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Møller, Bernd

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Aalborg University  
Department of Development and Planning



# **Geographical modelling of resources, supply costs and processes for wood fuels in Iceland**

Bernd Möller  
November 2007



NORTHERN  
WOODHEAT

**Northern Wood Heat**

## **Foreword**

This report has been prepared by Bernd Möller, who has been a visiting researcher at the Agricultural University of Iceland from 2004 to 2005. During this time a geographical model of wood for energy supply was prepared for the Northern Wood Heat project under the EU Interreg IIIB Northern Periphery Programme.

The report deals with the methodological considerations of analyses of the resource economics of distributed renewable energy resources such as wood chips from newly planted forests. A specific model is being described, including data input, modelling of forest to energy process chains, and preliminary results.

The findings in this report, including the methodology developed are considered preliminary as the involvement with the project was temporary and no successor for this work was found after the visit ended. The results of this work were discussed with the other project partners and presented at a project symposium in Joensuu, Finland in June 2005, a Northern Wood Heat project conference in Elgin, Scotland in November 2005 as well as a research conference (Möller, 2005) in Reykjavík, Iceland in September 2005. The content of this report, however, did not find application and reference in the final results of the Northern Wood Heat project.

Aalborg, Denmark, November 29<sup>th</sup>, 2007

# 1 Introduction

Wood fuels for heating have advantages against fossil fuels and other forms of heating. First of all, they can be considered CO<sub>2</sub>-neutral if the wood has been grown and harvested in a sustainable manner. This is widely understood as the main benefit of wood fuels. Another advantage is that wood fuels are local resources and can create local income, jobs and development. Furthermore, in replacing imported oil or electrical power, a region of a country can benefit from producing and using wood fuels when most of the energy demand is imported from abroad or other parts of the country.

By utilising wood that is left over from necessary thinning operations, timber production and forest health are maintained. Thinning costs could partly be covered through sales of energy wood. Essential for such a scenario are two things: forest operations must be cost-efficient and there must be a market for wood fuels. The economy of wood fuels very much depends on how efficiently the resources are managed in every link of the cost chain. Even marginal differences in the cost chain from forest to energy plant have significant influence. The geographical aspects of forest location relative to consumers of energy wood as well as forest operation and other forests.

Iceland is not an obvious location to implement a wood fuel supply system. All odds appear to be against such a solution. Almost 90 % of all heat demand is covered by geothermal heat. Production of electricity, which covers most of the remaining heat demand in geothermally cold areas, is based on hydro power and geothermal energy. Only about 1 % of the heat demand of Iceland's population of 300,000 is covered with oil, with a diminishing tendency (Orkustofnun, 2003). Electrical power for heating is subsidised and drilling for geothermal heat advances even in "cold" bedrock formations. Population and forest densities are very low, suggesting high transport and distribution costs. There is little experience with forest operations and management and no established forest industry. Information about the Icelandic forests is poor, as counts for data used to calculate standing tree volumes, growth and site index curves, and costs of silvicultural operations.

On the other hand, more than 4,000 ha of private forests have been planted within the Heradsskogar project in East Iceland, with another 13,000 ha to follow. With an estimated 20 solid m<sup>3</sup> per ha recoverable thinning resources, the currently annually planted 400 ha in the case area would produce 20,000 MWh of fuel per year 20-30 years from now. This is equal to annually 7,000 kWh for each of the 2,800 inhabitants, which comes close to what is needed to heat their homes today. If replacing light fuel oil with a fuel price of 9 €/ MWh, this production of local resource would create an annual turnover of 180,000 €.

A study of limited supply of bulky, comparably costly and difficult to procure resources must include not single techniques but interlinked chains of technologies. The economy of wood chip production not only depends on the cost of running a wood chipper; it also includes the costs of growing and felling trees, forwarding them to a chipper site, and finally storing and transporting them to locations where they can be used.

In contrast to supply cost calculations of commodities such as light fuel oil, the cost chain of wood fuels includes many factors determined by geography. Geographical density and distance between locations of production, supply and demand highly influence the amount of resources accessible at a given price. In other words, it depends how much biomass is accessible where. One m<sup>3</sup> of biomass located 100 km away from the plant has not the same value to the plant than the same amount in the plant's neighbourhood. Distance between source and consumer creates costs that have to be avoided by prioritising local fuels.

The nature of the problem makes it interesting to use a geographical information system (GIS). A GIS is by definition a system to include, store, manage, retrieve, visualise and analyse geographical data. Most GIS-related applications in Iceland deal with the first five of these aspects, whereas the analysis of geographical data is not as frequently used yet. Much emphasis is still on the production and collection of geographical data within various disciplines, but little is done so far to combine existing geographical data to an interdisciplinary decision support system within a GIS. In doing so, a project like this is likely to benefit from the work that has already been done in the fields involved. On the other hand, this means a number of problems related to data quality and the like. Compromises on data quality go hand in hand with the exploration of new applications for data.

To know the delivered fuel costs for a changing demand at a given location is an important decision parameter when planning a wood fuel supply system. To assess recoverable amounts of resources and their delivered costs at a possible energy plant site, a model called GRASP (Geographical Resource Assessment, Supply and Processes) has been designed. It is a method and an analytical framework developed at Aalborg University in Denmark in co-operation with Forest Research (now Scion Research) in New Zealand (Möller and Nielsen, 2007). It features a GIS-embedded, raster-based model for the analysis of resources and supply costs of processes from forest to end-use location, including growing forests, thinning, harvesting and chipping operations, forwarding, storage and road transport etc. The innovative element of GRASP is the translation of forest and logistical operations into geographically determined spatial modelling processes. Resource amounts and costs are described and modelled as continuous resource and cost surfaces, after which a statistical overlay operation of costs and resources returns the marginal costs of supply by cumulative amounts in so-called cost-supply curves. Every location features a differently shaped cost-supply curve.

The main idea behind GRASP is that resources often are available at a forest location with only marginal costs to pay, such as extraction and transport, but not for growing resources. Therefore the considerations can be vastly simplified excluding the economic consideration of profit maximisation by selection of crops or land use. The resulting marginal costs of biomass fuels can be used in several ways. Either to assess the total costs of a project of different scales; to determine the value of forest resources across a region depending on the location of an energy plant; or to help setting the sales price for sellers or buyers of these resources.

GRASP is dynamic as it models resources and their costs and flow year by year, typically for the whole investment period or the technical lifetime of a plant. Costs can change, resulting in changes of cash flow. Forest resources, once planted, are rather predictable. The model is GIS-embedded and very flexible in terms of its adaptability to regions and the requirements of cost chains. The generic algorithm can be applied to assess several types of costs of supply problems. It is also flexible in terms of geographical scale. With a proper data base it is possible to build highly disaggregated models, as many applications require it.

For this project the generic method incorporated in GRASP has been applied to the supply chain management problem in the Northern Wood Heat feasibility study of small- and medium scale wood fuel supply Iceland.

