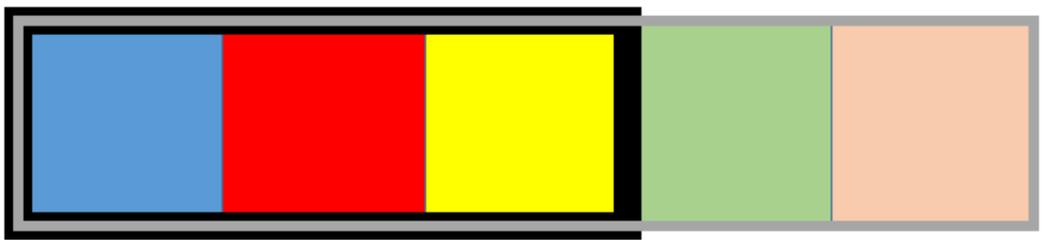


Figure 5. Example of a Clique (black box) and a Harvest cluster (grey box) in relation to the red tentative treatment unit, the Clique being all adjacent treatment units in relation to red (blue+red+yellow), and the Harvest cluster being potentially all five treatment units together if their area sum doesn't violate cluster parameter 3, as explained in the text.

Tools / Compute Stand Neighborhood

This tool calculates the area of other stands that are within the neighboring area of a specific stand. The neighboring area for each stand (polygon) is defined as the area within a circle with a radius (m) specified by the user from the centroid (center of gravity) of the stand (Figure 6). This tool is e.g. needed when applying the habitat restriction tool, see below.

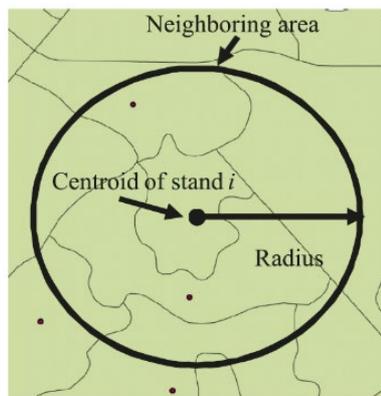


Figure 6. The principle for Compute Stand Neighborhood. From Öhman et al. 2011.

1.4.2 Case 2a: Available pre-calculation tools as well as optimization models are used

The optimization module in Heureka has built-in support for adding constraints handling two types of spatial aspects: clear cut size constraints and constraints for a minimum area of habitat in a landscape. However, this makes the optimization model becomes more complex and may for analysis including very many stands require that external optimization solvers such as CPLEX or Gurobi are used. In addition, it should be noted that using this feature may require great skills in optimization methods.

Clear cut size restrictions

Tools available in PlanWise makes it possible to restrict the total area of adjacent clear fellings, using either of the approaches named Unit Restriction Model (URM) or Area Restriction Model (ARM).

The URM properly belongs to case 2b, but is here briefly described in connection to the ARM and clearcut size context, and then not further elaborated upon. The URM employs identified adjacencies between two treatment units via their common border length, as a basis for formulating constraints saying that e.g. only one of the two can be final felled in the same period. When applying such a constraint in its current implementation in Heureka, the pre-calculation tool Tools – Compute Common Border Lengths must then first be applied, and the Common Border Length parameter must then be added to the optimization model. After those initial steps, the user is left to formulate the rest of the model. The URM clearcut size model must contain one variable that indicates whether a single treatment unit is being clearfelled in a treatment unit, and then a constraint that specifies that only one of two adjacent units may be clearfelled in a period.

The ARM is more complex but can compared to the URM more easily handle more than two adjacent treatment units at once. When applying an ARM in its current implementation in Heureka, the pre-calculation tools Compute Common Border Lengths and Compute Cliques and Harvest Clusters first must be applied.

The optimization model must then be expanded by adding the opening size constraint (Optimization / Add opening size constraint). Using this command the following parameters are set by the user:

- Last cluster period
- Green-up delay (periods)
- Maximum opening size (ha)

Necessary sets, parameters and constraints are then added to the optimization model. The main constraint here specifies that for every clique and time period, no more than one intersecting cluster may be active (here, final felled).

Example of using the ARM clear cut size restriction

An example of the solution characteristics and outcome of such a restriction is shown in Figure 7 and Table 1.

The analyses are done for the "Mistra Digital Forest Testsite" located outside Sundsvall, consisting of 5 094 treatment units, with a total area of 32 036 ha of productive forest land, using a planning horizon of 100 years divided into 20 planning periods.

In our example, the ARM has limited effects on the objective function value, but increases the build and solution time drastically due to the very large number of variables and constraints that is associated with the current ARM formulation in Heureka, presented by Goycoolea et al. (2005).

Table 1. Solution characteristics for an optimization problem applied to a test case area consisting of 5 094 treatment units, with a total area of 32 036 ha of productive forest land. Heureka PlanWise version 2.19 was used on a Dell PC with a Intel(R) Core(TM) i9-10885H CPU @ 2.40GHz and 8 cores, with 64 Gb RAM.

Problem	Description	Even-flow¹	Reserve²	Spatial conditions³	Build time	Solution time	Objective function⁴
1	Max NPV	-	-	-	-	-	1.00
2	1 + even-flow	x	-	-	46s	0.3s	0.995
3	2 + ARM	x	-	x	13 953s	10s	0.988
4	3 + Reserve	x	x	x	14 967s	383s	0.969
5	1 + Reserve	x	x	-	56s	0.6s	0.978

¹ 10% Maximum decrease and increase of final felling between two consecutive periods.

² Planning reserve, i.e. a buffer of potential final felling volume not utilized in a given period, here +100% in addition to the actual final felling volume

³ ARM, maximum opening size 10 ha, 1 period green-up delay, all 20 time periods.

⁴ The value of the objective function for the problem.

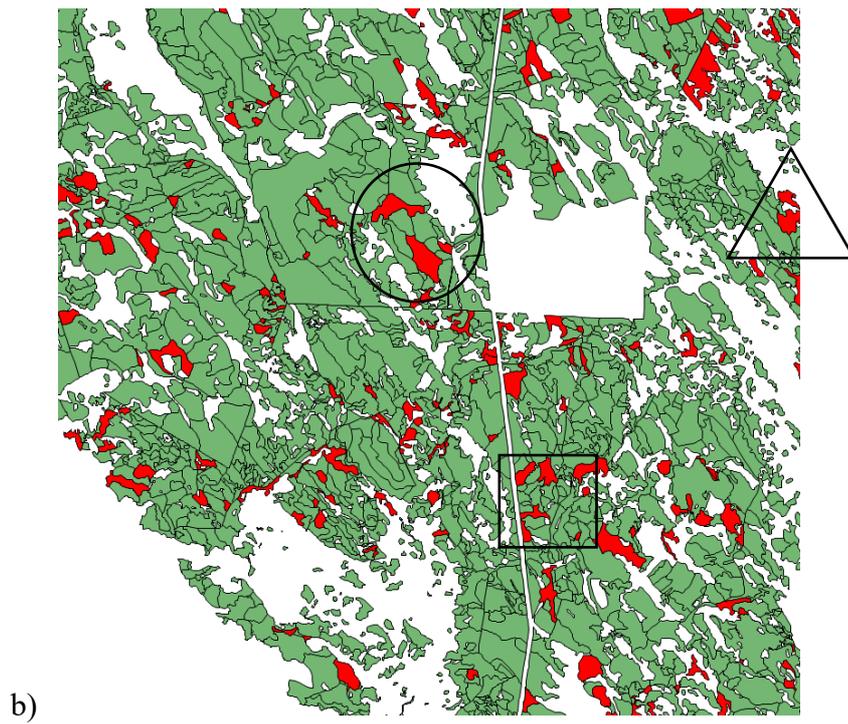
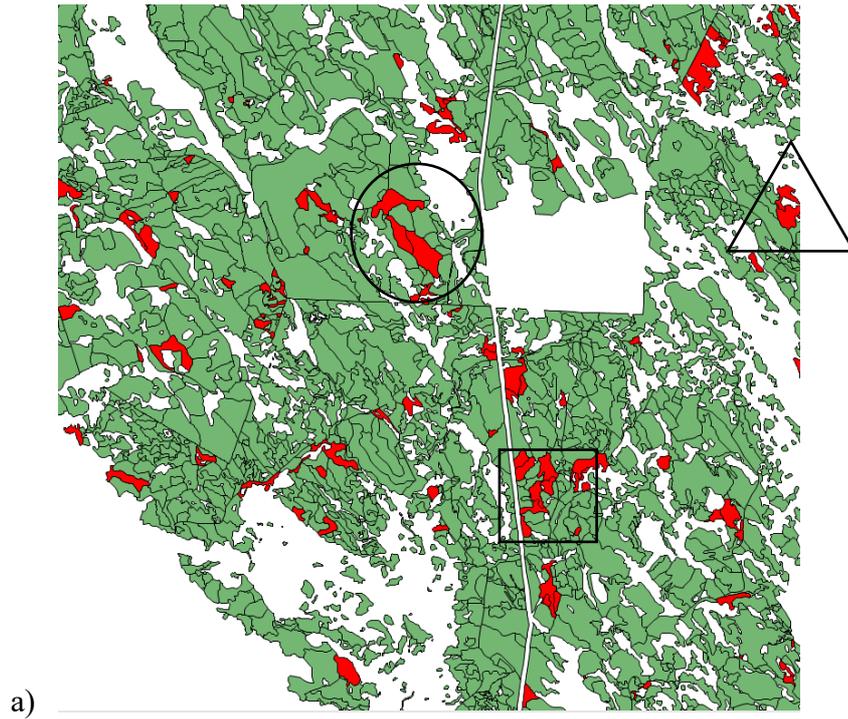


Figure 7. Clear felled areas in red, period 1, for problem 2 (a) and problem 3 (b), according to Table 1. Areas marked with \square , \circ and Δ highlight differences in the optimization solution relating to the ARM criteria applied in (b).