## 2 Objectives of the study

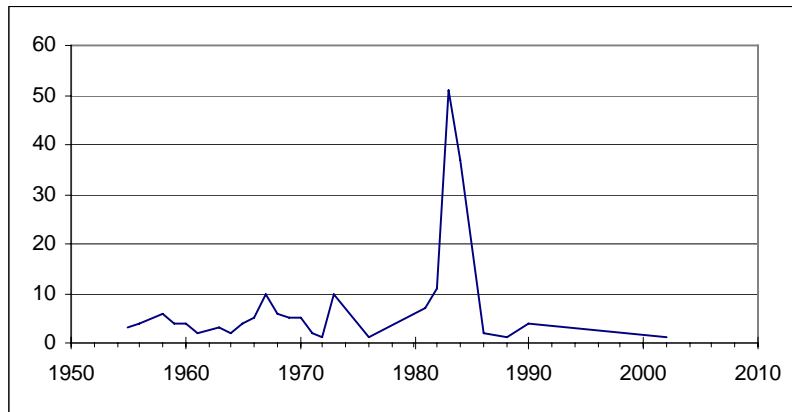
This project aims at the development of a decision support system for the future utilisation of thinning residues from planted Larch forests in Eastern Iceland as wood fuels. In the national Hallormsstaður forest and the private forests of Heraðsskógar, Larch has been planted since the 1950's and 1980's, respectively. These forests have now or will soon reach an age at which thinning operations are required to secure timber production. Thinning operations, however, are very costly in Iceland, mainly due to lack of experience, the low forest density and the generally high price level. Income from selling thinned wood as energy wood would make thinning more attractive, in particular to private forest owners in the Heraðsskogar programme.

Only few experiences and reliable data exist on the yields and costs of thinning operations. The costs of these measures highly depend on the investments made into forest machinery, on the amounts and thus the achievable annual utilisation, and on the level of experience. The use of GRASP may contribute to increase the knowledge on the resource-economic aspects of this project. It is much less costly to carry out model calculations on a large scale than actual forest operations. For good modelling results, though, a sound data base has to be established. As this does not exist for several parts of the cost chain, modelling must be done in an iterative approach, where preliminary results are reported to an auditory of decision makers and project participants, partly to hear their comments and suggestions, but most importantly to gradually improve the data basis by motivating partners to improve data collection. It is important to keep in mind the development of the cost supply model depends on the delivery of data from many different partners. Few resources for primary data collection are available within the project, so that secondary data collection is the main source of model input.

The main idea behind producing income from forest thinning is to establish a medium-sized wood chip boiler in a central location, which is to be supplied with local fuel from thinning operations. The location of the boiler is Hallormsstaður, either the forest station or a nearby hotel. The boiler will have an installed capacity of about 300 kW heat, which at 4,000 hours of full load operation and an average efficiency of 80% results in an annual consumption of about 1,250 m<sup>3</sup> loose wood chips (560 m<sup>3</sup> solid). This material will preferably come from Hallormsstaður forest, but if supply is not sufficient, Heraðsskógar forests could add to the supply, encouraging the forest owners to thin their planted forests.

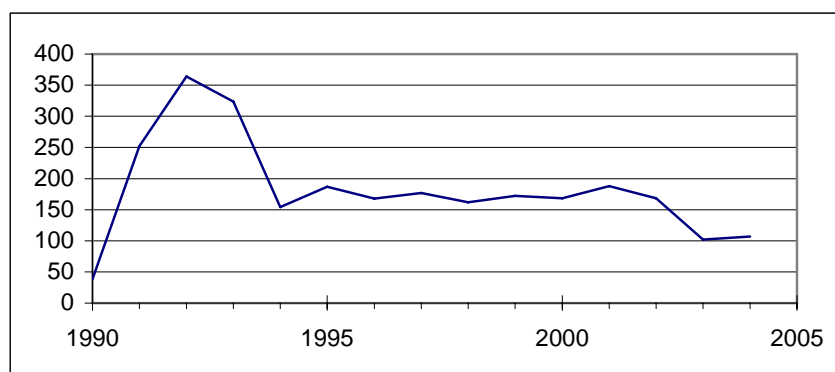
Because it seems that wood resource availability is much better than these figures, some of the farms involved could produce their own fuel wood, making themselves independent from electrical or oil heating. This scenario would have to assess the economic and resource feasibility against established technologies such as subsidised electric heating, micro hydropower and new geothermal well. The study aims to assess the sufficiency of wood fuel resources and some of the costs associated with individual wood fuel supply.

The temporal dimension is important. Plantations of Larch in Hallormsstaður have now reached an age at which many of them will have to be thinned within the next decade if ages of first thinning of 17 to 30 years are applied, see Figure 1. This figure also shows a peak in planted Larch in the 1980's, which will result in years with thinning demands many times the average. In recent years the plantation of Larch has come to a close.



**Figure 1: Annually planted hectares of Larch (Larix) in Hallormsstaður forest. The years 1983 and 1984 have contributed to a peak.**

Heraðsskógar forests on the other hand are rather young, meaning that their first thinning will be about a decade after Hallormsstaður, see Figure 2: Annually planted area of Larch in Heradsskogar forests, 1990-2004. The high volumes of the first years have since seen a decrease. The perspectives for the next years show even smaller volumes. Figure 2. For the future there seems to be a tendency that Larch will lose its role as the most important species and play a less dominant role. However, as two thirds of the areas under contract are to be afforested yet, there is still a large potential. On the other hand, the pace at which plantation of Larch is going to proceed is unknown and therefore future plantations of Larch have not been included in the first model described here. Some kind of random seed approach could be used to model plantation of Larch on the remaining contract areas.



**Figure 2: Annually planted area of Larch in Heradsskogar forests, 1990-2004. The high volumes of the first years have since seen a decrease. The perspectives for the next years show even smaller volumes.**



Comparing the time horizon of the established plantations from planting to first thinning, and the average lifetime of the technical installations for a medium sized boiler station, a time horizon for the study of 20 years seems to be sensible. Any longer period will demand a “what-if” approach of plantation scenarios, or cause problems with the assessment of economic figures as economies of scale grow through that period.

The feasibility of wood fuel supply depends largely on two factors. First, thinning operations have to be cost efficient and produce wood chips in sufficient quantities and quality when they are needed. This requires knowledge of and investment into forest operations and equipment. Furthermore, these operations are highly determined by economies of scale. Second, transport distances add a considerable cost to harvest and processing. In East Iceland, distances are comparably high because forest and population densities are generally low compared to countries where wood fuel solutions have proven successful. Therefore transport costs have to be minimised and resources used as locally as possible.

Many parameters and factors in this study are very uncertain and even unknown by now. Any computational aid in the form of a computer model or decision support system must therefore accommodate uncertainty and allow for the adjustment of modelling parameters in order to present not one result, but rather tendencies or development possibilities and their uncertainty. It must be stressed that since most of the data collected has considerable uncertainty, this is reflected in the results, which have to be interpreted with great care. The outcome of this feasibility study can therefore by no means be a “go” or “no go” for a wood heat project. The results of this study can not support a standard investment analysis. It is rather a tool in a “what if” fashion, which assists a learning process at the end of which the partners involved know more about the application of wood heating technology from forest to end-use in their own geographical settings.

### **3 Overview on the case region**

The region of Northeast Iceland selected as a case is primarily defined by the locations of the Heradsskogar forests. All Heradsskogar forests are located within Fljotdalsherad and Fljotdalshreppur municipalities. It was decided to include the Austurlandsskogar forests for the resource side of the analysis. Austurlandsskogar forests are located in the neighbour municipalities.

The geographical boundaries of the case study were therefore set as the Fljotdalsherad and Fljotdalshreppur municipalities, which cover 10,445 km<sup>2</sup> or rather precisely 10 % of the land mass of Iceland. Extending the case region to include Austurlandsskogar, the area increases to include Seydisfjord and Eskifjord districts, covering 16,300 km<sup>2</sup> or 15.8 % of Iceland. For further reference the smaller case study area is referred to as case region and the larger area as *extended* case region.

#### **3.1 Geography of the case area**

The extended case area stretches from the central parts of Iceland with their glaciers and deserted highlands to the coastal lowlands in the Northeast and the fjords in the East. The average elevation for the extended case area is 568 m above sea level; the highest peak is 1,820 m. 70 % of the area is situated above an elevation of 440 m, where afforestation is impossible; only 16 % of the area is less than 200 m above sea level. The annual average temperature is minus 0.5 degrees Celsius for the whole area, while areas below 440 m have an annual mean temperature of 1.8 degrees Celsius.