Habitat restrictions

The optimization tool in Heureka also has built-in support for adding constraints regarding amount of habitat for a certain species. This approach means that the demand for amount of habitat is endogenously included (case 2a) in the formulation of the optimization model and the spatial layout is a result of the optimization. This is in contrast with the post analysis habitat evaluation tool that is described in case 3 below.

A habitat model is based on a species need for resources for survival and reproduction, i.e. a habitat model does not specify where different species are found, but instead identifies areas where there are conditions for the species to survive and reproduce. In a non-spatial habitat model only information about the conditions in the stand is needed for deciding whether a stand qualifies as habitat or not, while in a spatial habitat model, information about the conditions in the stand and information about the conditions in surrounding areas is also needed for deciding whether the stand qualifies as a habitat or not. The demands that could be automatically included in an optimization model in PlanWise express a species needs using a spatial habitat model. Thus, the habitat model for describing if a particular stand is a habitat consists of two parts: stand-wise conditions and spatial conditions. Both conditions must be fulfilled before a stand qualifies as a habitat in one period. The stand-wise conditions are only dependent on the condition in the stand. Thus, depending on the needs of the species, a number of conditions should be fulfilled (e.g., the stand should have a certain age, volume, tree species composition, etc.) before the stand could qualify as a habitat. The second set of conditions express the spatial needs of the species. Within the neighboring area of a stand, a certain area should also fulfill the specified stand conditions.

The needed model parameters, variables, and constraints for including a habitat demands are pre-formulated in Heureka and can automatically be included in the model formulation of an optimization problem. This is done by adding neighbourhood constraints available in the optimization tab (Optimization / Add Neighborhood Constraints). After this is done the user must specify three parameters in the optimization model:

- the stand specific conditions that should be fulfilled before a stand qualifies as a habitat (the habitat condition parameter, `habitatCondition[i,j,p]`),
- the amount of suitable habitat required within a stand's neighbourhood for the stand to be qualified as habitat (`minHabitatAreaInNeighbourhood`)
- the minimum proportion of the entire forest that should meet the habitat conditions in each period (`minTotalHabitatAreaProportion`)

Before solving the optimization problem, the user must also run the tool "Compute stand neighbourhood" to calculate the area of each other stand that is within the neighboring area of a stand (Figure 6). When this tool is executed the parameter standNeighbourhood is filled out.

Example of using the endogenous optimization habitat model

The objective of the analyses is to highlight the impact of including a restriction on a minimum area of suitable habitat for two different species, Siberian jay, and a "fictive" species, in traditional harvest assessment problems. The Siberian jay is an example of a species where it is not enough to adapt the management in a specific stand, but where you also must take spatial considerations as the species has both specific requirements at the stand level and also at the landscape level. Here, if a stand is to be classified as Siberian jay habitat, the age in the stand must be at least 60 years, at least 25% of the standing volume must consist of spruce and at least 70% of the standing volume must consist of conifers. In addition, there should be at least 50 ha with the same stand characteristics within the neighbouring area of the stand, i.e. a 200 ha area corresponding to a circle with a radius of 798 meters counting from the centroid of the stand (cf. Table 3). The "fictive" species represent species that need old forests. If the stand should be classified as habitat, the age in the stand must be at least 100 years. The spatial conditions that should be fulfilled were the same as for the Siberian jay, i.e. there should be at least 50 ha with a mean age over 100 years within the neighbouring area of the stand.

The analyses are done for a smaller part of the "Mistra Digital Forest Testsite" located outside Sundsvall using a planning horizon of 50 years divided into 10 planning periods. First, a set of potential treatment programmes were generated for each stand in the area. These programmes all consisted of different variants of even aged forestry together with one programme leaving a stand unmanaged during the planning horizon. Next, the optimal programme for each stand was selected using the optimization module. To investigate the effects of including habitat demands with and without spatial considerations, five different optimization problems were defined:

- Problem 1 included a demand that 10 % of the area in period 10 should consist of stands fulfilling the standwise conditions for Siberian jay, i.e. the habitat demands did not include any spatial demands.
- Problem 2 included a demand that 10 % of the area in period 10 should consist of stands fulfilling both the stand-wise and the spatial conditions for the Siberian jay.
- Problem 3 included a demand that 10 % of the area in period 10 consist of stands fulfilling the stand-wise conditions for the fictive species, i.e. the habitat demands did not include any spatial demands.