The 120 farms participating in the Heradsskogar programme and the Hallormsstadur forest are concentrated in the central valleys of the glacial rivers. Most Austurlandsskogar forests are located in the East fjords.

## **4 Geographical analyses of resources, supply and processes along the cost chain**

If the locations of production and consumption of a commodity such as wood for heating purposes are known, this allows for the assessment of a series of aspects related to the economy of the entire cost chain from forest to energy plant. First of all, the growing of trees and the amounts of biomass recoverable through silvicultural operations such as thinning and harvesting can be quantified and located. Variations in site indices and environmental factors may necessitate the geographical assessment of forest resources.

Secondly, the various processes involved with removing wood from a stand, forwarding it to a landing or to the road side where it can be chipped, may include geographical factors such as the accessibility of forest stands, local topography or the time it takes forest workers to commute to their workplace.

A major factor in the determination of the delivered costs of wood fuels is the transport on roads from forests and landing sites to a processing or energy plant. Loading and unloading a lorry induces terminal time and the travel distances and road conditions determine wages, depreciation of investment, fuel costs and the like. The low energy density by transport volume makes the transport costs of wood fuels a critical element of the cost chain.

Finally, the demand side location where wood is used for energy production also is a key element of the analysis of supply chains. First of all, the access to plenty of wood resources nearby decreases costs. Connected to this is the size of the operation, i.e. the annual fuel demand. The higher the demand, the higher the specific transport costs because resources have to be transported from further away. The resource area of a location grows with its demand.

### ***4.1 Methodological considerations***

If forest resources, the various cost chain elements and the amount and location of demand can be mapped, these factors need to be combined by means of geographical analysis. In raster-based GIS, where landscape elements are mapped using square cells with continuous fields, geographical analysis is applied in the form of functions between cells of one raster dataset and another. Thereby the single cell, but also its neighbourhood or defined zones of a raster theme can be the target. The magnitude of possible functions is available through so-called map algebra.

In GRASP a distinction is made between resources and costs. Resources accumulate to usable amounts of wood, which are located around the case area and may come from different sources. In practice a series of raster data themes containing resources of several origin are combined in a raster that holds all values of resources in a unit such as solid

m<sup>3</sup>, tonnes or Giga Joule. The procurement and the transport of these amounts are usually connected with costs. These costs can likewise be mapped using raster themes. And like amounts of resources, costs can have their origin in several stages of the cost chain.

Transport costs are a special case. The costs of transport increase with distance, so transport costs can only be calculated for one consumer location at a time. Thereby each location in the case area will have a distinct cost structure and the transport costs will usually follow the patterns of transport infrastructure. Transport costs in GRASP are calculated using an incremental least distances function, which calculates the rising costs from origin to all areas in the case area in a two-stage process. First the costs are accumulated along a linear raster representation of the road network, which may include friction values such as the achievable travel speed, using a cost-weighted distance function. This results in a linear raster holding the shortest distance to the origin. Secondly, the distance along the road network is perpendicularly allocated to areas away from the road, using a function called Euclidean allocation. Thereby all raster cells of the case area receive a value for the shortest distance to the point of origin. If costs are related to distance, this will also be the least cost of transportation. In a subsequent process, distance is converted to costs by applying fixed and distance-specific transport costs.

All costs are given as specific numbers (e.g. ISK / m<sup>3</sup>) and they finally sum up to continuous cost levels in all areas of the case region. Costs are finally grouped into zones of integer values, e.g. Euro-cents or Icelandic Kroner, which means that now all areas within the case region are part of a cost zone. There can be hundreds of cost zones. The smaller the increment of costs the smoother the final result.

According to resource economic principles, the resources located in zones with the lowest costs are the most attractive, while it is less appealing to use more expensive resources before less costly have been utilized (In practice also the amount of resources at a given location has influence on its attractiveness). To establish a relation between accessible amounts and their costs, the layer structure of a GIS is quite useful: by overlaying the resource and the cost raster, for each location the amounts and their specific costs are already known. Next, the two figures need to be sorted by costs, multiplied and accumulated. This is done in a two-stage process. First, by a function called zonal statistics the amounts within all cost zones are summarised and ordered by cost value. This results in a table, which is converted into a spreadsheet, where absolute costs are calculated as the product of amounts and specific costs, after which absolute costs and amounts are accumulated and divided by each other. Then a diagram is prepared using the accumulated amounts and their average (or marginal) costs. This diagram is called a cost supply curve.

Cost supply curves establish a relation between the amounts and the costs for a given location. Each location on the map has different access to the road network that connects to larger or smaller amounts of biomass. This can be read from the cost supply curve by comparing two locations, see fig. From a number of likely locations the best location is the one with the lowest average costs for a given resource demand. For another demand, however, a different location may have lower costs. A cost supply curve therefore also

takes into account the demand. Different demand results in different costs. The rates at which costs develop for a point on the curve indicate the sensitivity of supply costs.

According to cost supply curves, smaller plants have lower costs of fuel supply simply because specifically less transport is required. However, this allows not concluding that smaller is better. First, the costs calculated here do not reflect the fuel price. A supplier will usually set one price for all locations, except very remote ones, using the marginal transport costs as a rule. Economy of scale typically grants the larger customer a lower wholesale price. Second, fuel costs comprise usually a smaller proportion of the total generation costs for larger plants than for smaller units. This is because specific investments into boilers, buildings and auxiliary equipment are lower for larger units. Accordingly, to find out which plant size is better for a location, a cost supply analysis has to include all cost elements and calculate the generation cost or even the net present value of an investment for a location.

## **4.2 Model implementation**

From a number of possible software choices, ESRI's ArcGIS 9 was chosen to build the GRASP model. ArcGIS is widely used, which means that GRASP can be adopted in many GIS departments and workgroups. It features a graphical modelling user interface called Model Builder, which is visually more appealing than scripts and more user friendly for updating and maintaining the model. On the downside, ArcGIS is expensive and implementations of highly structured models can be time-consuming and slow to compute.

The model has been organised as a number of sub-models with different handles and options for parameter adjustment. The widely different modelling approaches for thinning resources in Hallormsstadur and Heradsskogar necessitated building two separate thinning resource and thinning cost models. Also forwarding, chipping and storage costs are modelled separately for the two forest projects because of their different organisation. Common to both, however, is the road transport model. One overlay model takes care of producing cost supply tables for the whole case region.

The model calculates resources for every year between 2005 and 2030. Costs are so far only calculated once, leaving out discounted costs or development of specific costs in this period. This could be done in the next version of GRASP.

In constructing the model elements the main objective was to build a transparent model, which can be updated or altered with few efforts. Therefore the model is not optimised for computational speed. Some sub-models as the resource and thinning cost calculators are very extensive because they perform calculations repeatedly for all scenario years. Using point locations instead of real forest cells for the Heradsskogar forests brought along a rather complex way of model. It would have been easier to build this part of the model in a relational database programme such as Access, or even using a spreadsheet, but because the overlay of resources and costs demands the conversion to raster data anyway, the difference is not that important.

## 5 Data

Obviously, data is important in a data-intensive project. The best available data has to be found and documented for further reference. Analysis and modelling has to be adapted to the data that exists. There were no funds available in this project to start intensive primary data collection, so the aim was to rely on existing data as much as possible. Preferred data sources were actual operation databases and forest plans, as well as reports recommended by the forest managers.

### 5.1 Forest data

Icelandic forest databases are generally less developed than in other countries. Annual statistics of the national forests are very general in terms of geography. There are no statistics on the inventory of private forests. A national forest inventory is on its way, but forest management systems do not exist as yet. Some approaches to map and quantitatively describe Icelandic public and private forests, however, do exist and have been developed through time. These are maintained by the various actors in the forest sector, e.g. the Icelandic Forest Service or Heradsskogar, and subsist in various software formats and standards. Common to all systems is the ongoing technological transition from CAD- and DBMS-based systems to GIS at the public and private forest stations and companies.