- Problem 4 included a demand that 10 % of the area in period 10 should consist of stands fulfilling both the stand-wise and the spatial conditions for the fictive species.
- Problem 5 did not include any habitat demands at all.

All problems had the same objective function, namely to maximize the NPV. The resulting NPV for the different problem is shown in Table 2 and the spatial layout of stands fulfilling the stand-wise conditions for Siberian jay (problem 1 and 2) respectively the fictive species (problem 3 and 4) are available in Figure 8. Building times and solving times for all five problems are available in Table 2. In short, the more demanding fictive species has a higher impact on NPV and solution time than the Siberian jay (Table 2). Adding spatial conditions considerably increases the building time for both species, but only the solution time for the more demanding fictive species (Table 2).

Table 2. Solution characteristics for an optimization problem considering species habitat demands, applied to a test case area consisting of a smaller part of the Mistra Digital Forest Testsite outside Sundsvall. Heureka PlanWise version 2.19 was used on a Dell PC with a Intel(R) Core(TM) i9-8950HK CPU @ 2.90GHz and 6 cores, with 32 Gb RAM.

Problem	Species	Habitat demand	Stand wise conditions	Spatial conditions	Build time	Solution time	Objective function¹
1	Siberian jay	10 %	x		4.8s	0.1s	0.9995
2	Siberian jay	10 %	x	x	614s	0.5s	0.9909
3	Fictive	10 %	x		4.7s	0.7	0.9634
4	Fictive	10 %	x	x	623.9s	25241.5s	0.9164
5	No	0 %			0	0	1

¹The value of the objective function for the problem.