A general recommendation and meta data prescription for mapping forests during establishment has been developed by Arnór Snorrason, Icelandic Forest Research, since 1987 (Einarsson *et al.*, 2004). Based on these recommendations mapping of forests was originally done using a CAD-based technical drawing system (Bentley Intergraph Microstation), extended with a tabular database system (a MS Access compatible DBMS). Only recently GIS has become more widely used, with ESRI's ArcGIS becoming the most widely used software environment.

Forest areas have seemingly been mapped using non-rectified aerial photos and satellite images, implicating that the areas derived from these maps differ with up to 7% from reality. High resolution orthophotos are expensive but the best available mapping technology, yet nowadays most forests are mapped using aerial photos or satellite images (SPOT 5) at highly reduced costs. Disadvantages are the low resolution and the far from precise geographical references. The possibility to use the false-colour images for remote sensing-based image analysis and automated land use recognition is not utilised. Forest features are usually mapped manually as areas (polygons), using the background image as the geographical reference. In most cases no standard references are used, nor are forest maps rectified using trig points or the like. This causes problems when forest maps are overlain with other GIS-data. To be congruent with digital topographical maps such as IS 50 by the Icelandic National Survey the produced maps need to be rubber-sheeted or stretched to fit the true planar extent.

Apart from mapping forest geometries, forest inventories consisting of information about species, age, silvicultural measures and the like are difficult to procure in Iceland. A na-

tional forest inventory is really needed. Site indices and growth curves have not been produced systematically for Iceland. Single studies by Snorrason (unpublished) and others have produced information about tree growth as a function on environmental factors for a few sites only. Important parameters for site index assessment, such as height, diameter in breast height etc. only exist for few forests. A full dataset for the production of site index curves was neither available for Hallormsstadur nor parts of Heradsskogar forests.

Forest maps are rarely kept up to date. The newest map content of Hallormsstadur is from the year 2000, and updates of Heradsskogar maps are a not even properly documented.

### **Hallormsstaður**

For the national forest in Hallormsstaður and its neighbour Mjóanes an extensive mapping project was carried out by Lárus Heiðarsson of the Icelandic Forest Service in Egilsstaðir. Lárus has used forest maps and registers from the year 2000 together with SPOT 5 satellite images to map all planted and auxiliary plots in an area comprising 620 ha. Many useful data are included in this map, most importantly being the planted species, the stem density, dominant height and the year of plantation. Mapping, however, is not entirely complete. For example, species, age and stem density are registered for 139 ha of the approx. 176 ha mapped Larch forest, equal to 20 % loss. It is recommended to update the mapping of Hallormsstadur with age and species data for the remaining stands of Larch.

### **Heraðsskógar**

For Heradsskogar an extensive relational database (“Gullagrunnur”) exists, which is used for the daily administration and planning of the afforestation projects. In this project, it forms the main and only source for the afforested area by species and year of afforestation. For each participating farm it contains one or several compartments, under which the individual stands are registered. Plantation jobs are registered with species, number of seedlings and year; while areas are registered for the stands only. In this way the area of the forest cells cannot be extracted together with the plantation year. Instead the number of seedlings is divided with an average stem density of 3,600 per ha. Using the number of seedlings, however, has the advantage of being rather precise because the participating farms receive financial report for the number of planted trees, not hectares. It has been assessed that information about tree mortality in the first years is much more uncertain than these figures used, so they will not add as much to the total error bias.

Using MS Access, a query was written to extract the number of stems by farm number and year. Because the year and/or the species and/or the stem number are not registered for all afforested areas, some plots have been lost on the way. The total number of seedlings is only slightly different from the data published in Heradsskogars annual reports.

The query result was then imported into MS Excel, where a pivot table was made to summarise the number of seedlings for each farm and year by year. Some faulty years (1700, 1980) were extracted and also a single farm, which obviously served as a dummy.

In order to place these data on a map, the names of 121 farms were related to a point data theme with a place name register from the IS 50 digital vector map. In case two or more farm locations had the same name, the old municipality names contained in Gullagrunnur were used to sort out the right location. In case more than one farm with the same name existed in the same municipality, the national land ownership databases at Fasteignamat Ríkisins (the National Property Agency) and Nyttjaland (the National Land Ownership Database) were queried on the land parcel level.

There is no national cadastral system in Iceland, which made it difficult to locate as many as 10 % of the farms properly. For some farms no point locations in the IS 50 map were existing, so they had been made up with the land parcel as the only reliable reference. The resulting farm locations should be precise within at least one kilometre for a few outliers, and within a couple 100 metres for the majority of farms. The precise location of the farms is subordinate because a few kilometres more or less do not compromise the calculation of transport costs.

## **5.2 Road network data**

A national road network theme exists in the IS 50 digital vector map. With a recommended scale of 1:50,000 the theme is sufficiently detailed for the project. It is, however, already 5 years old, adding some uncertainty on the quality and the location of roads. Iceland is in a constant process of improving its roads and new roads are constantly being built. But because road properties such as surface and number of lanes do not play a role and major road construction projects have not been carried out in the case region, the existing database was assumed to be sufficient for the purpose.

## **5.3 Building data**

Geographical and descriptive data on the building stock in the area is used in two places in the model. First, the location of energy demand requires the location of heated buildings. Second, the participating farms have to be located for the assessment of farm gate prices and resources of wood fuels.

To map buildings consistently with roads and other features, the IS 50 building theme was used for locating buildings and farms. Farm locations were found using the place name field in the building database, and, in case there were several buildings with the same place name, the property number was used to locate a building without doubt.

Locations of heated buildings did also require the use of the land parcel theme produced by LBHÍ and in future managed by LMR. The calculated total heat demand was summarised to the presumed main building on each property registered in this database.



There were few farms and quite a few records from the building register, which could not be spatially organised. In these cases help was sought at FMR.

#### ***5.4 Geological data***

In order to assess the possibilities to use geothermal heat in parts of the case study area, some data were delivered by the Geological Survey of Iceland (ISOR). A polygon theme with the bedrock age, and point themes with geothermal boreholes, geothermal features and district heating systems were used for this analysis. The data is frequently updated and assumed to be rather reliable, as it forms the basis for continued planning and decision making on the important geothermal resources of the country.

#### ***5.5 Other data***

In addition to the above mentioned data necessary to carry out the analyses, a few geographical data sets were used for cartographical purposes such as the production of maps for visualisation and illustration. A digital elevation raster (DER) with a 1 ha resolution was produced using elevation lines from the IS 50 map, which were converted to a continuous theme by a triangulated irregular network (TIN) interpolation and subsequent conversion to a raster. This DER served as the common spatial extent and analysis mask for all sub-models. A hill-shade model was produced to give the DER additional visual strength as a background map.

Other themes used were hydrological features, land use, micro-hydropower stations, and place names; all derived from the IS 50 and IS 500 digital vector maps.

## 6 Model design

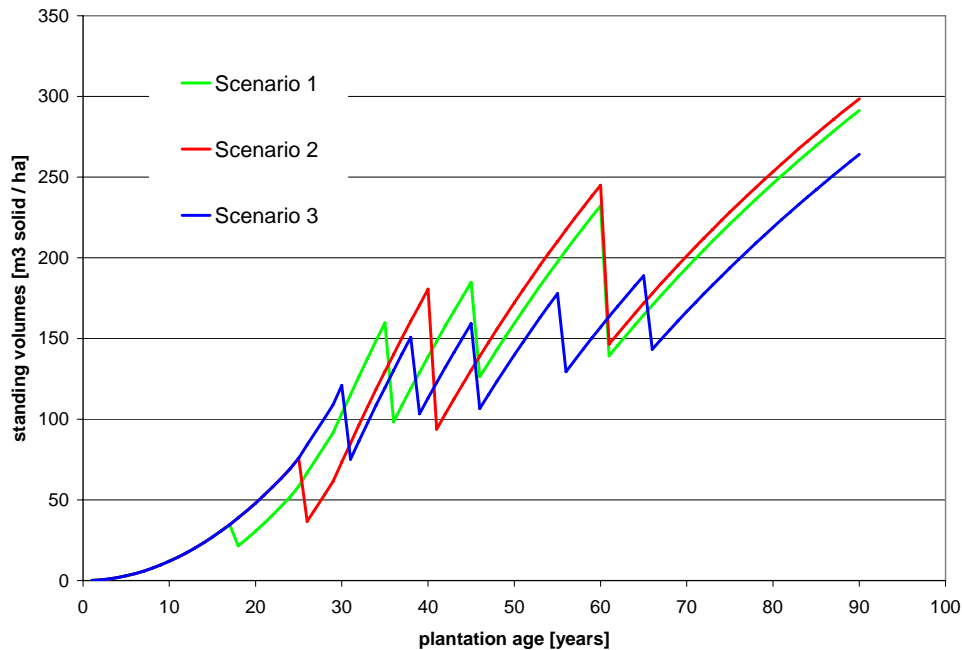
This chapter presents the main ideas behind the models developed for the project. Two main ideas lay behind this model, as described in chapter 4. A very data-intensive part is the detailed modelling of the location and amount of recoverable thinning resources many years into the future. This part produces also the costs, as resources and their costs of procurement are attached to the same process. The second part involves the logistics and the remaining cost chain elements such as forwarding, chipping and road transport. Using more general model parameters, it is less data intensive when it comes to detailed mapping, but the higher number of model parameters requires extra thought and consideration. It is mainly here that alternatives regarding forwarding, chipping and transport technologies are modelled.

### 6.1 Growth and thinning residue models

Sub-models for calculating the extractable resources from thinning processes have been developed separately for Heradsskogar and Hallormsstadur forests. Both models, however, produce the same type of results.

The general idea behind the resource models is that for the species chosen, the extractable biomass is known for the years in which the trees should be thinned according to the decision model by Vesterager & Sundstrup (2000). Wood resources of a given amount are thus available at the stand site in a given year after plantation. This does not take into account that silvicultural management may postpone or reschedule thinning operations. In reality, a forest compartment is thinned according to thinning prescriptions as well as the availability of manpower, demand for wood fuel, etc.

Vesterager & Sundstrup (2000) have produced thinning plans for Hallormsstadur and other forests in the region. These plans are tables, which establish a relation between stand age and thinning residues per ha for the same site index. The same site index curve is used for the whole case area, which seems to be a safe assumption according to Heidarsson (2005). The thinning plans were produced with two alternatives, resulting in three possible thinning scenarios, where, economically, 1 is the most likely and 3 is the least likely of those alternatives. All scenarios produce slightly different amounts of timber at the rotation age of 90 years, and the recoverable thinning resources and the costs associated with thinning the stands are different. An overview of the thinning scenarios is given in Figure 3. These thinning scenarios were applied for Hallormsstadur as well as Heradsskogar with no modifications.

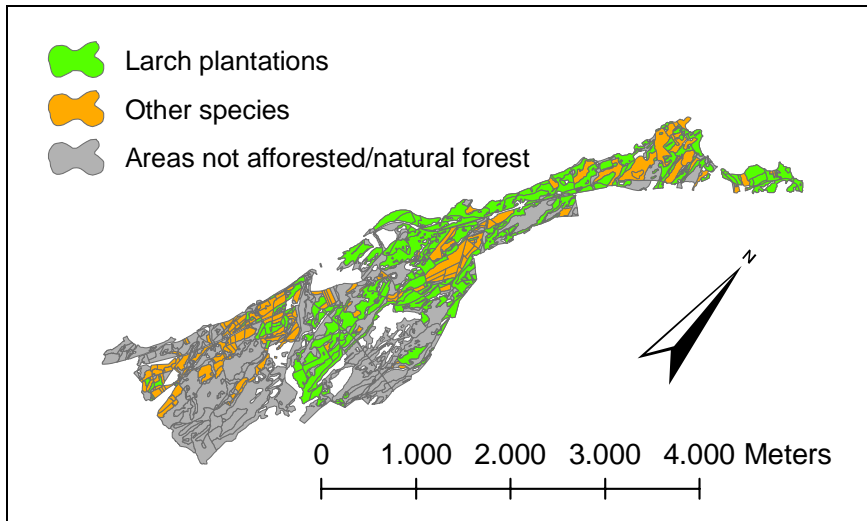


**Figure 3: Thinning scenarios based on the recommendations by Vesterager & Sundstrup (2000). Three to five thinnings sooner or later in the plantation life result in different timber output at a rotation age of 90 years, with different recoverable thinning volumes and at different costs.**

### Hallormsstadur forest

Areas of larch by age were available in the Hallormsstadur map by Heidarsson (2005), see Figure 4. This map was converted into a raster of 1 ha cells (100 x 100 metres) for more efficient raster modelling. The error induced is not significant, because the average stand size is about 1 ha, and the total area has been maintained in this process. The benefit of using a 1 ha model is that it is no longer necessary to calculate the area. The number of discrete cells in the raster model is proportional to the forest area.

A grid with the plantation year of each department has been produced to calculate the stand age for each scenario year. Age was then reclassified to resources in solid m<sup>3</sup>. The result is a series of grids for the years 2005 to 2030, which show a geographical distribution of thinning residues. From these grids a few statistics such as the annual sum, average etc. can be produced, but their main purpose is to be overlain with cost data.



**Figure 4: Map of Hallormsstadur forest showing areas where larch plantations have been registered; plantations of other species; as well as areas not afforested or where natural birch forest grows.**

An example for an annual thinning resource map is shown in (Insert figure here). As can be seen from the figure, the total number of forest cells is rather small, which might suggest that the cell size either can be decreased or the forest size be increased, e.g. in a scenario where Hallormsstadur gradually grows.

### **Heradsskogar forest**

Detailed forest maps were not readily available for Heradsskogar forests, which is why it has been decided to treat the 121 individual forest projects as point locations. The amount of resources and the costs associated with thinning were considered to be “at farm gates”.

The point theme for the participating farms was joined with the area planted every year and the plantation years, resulting in two new point themes, which were converted to raster themes holding plantation area for each year from 1990 to 2004, as well as the plantation age. The two raster maps were used to calculate stand age for each of the plantation years. Then age was reclassified to specific volumes and costs by area, and multiplied with areas. Then for each of the plantation years costs and volumes were summarised to produce the total volumes recoverable at every farm location at the calculated costs and for all years between 2005 and 2030.

Fig 4 shows the location of the participating forests and their volumes and costs for a chosen year. Locating costs and volumes at farm gate does not create much error, as most of the plantations are located close to farms anyway and the farm house location usually is the best accessible spot on a farm, making it an obvious pick-up place for forest residues.

## **6.2 Least cost distance road transport model**

The Icelandic road network is composed of a main ring road, which circumcises the whole country mainly in the coastal lowland rim; a number of secondary roads that connect smaller settlements; and a few mountain roads only usable in summer with 4WD vehicles. Most of the ring road surface is covered with asphalt, while the majority of secondary roads have a gravel surface. On almost all roads an average speed of 80 km/h can be maintained by standard trucks, while travel time increases considerably on mountain roads.