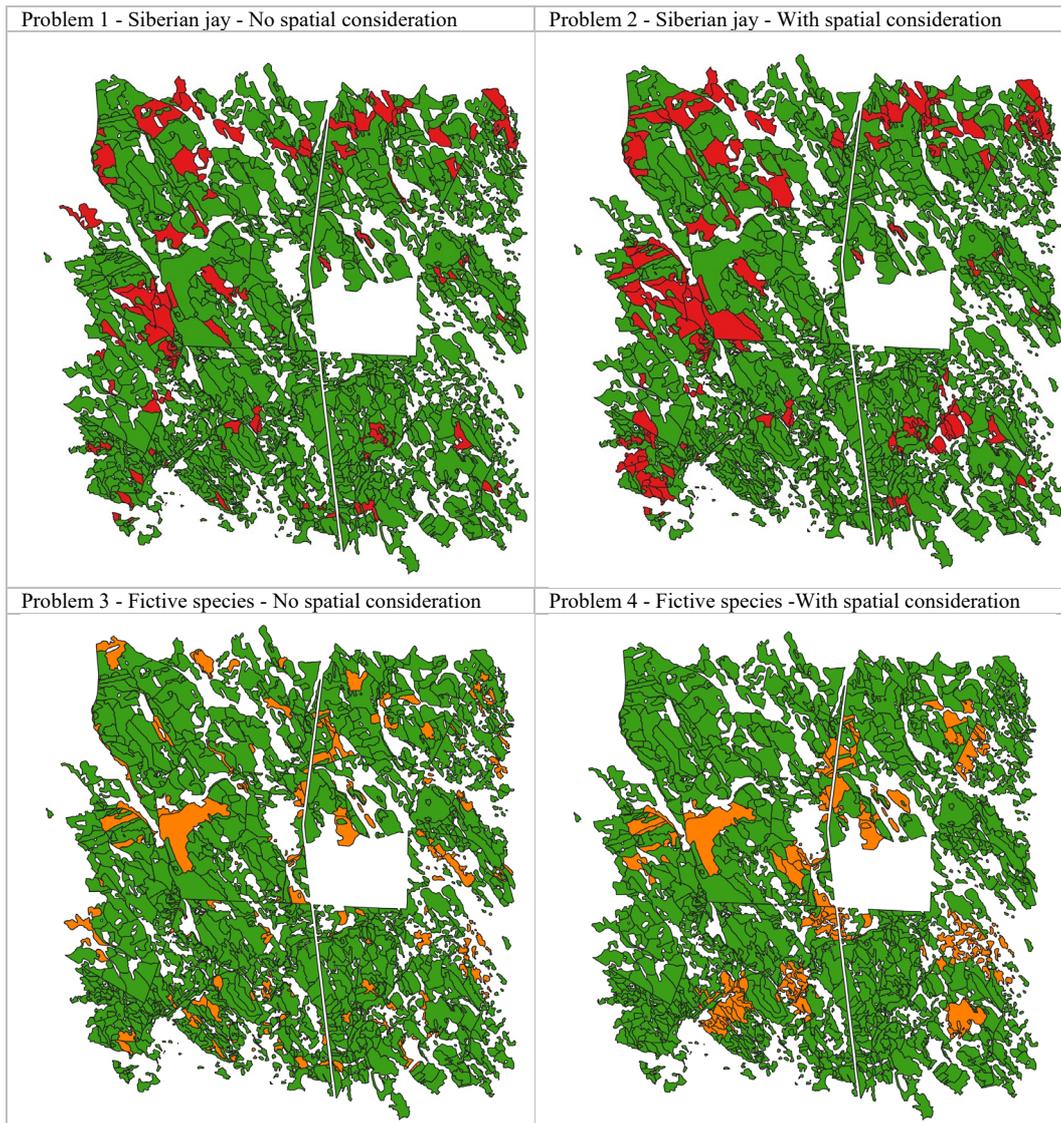


Figure 8. Stands that fulfill the stand-wise condition for the two species; Siberian jay (above) and fictive species (below) in period 11.

1.4.3 Case 2b: Available pre-calculation tools are used but the user formulates the optimization model

The tools described above can also be used to formulate and solve other spatial problems but where the user formulates the optimization model. For example, the user might want to solve a problem aiming at decreasing the wind exposure for storms over time through the minimization of vulnerable edges between neighboring stands. If so the tool for computing common border length has first to be applied. In a paper by López-Andújar Fustel et al. (2021) an optimization model is presented for selecting forest management activities for every stand over time so that the length of vulnerable stand edges (edges with large height differences between neighboring stands) is minimized.

Another example of a problem where the compute common border length tool is used is the study of Öhman et al. (2021). Here a model for identifying suitable areas for voluntary set aside is presented. The model aims at minimizing the fragmentation of set aside areas and at maximizing the NPV of future forest management. In the model fragmentation is minimized by minimizing the total circumference of set aside areas and already existing reserves. This is accomplished by calculating the sum of the perimeter of all stands that are set aside. If two stands sharing a common border are set aside, this sum is reduced by double the length of the common border to obtain the perimeter of the aggregated set aside areas.

One example where the tool for computing stand neighborhood is used is found in Wilhelmsson et al. (2021). Here a new model for forming aggregated dynamic treatment units (DTU) is presented. The DTU approach is needed when raster cells are used as planning units instead of stands. The reason for this is that the NPV traditionally is calculated at the planning unit and revenues and costs for treatments in one planning unit are not affected by actions taken in surrounding areas. Thus, potential economic gains for clustering harvests, e.g., reduced costs for the transport of machinery, are not considered. Therefore, maximizing the NPV without including spatial considerations in the planning model may lead to a dispersed pattern of harvest areas that are unviable for harvesting operations in reality. The model presented in Wilhelmsson et al. (2021) includes a demand that a certain proportion of the raster cells selected for thinning or final felling in a period must be defined as clustered. A raster cell is clustered if the raster cell itself is selected for thinning or final felling and if a certain number of raster cells within the neighboring area also are selected for thinning or final felling in the same period. To this end, there is also a possibility to assign each treatment unit a Road ID, which is thought to be the same for all treatment units located so that terrain transport of harvested volumes is best directed to that forest road. The Road ID can then be used in optimization models that account for e.g. machine relocation costs and road opening costs.

1.5 Case 3: The post-optimization approach

The last case (case 3), handles spatial aspects when a solution of a planning problem is found, i.e., after running the optimization routine. So far only one tool is included; the post-analysis habitat evaluation tool, which is described further below.

1.5.1 The post-analysis habitat evaluation tool

A tool is available in PlanWise for the evaluation of suitable habitat area for a set of species after you have produced a forest plan or made an analysis. Since this tool evaluates the result after you have run the optimization (and as it is also applicable

in RegWise) this tool is called the post-analysis habitat evaluation tool. At present, this tool for habitat evaluation includes models for six species (Edenius and Mikusinski (2012), Table 3). It is also possible for the user to formulate new habitat evaluation models. The results of the habitat evaluation are the total area of suitable habitat within an analysis area as well as a habitat suitability index (HSI) for each stand. HSI is a function of stand-wise (non-spatial) criteria and in most of the available models also spatial (neighborhood) criteria. Stand-wise attributes are made up of, e.g., stand age and density, tree species, etc. (Table 3). It is also possible to consider edge effects affecting a zone inside of the border of a stand. At present, it concerns one of the available models (the Witch's hair lichen).