Most of the roads linking forests and settlements in the case region are sections of the ring road as well as secondary roads. Only few mountain roads seem to offer alternative routes, but in reality they are unattractive to commercial transport and can be excluded from the road transport model. Fig shows a road map for the case study together with its topography and the location of Hallormsstadur forest station.

Connectivity and circuitry of a network are good indicators for the quality of connection through a road network. The connectivity  $\gamma$  is calculated as the number of arcs (road segments connecting nodes) divided through three times the number of nodes (cross-roads, intersections, ends) minus 2. A connectivity index of 0 means no connectivity at all, and a 1 indicates that all nodes on the network are connected to each other. The roads in the case area have a connectivity index of 0.8. Circuitry as a measure to assess the possibilities to find alternative routes has not been analysed. The system is rather closed, as only four roads leave the area, two being sections of the ring road, another being a mountain road. The nearest forests outside the area are rather far away and the delineation of the case region does not cut off alternative routes. These aspects comprise good opportunities and reason to carry out an accessibility analysis for the case region.

The geographical database used was the IS 50 digital vector map by LMI (2000). Its detail and level of maintenance was judged to be sufficient for the project, partly because the conversion to raster adds an error of up to 100 m to the precise location of roads, partly because its degree of detail fits with the locations of farms and forests, and finally because it was the most comprehensible at hand. If the transport model needs to be fine-tuned to accommodate travel time instead of plain distance, the road surface and construction data contained in this data base would allow for a classification of truck speeds.

To use the IS 50 line theme for cost weighted distance analysis, it needs to be converted to a linear grid. This conversion induces errors, mainly because the distance between locations is no longer given by the length of the line that depicts the road, but of the cell size of the raster theme and, in case a cell is travelled over diagonally, the cell size times the square root of 2. The road distance between Hallormsstadur and Egilsstadir, according to the IS 50 line segment length, is lengthened by 4 % compared to the 100 m raster model, an error easily compensated for if acceleration and braking would be included. Another error is induced by using a linear raster rather than a true network data base with nodes only where roads are interconnected. This way all crossing roads become intersections; an error significant when analysing motorway intersections. But because there are no unconnected road intersections, and no one-way roads or the like, this is not a prob-

lem. Finally, in areas with a road network density higher than the square root of the raster cell area, roads become interconnected without being that. This is usually the case in built-up areas. But since not much traffic is passing through the few instances of built-up areas in the case region, this is not a problem, either.

### **6.3 Cost chain modelling**

In the following the elements of the cost chain, from thinning operations to road transport from landings to an energy plant, are described. Data input as well as the implementation of the process model are described and suggestions for improvements are given where appropriate.

#### **Thinning models**

Only one thinning model, developed as part of a Master's project in forestry at the Royal Veterinary and Agricultural University of Denmark, is applied (Vesterager & Sundstrup, 2000). This model uses an average site index for the whole Fljotsherad region, where the case region is located. Considerable differences in local productivity may therefore be expected.

Thinning resources are calculated including stems and bark, but excluding branches and needles. Excluding thick branches from the model might reduce the amount of recoverable biomass resources, but as thinning strategies aim at producing trees with focus on stem quality, this underestimate of resources should not be a big issue, albeit during thinning usually the unwanted trees are removed, among them often being the ones with thick crowns.

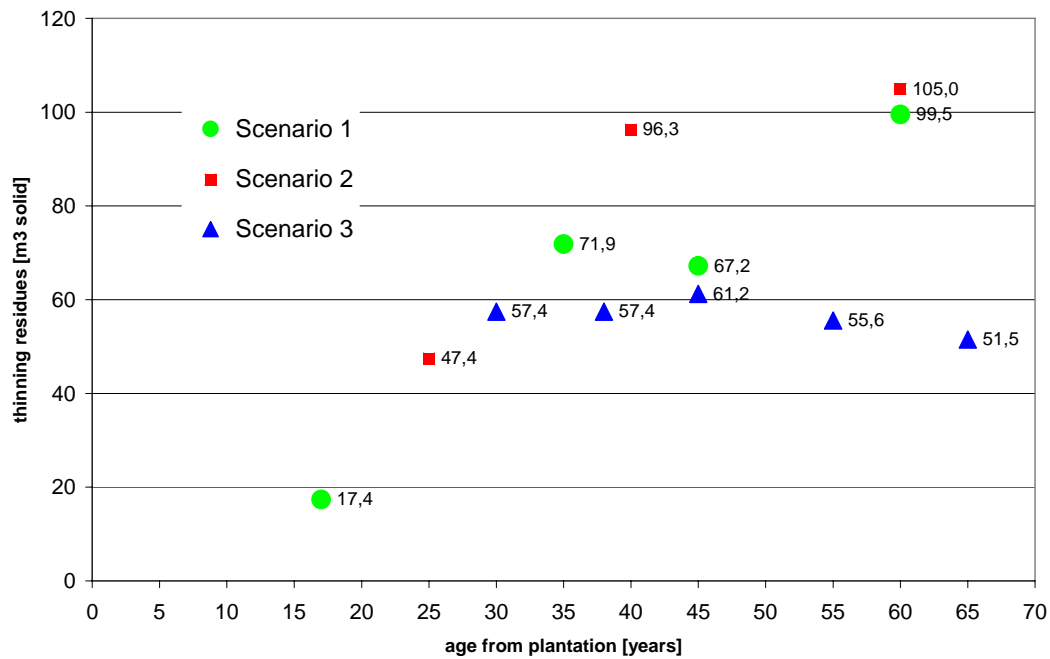
The model in its present form equals stem volumes of trees to be thinned at the calculated age with the volumes recoverable as wood fuels. In reality tops and stumps would be left in the forest. The volume unit, solid  $m^3$ , is kept through the entire cost chain although drying might reduce the volumes.

The thinning model suggests thinning operations at several ages, see Table 1. Being a recommendation only, it can not be certain whether these ages are applied in reality. But since this is the best offer in a situation where experience with thinning is little, it was chosen to work with these curves.

Stand age	Thinning resources [m <sup>3</sup> /ha/year]
0 - 16 years	0
17 years	17
18 - 34 years	0
35 years	72
36 - 44 years	0
45 years	67
46 - 59 years	0
60 years	100
61 - 89 years	0
90 years	239
Above 90 years	0

**Table 1: Ages of stands and the recoverable thinning residues, suggested thinning strategy 1 of 3.**

The thinning curves have been implemented in the model as reclassifications of the plantation years for each stand or raster cell. Age is calculated for all scenario years, and reclassified to either the recoverable thinning resources when the stand is ready for thinning at this age, or to the value zero for the years in between. Figure 5 shows the recoverable thinning residues for the three suggested alternatives.



**Figure 5: Recoverable thinning volumes by stand age for the three thinning scenarios suggested by Vesterager and Sundstrup (2000). 3 to 5 thinnings bring the typical stand of Larix to maturity at an age of 90.**

The model includes all three alternative thinning scenarios, and new thinning specifications can relatively easily be produced by coding new or changing the existing reclassification tables in the thinning models for Heradsskogar and Hallormsstadur.

A local reduction of the amount of recoverable resources, be it due to the wish to leave some resources in the forest or because a certain type of harvester is used, can be achieved by adding a multiplier raster to the model.

The thinning resource model produces raster data sets for the two forest projects individually, for the three thinning alternatives, and for all scenario years from 2005 to 2030. The raster data sets hold values in m<sup>3</sup> solid pr. ha, assigning a value "0" to cells outside the forest areas but within the case region. The latter is required for the spatial addition of Hallormsstadur and Heradsskogar rasters.

The thinning costs model works in the same way. The only difference is that age values are reclassified to costs per area unit, in this case in thousands of ISK / ha because the ESRI Grid format uses integer values for raster themes. Costs can be changed by editing the reclassification tables. If the economic calculations should include a net present value calculation or an inflation rate, then the cell values need to be discounted with the difference of the scenario year and a reference year. This type of calculation could be added to the model.

## **Forwarding costs**

Felled stems need to be forwarded to landings or processing sites. This can be done in several ways, depending on the choice of machinery or cost chain element. Common to all technological possibilities are the geographical factors tree density, thinning volumes by area unit, distance to forest track and distance along forest track to landing. Forwarding costs are modelled as functions of local geography only for the Hallormsstadur forest. The lack of distance and area for the point-based Heradsskogar forests make it pointless to include forwarding costs as a function of local topography. Instead, cost factors are multiplied with wood volumes.

The forwarding cost model calculates the distance from the centre of a forest cell to the nearest forest track, adding half the cell size (50 m) to avoid zero-values. It then multiplies this distance with the resource extracted from the cell and multiplies this value with a specific cost given in costs per volume unit and distance to forest track (ISK / m<sup>3</sup> solid / m). This cost factor is assumed to be useful for the manual extraction using a tractor-mounted winch as well as for harvester-forwarder systems.

The second part of the forwarding cost uses the calculated distance along forest tracks and roads to four landing sites in the area. Forwarding costs are calculated as a function of track distance and average forwarder load. These data can be used to model the existing form of forwarding using a grapple and a tractor with trailer, or a harvester-forwarder. This part of the process can also be included in modelling a chipper-forwarder, as it



represents the commuting of the vehicle between the approximate forest stand location and the nearest landing.

There have not been representative data collected for the costs of extracting stems from the stand to the nearest forest tracks. Instead, an estimate is used, based on a single thinning event in Hallormsstadur in the year 2004. The costs are assumed to be a function of volumes and distance from the stand to the nearest track. This extraction model should operate at a much smaller scale, but to keep model elements consistent the same raster resolution of 100 m was chosen.

For the cost assessment it was estimated that a tractor and two operators can pull 1 m<sup>3</sup> of wood at a speed of 0.25 m/s forth and back. A tractor costs 2,200 ISK/h, two men 4,440 ISK/h, which translates a cost function of 7.4 ISK/m<sup>3</sup>/m. Fixed costs are not considered as no terminal time is involved.

The cost function is implemented using a raster with the distance to the nearest forest track and the recoverable volume raster.

For the model calculating the forwarding costs along tracks in this preliminary version the following cost data was used. According to Thor Thorfinsson, stand no. 216-1 in Hallormsstadur was thinned in the year 2004. Planted in 1983 with Russian Larch, the 3.7 ha of forest were thinned from 3,000 to (estimated) 1,500 stems pr. ha. Using the growth curves by Vetsterager and Sundstrup (2000), the 21 year old stand produced 24 m<sup>3</sup> (solid) extractable stem wood pr. ha, or 88.8 m<sup>3</sup> in total. It took 20 working hours to remove these resources and to transport them to a landing 1.5 km away. At an hourly cost of 5,500 ISK for a tractor with timber trailer and driver, an estimated 15 minutes of terminal time and an hourly transport speed of 1.5 km forth and back (including loading on the way), this leads to the following cost function:

$$C = c_{\text{var}} V d + c_{\text{fix}}$$

Where

- C: total costs
- $c_{\text{var}}$ : variable costs pr. m<sup>3</sup> and km
- V: volume (pr. ha)
- d: distance to landing
- $c_{\text{fix}}$ : fixed costs (terminal time)

This cost function is the basis for the calculation of costs of extraction from forest track in a raster model. Distance to landings is calculated using a 100 m grid.

## Chipping costs

Chipping costs are not much influenced by geography, and therefore calculated as functions of volumes. Several sizes of chippers with different costs can be modelled by classification of volumes per area or forest compartment. As chipping costs are independent of

location and distance, they are modelled as a constant factor multiplied with the recoverable volumes.

### **Road transport costs**

The costs of road transport are modelled on the basis of the transport distances calculated in the road transport model, the load volumes and an optional fixed cost per trip allowing for terminal costs. The model differentiates between two types of vehicles used. For shorter distances up to a distance free of choice the same tractor also used for forest forwarding is applied. Distances above that are managed by a truck. Tractor and truck have different costs per kilometre and different load volumes.

The model is implemented as follows. First, the model calculates the distance to a selectable location, in this case Hallormsstadur forest station, along the road network. Mountain roads can be classified as being extra time consuming or excluded from the road transport model using a reclassification process. With the distances calculated, the model uses a Euclidean allocation function to assign a distance value to every cell in the case region. Then the model separates between distances covered by tractor or by truck using a conditional statement. For each modes of transport the costs are calculated as a function of distance and transport volume pr. load. A fixed terminal cost is added at the end.

Model variables are the Shape-file with the location of processing or energy plant, the minimum distance for truck transport, the truck- and tractor costs pr. kilometre, the load volumes for both types of vehicles, and the fixed trip costs. Figure x shows the user interface of the road transport model. Once the model has been run for a location, the road costs are saved in a grid called "roadcosts\_m3", which is used by the overlay model to produce a cost supply table for each year and thinning scenario.

### **Addition of costs**

All costs along the cost chain add up to a total cost to be applied for cost supply overlay. This requires that all cost raster data sets cover the same area as the case region. Locations without costs assigned must have the value zero and no-data cells are not allowed. Costs are added in the overlay model. Because thinning costs are in thousand ISK pr. ha, they need to be divided by the recoverable resources. This is done in the overlay model because additional costs or a smaller amount of resources might be the result of changes to either the cost model or the resource model.

It is possible here to add more cost chain elements, or to assign additional costs, e.g. in form of levies by area unit, for parts of the region or as balancing factors of some sort.

## 6.4 Overlay of resources and costs

The knowledge of amounts of resources and their aggregated costs along the cost chain and for each raster location in the case region makes it possible to combine both types of information in a spatial summation of resources by incremental costs. This is done using the zonal statistics as table function in ArcGIS Spatial Analyst tools. Zones are here defined as the integer values of costs (in ISK) calculated for each cell in the case region. The values to be summarised are the recoverable amounts in solid m<sup>3</sup>. The zonal statistics as table function results in a table in Dbase4-format, where for each instance of a cost value [in ISK / m<sup>3</sup> solid] holding resource values the sum and various other statistics are reported. The table is sorted by increasing costs. The only fields of the table necessary to produce cost-supply curves are called VALUE, COUNT and SUM. VALUE contains the costs, COUNT is used to check the area (its contents are the number of cells and hence the area in ha), and SUM contains the amounts of biomass at the given costs. All other fields of the table can be deleted.

To produce a cost-supply curve the resulting table is copied to an MS Excel spreadsheet, and four more columns are added, see Figure 6. The first contains the costs [in ISK] as the product of specific costs [in ISK / m<sup>3</sup> solid] and amounts [in m<sup>3</sup> solid]. The next column accumulates the costs by adding the costs for a cost zone to the costs of the previous zone. The third column accumulates the amounts, and the fourth column divides accumulated costs by accumulated amounts to produce the marginal costs. A cost supply curve is then produced drawing an x,y-diagram using the accumulated amounts as x-values and the marginal costs as y-values. Several curves can be combined in this way.