The evaluation procedure is performed in nine steps as follows in each time period:

Step 1: Each stand polygon is evaluated whether it fulfills the local conditions for HSI = 1. If so, the stand polygon is temporarily assigned HSI = 1 Figure 9.

Step 2: For stand polygons that does not fulfill the local conditions for HSI = 1 it is checked whether they fulfill the local conditions for HSI = 0.5. If so, the stand polygon is temporarily assigned HSI = 0.5, otherwise HSI = 0.

Step 3: The map of the analysis area is transferred to a raster map (raster cell size 25 x 25 m² as default in the available models) and each raster cell is given the HSI value 0, 0.5 or 1 depending on which stand polygon the center of the raster cell is located within and the outcome of steps 1 and 2 (Figure 9).

Step 4: If the current habitat model includes adjustment for edge effects, the values assigned in step 3 are adjusted for cells that are affected by edge effects, see e.g. Table 3 footnote 2. (If there are no other spatial conditions in the specific habitat evaluation model, then go to step 8.)

Step 5: The suitable habitat area within the neighborhood (a radius as a function of the specified neighborhood area for the specific HSI evaluation model) for each raster cell is calculated. This step is made over the analysis area by a “moving window” as follows (Figure 9 top right):

$$A_j = a \sum_{i \in N_i} s_i \quad (\text{Eq. 1})$$

where:

A_j is the area of suitable habitat within the neighborhood of raster cell j

a is the area of a raster cell

N_i is the set of raster cell in the neighborhood of raster cell j (including raster cell j)

s_i is the local habitat score for cell i (0, 0.5 or 1)

Step 6: Each raster cell is evaluated whether it fulfills the spatial condition (area of suitable habitat) for $HSI = 1$. If so, the raster cell is assigned $HSI = 1$, otherwise $HSI = 0$, in a new (second) raster layer.

Step 7: The HSI scores in the first raster layer are updated by combining the first and second raster layers (multiplicatively) for each raster element (Figure 9 bottom row).

Step 8: A mean HSI value is calculated for each stand polygon. Firstly, HSI values ($HSI_{updated}$, Figure 9) are summed for the cells included in the polygon. Thereafter, this sum is divided by the sum of raster cell areas within the polygon. This stand-wise mean HSI value is available as a result variable (Habitat Data – [species name]) and can be shown in tables and maps.

Step 9: Finally, the polygon mean HSI value is multiplied with the polygon productive forest area to end up with the area of suitable habitat in the polygon. This procedure is applied to avoid the potential problem with the polygon area being different from the polygon productive forest area, the latter being the area used by Heureka. The habitat area result is available in the Optimization Results – Tables and Graphs Report Builder as the total area of suitable habitat within the analysis area.

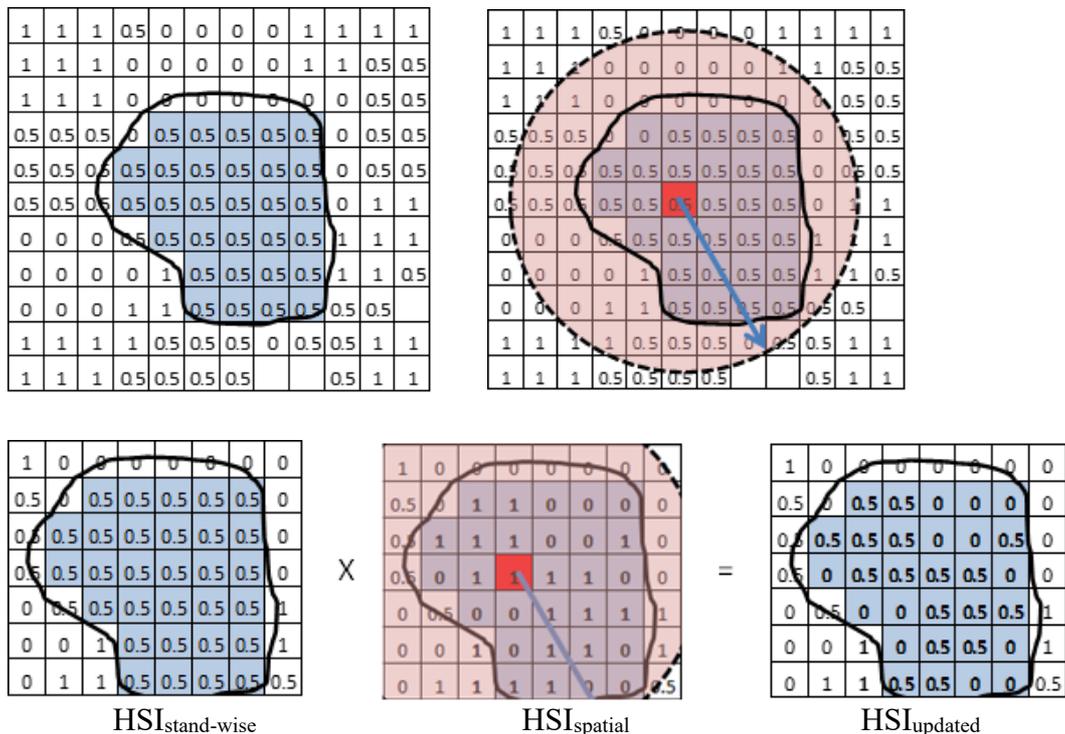


Figure 9. Stand-wise habitat suitability indices after the habitat evaluation step 3 (top left). Evaluation of landscape level criteria by a “moving window” in step 5 (top right, Eq. 1). Calculation of final raster cell HSI score as a function of stand-wise and spatial scores (steps 5-7, bottom row). The procedure also has other steps; steps 8-9, see the text. From Wikström (2012).

Table 3. Criteria for local conditions (stand or raster element) and spatial conditions in the habitat suitability index models available in the (raster based) habitat evaluation models. From Edenius and Mikusinski (2012)

Species	Criteria (stand-wise or spatial) and habitat scores		
	Stand-wise ¹⁾		Spatial
	0.5	1	1
<i>Alectoria sarmentosa</i> Witch's hair lichen	See comment 2) below	Stand age \geq 100 years and spruce $>$ 80%	N/A
<i>Harminus undulatus</i>	Stand age \geq 100 years	Stand age 60-100 years or 3-10 years	N/A
<i>Dendrocopus minor</i> Lesser spotted woodpecker	Stand age \geq 60 years and deciduous 25-50 %	Stand age \geq 60 years and deciduous \geq 50 %	Habitat \geq 40 ha within 200 ha
<i>Perisoreus infaustus</i> Siberian jay	Stand age 30-60 years and conifer \geq 70 %	Stand age \geq 60 years and conifer \geq 70 % and spruce \geq 25 %	Habitat \geq 50 ha within 200 ha
<i>Bonasa bonasia</i> Hazel grouse	Stand age \geq 20 years and spruce \geq 25 % and deciduous 5-15 %	Stand age \geq 20 years and spruce \geq 25 % and deciduous 15-40%	Habitat \geq 20 ha within 100 ha
<i>Sciurus vulgaris</i> Red squirrel	Stand age \geq 70 years and spruce 25-50 %	Stand age \geq 70 years and spruce \geq 50 %	Habitat \geq 10 ha within 200 ha

¹⁾ Tree species proportions refer to stem volume

²⁾ If stand criteria for HSI = 1 is fulfilled but the stand is adjacent to non-forest land, clear cuts or stand with age \leq 50 years, HSI = 0.5 is assigned to raster cells within a 50 m wide edge zone.

Graphical user interface

The graphical user interface (GUI) for habitat evaluation models is available under Tools / Evaluate habitats (post-analysis). Here, evaluation model(s) and which optimization result to be used is specified. The available habitat models can be modified, and new models created, the parameters stated by the user. The following parameters are available in the GUI:

- Raster cell size (25 x 25 m² for the available habitat evaluation models)
- Criteria for stand habitat score 0.5 and 1, respectively (see Table 3)
- Edge effect if any:
 - Reduction factor (0.5 for the present Witch's hair lichen model)
 - Distance (50 m for the present Witch's hair lichen model)
- Which period(s) to be evaluated
- Neighborhood criteria if any (see Table 3):
 - Neighborhood area (stated as a radius (m) or area (ha))
 - Minimum habitat area required (stated as area (ha) or proportion (%))

State-of-the-art in Heureka PlanWise analyses in 2022 and potential further development

2.1 Current use of Heureka

Two outreach activities related to this report have been performed during fall 2022: A workshop with practitioners in long-term forest planning on the theme “Challenges in long-term forest planning” was performed on November 24th in Stockholm gathering 14 attendants from practice and research. Furthermore, a brief questionnaire has been circulated via email targeting advanced users of Heureka PlanWise with regards to their usage pattern: size of analysis area, complexity of the optimization problem, chosen third-party build and solver software and comments on desired progress in analysis capacity. Results from the questionnaire indicate the following:

- Single TPG runs comprising up to 590 000 stands have been reported successful. (Note: during 2022, TPG performance on multiple CPU cores have significantly improved in Heureka version 2.19, cutting TPG time consumption with two-thirds.)
- A number of solutions and software outside the Heureka DSS are used to build the optimization problem, due to the comparatively high time consumption associated with building large optimization problems using the built-in ZIMPL functionality (cf. also Table 1 and 2).
- Although a rising interest in considering spatial aspects in planning e.g. maximum opening sizes are noted among practitioners, only a few known use cases in applied forest management planning exist.

Thus, it seems that despite Heureka is today widely used as decision support in practical forestry, spatial aspects are still mostly included in teaching, environmental analysis and research. Direct consideration of spatial aspects using Heureka PlanWise is noted in a number (roughly 15-20 out of a total of 80-90) of

scientific studies published since 2009 (see www.slu.se/sha and Publications). Strategic forest planning in practical forestry is still predominantly performed using stratum-based or other non-spatial approaches among large Swedish forest owners (Ulvdal et al. 2022), although spatial aspects influence typical strategic-level planning problems (Öhman et al 2020b). The *Planning reserve* is a tool employed in strategic forest planning, as a proxy for uncertainty as well as seasonal aspects, maximum opening sizes, and other planning aspects and restrictions which are not explicitly included in a typical strategic planning process (Ulvdal et al. 2022). When using a stratum-based approach, many spatial aspects can only be addressed using such proxies.

2.2 Potential further development of the Heureka system

In the following section we summarize our findings from the work of writing this report, as input on potential further development of the Heureka system.

First, the optimization module in Heureka still requires great knowledge and skills in optimization methods. This can be addressed by simplifying the user interface of the optimization model design functionality, both via more predefined optimization models included in the standard installation package together with a better overview of them, and via the new optimization wizard released in version 2.20 designed to help the user create an optimization model with specific desired restrictions. Currently, no spatial restrictions are available in the optimization wizard. Especially the use of neighbourhood restrictions – i.e. for habitat restrictions or adjacent set asides – in Heureka could be simplified, since little internal support in defining or adjusting habitat restriction parameters and conditions are given to the user at present. Such restrictions also raise high demands on optimization build and solver.

Second, formulating and solving spatial problems with Heureka is today in many cases time consuming, see e.g. Tables 1 and 2. The time required to build spatial problems can in some cases amount to several hours and even if external solvers such as Gurobi and Cplex are used, the solution times can also be long. Except for improving optimization build and solver performance through new and more effective problem formulations (better spatial problem structuring, e.g. Gharbi et al. (2019)) new supported third-party software stands out as a first step towards better support for spatial analyses with the Heureka DSS. The recent change of free solver from LpSolve to CoinOR CLP/CBC is such an example. To this end, it is also tempting to recall one of the motives behind the naming of the Heureka DSS: during the initiation of the research programme, it was foreseen that optimization approaches would have to involve heuristics in order to solve the giant problems that were to be formulated during the usage. However, no such integrated

functionality has been developed so far, partly because more complex problems have turned out being possible to solve by exact methods. Some scientific studies have, however, involved Heureka PlanWise TPG and heuristics analyses in an external environment (e.g. Wilhelmsson et al. 2022).

Third, current GIS functionality in Heureka consists of a thematic map viewer with selection functionality for forest domain definition, and a number of predefined geoprocessing and spatial analyst tools, mentioned earlier in this report. Additional GIS functionality, either internal or improved integration with third-party software, could facilitate increased use of spatial analyses. For example, terrain transport distance and road ID assignment must today be provided externally at the data import, and result presentation of optimization variables (both spatial and non-spatial) like cliques, harvest clusters and habitats currently require comprehensive SQL and GIS operations.

Fourth, no integration with the freely available ALS-based datasets that have emerged during Heureka's lifetime produced by SLU and Skogsstyrelsen (Skogsstyrelsen, 2016, Skogsstyrelsen, 2022) is currently supported. With new functionality for data fusion and/or segmentation, forest planning analyses with spatially comprehensive data could be equally available for all users of the system – potentially meaning all forest owners as well as other stakeholders.

Fifth, the Heureka system could potentially be published as open source, which would enable user-initiated development of sought-after spatial functionality. Possibilities and challenges associated with such solutions and more open data in general could be further investigated for guidance on potential development efforts to this end.

2.3 Conclusion:

Altogether, both the needs and possibilities for spatial analyses with the Heureka DSS have increased to this day, as demonstrated in this report. However, some pivotal remaining critical development tasks have been identified as currently prohibiting a broader use of spatial analyses with Heureka. This includes to simplify the interface of the optimization model, reduce the build times associated with the formulation of various optimization problems, include free solvers of optimization problems, improve GIS functionality, enable the use of open data in various forms of analysis using the Heureka systems and publish Heureka as open source. This report provides guidance on potential further development of the Heureka system, primarily related to increased use of spatially comprehensive data in long-term forest planning analyses, and will hopefully serve as input for further system management steering and development.

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