	A	B	C	D	E	F	G	H
1	VALUE	COUNT	SUM	costs	acc costs	acc amounts	marg costs/acc amounts	2005
2	333	1	0	0	0	0	0	
3	335	6	0	0	0	0	0	
4	336	3	0	0	0	0	0	
5	338	5	0	0	0	0	0	
6	339	5	0	0	0	0	0	
7	340	11	0	0	0	0	0	
8	341	8	0	0	0	0	0	
9	342	102	0	0	0	0	0	
10	343	8	0	0	0	0	0	
11	344	39	0	0	0	0	0	

**Figure 6: The spreadsheet used to produce cost-supply curves from the overlay statistics resulting from the GRASP model. The Fields VALUE, COUNT and SUM (columns A, B and C) are taken over from the original Dbase4-table; columns D, E, F and G are used to calculate the costs, accumulated amounts and costs, and the marginal costs per accumulated amounts. Field H1 is used as a label field for the cost-supply curve.**

## **7 End-use heat consumption and wood fuel markets**

Wood heat has to compete against subsidised electric heating, which also requires less investment into heating technology, and geothermal heat, which becomes more and more available even in areas so far considered geothermally “cold”. Therefore, of the total heat consumed, only the share that is located outside areas with district heating, individual geothermal heat supply as well as micro-hydropower, can be considered a possible market for wood heat.

The study presented here includes a GIS-based market survey for small-scale wood heat, ranging from the use of wood in summer houses to the installation of small and medium-sized boilers. It could be seen as a form of “heat atlas”, as it tries to quantify heat demand geographically.

The study starts with an attempt to quantify the heat demand in individual farms. The next part of the study features an exclusion of unlikely locations. The final part tries to quantify the amount of heat used in the remaining settlements and houses.

### ***7.1 Assessment of individual heat demand***

The heat demand of a building is usually defined as the amount of thermal energy required to maintain a certain indoor temperature. In the context of this study, heat demand is the annual share of the energy consumed in a single building of all buildings in the area, by the proportion of its heated floor space or volume.

Heat demand in buildings can be assessed in different ways. The truest inventory of heat demand is made by installing meters to register annual consumption of energy carriers and levelling out climatic differences from one year to another. This option has been out of scope for the study.

A less time-intensive approach is the preparation of questionnaires. The questionnaire produced for this project (see Jonsson) returned only results for a quarter of the participating farms, which are less than half of all homes outside towns with district heating networks. By regression analysis of questionnaire replies a few correlations between queried factors and data registered in a national property register could be established.

For this purpose an excerpt of the national property register at Fasteignamat Ríkisins (The Icelandic Property Agency, FMR), which is used for the valuation and taxation of property, was ordered. The excerpt included, for each building registered, the property number, by which it can be geographically referenced to a land parcel; the type of building; its volume; and its outer wall materials. By the type of building it could be told which buildings are heated and which not.

## Building stock in the case area

Building type	No of sub-types	No of build-ings	Volumes [m3]	Percent of total volume	Assumed heated
Agricultural buildings	70	1.191	643.386	38%	Partly
Detached dwellings	54	838	402.380	24%	Yes
Public buildings	74	232	256.753	15%	Yes
Commerce and service	53	102	139.755	8%	Yes
Other	73	506	107.746	6%	No
Industrial buildings	24	77	97.379	6%	Partly
Summer house	45	171	26.786	2%	Partly
Appartment buildings	9	18	10.850	1%	Yes
Terraced homes	1	10	4.816	0%	Yes

Table 1 shows a summary of the building types registered by their count and sum of volumes. It has been necessary to make a clear and unambiguous set of building types. As it can be seen from the number of sub-types recorded in FMR's database, there is no clear classification so far, making it difficult to describe building types.

Building type	No of sub-types	No of build-ings	Volumes [m3]	Percent of total volume	Assumed heated
Agricultural buildings	70	1.191	643.386	38%	Partly
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Appartment buildings	9	18	10.850	1%	Yes
Terraced homes	1	10	4.816	0%	Yes

**Table 1: Building types in the case area, based on a reclassification of building types registered by Fasteignamat Ríkisins.**

The table shows building volumes in m<sup>3</sup>, making it necessary to convert to areas of heated floor space used in the statistics. By far the highest volumes are registered for agricultural buildings, followed by various forms of dwellings and other types of buildings. Some types of buildings are assumed to be heated, some not, while a few building types are assumed to be partially heated, either in terms of area or time of the year. Among the 3,145 buildings registered, 1,200 are assumed to be heated by this classification.

For farm houses and heated agricultural buildings in connection with Heradsskogar farms is most interesting to know their head demand for a self supply scenario in farms would consider either to sell wood to a larger boiler or to use the wood themselves. However, currently there exists not enough data to model either side of the supply chain.

## **Assessing the specific heat demand**

An assessment of the specific heat demand by building type has so far been impossible because of two reasons. First, there exist no statistics on the heat demand of buildings. Second, the questionnaire did not produce data that could be used to carry out a regression analysis from which specific energy consumption data could be derived. The buildings connected to the participating farms show a high diversity and too few common characteristics to be used for comparative analyses of this kind.

FMR does register a few physical building properties, but without a proper reference group, specific heat consumption values are impossible to produce.

## **Statistical analysis of the questionnaire**

Out of the 121 farms currently participating in the Heradsskogar programme, 36 have replied the call for answers with more or less detailed and useful data, equal to a return rate of 30 %. Of these 36 replies, 29 could be identified by their farm name, which lets the return rate useful for geographical analysis decrease to 24 %. 29 out of the 36 (81 % of the farms) have a permanent residence on their grounds. There are 1 to 2 residential buildings on each farm, with mostly one or two, rarely more dwellings. Most of the farms are not mainly used for silviculture; sheep farming, horses and tourism are the main forms of commerce.

## **Calculation of the heat demand for analysis**

In the FMR table, property data for 1,214 individual property parcels is registered. Of these, only the buildings which belong to the participating farms are included for further analysis, leaving out the remaining farms and the buildings in the towns, which are heated collectively anyway.

## **7.2 Exclusion of geothermally heated farms**

Geothermal heat covers almost 90 % of the total heat consumed for space heating, hot water, industrial processes, public baths and horticulture. During the past two decades in particular district heating networks have been installed in an increasing number of areas. Installation costs are determined by the distance to a geothermal well and the costs for the well itself. Pipe networks have seen a decrease in costs since the evolution of PEX-type heating pipes that are delivered by the roll. Geothermal drilling has also advanced, and drillers are now able to offer wells to deeper depths and horizontal drilling techniques at lower prices than just a few years ago. This means that the likeliness of new geothermal heating systems is a function of access to geothermal reservoirs and heat consumption density. The first determines the costs of drilling, the latter the costs for heating networks.

The specific costs of drilling decrease with the number of users. In case of individual boreholes for one consumer only, the costs are much higher. In a GIS, the consumer density and the age of the bedrock have therefore been pinpointed as the two determinants for access to geothermal heat.

The case region is outside high-temperature geothermal heat areas, where steam evaporates from the surface of the Earth. The most close by of these areas, Hróthálsar, is still more than 50 km away from the nearest farm in the case area.

### ***7.3 Exclusion of farms heated with micro-hydropower***

Small hydropower plants with an installed capacity of between 0.1 and 120 kW are quite commonly used to produce cheap electricity for heating purposes. 461 plants with a total capacity of merely 4.2 MW exist in Iceland. They are usually not connected to the public grid, but produce power to resistors only. In the case region, 30 plants with a total capacity of 450 kW are estimated to produce 1,500 MWh annually. It is assumed that the plants can produce a certain share of a farm's heat demand, depending on the installed capacity and the heat demand at the farm; the latter and the number of full-load hours of the turbines being estimates.

There is no data available on which farms the micro plants belong to. Instead it was assumed to be a safe estimate that a hydropower plant belongs to a farm if it is located on that farm's property. This analysis was carried out with selection by location and a spatial joint.

## 8 Results

The results presented in this chapter are preliminary and subject of further discussion between the project partners. It should be stressed once again that the results of this report are not so much the numbers of amounts and costs, but the model framework and structure as well as the implementation of the model. Results can in most cases easily be recalculated in case conditions and variables change.

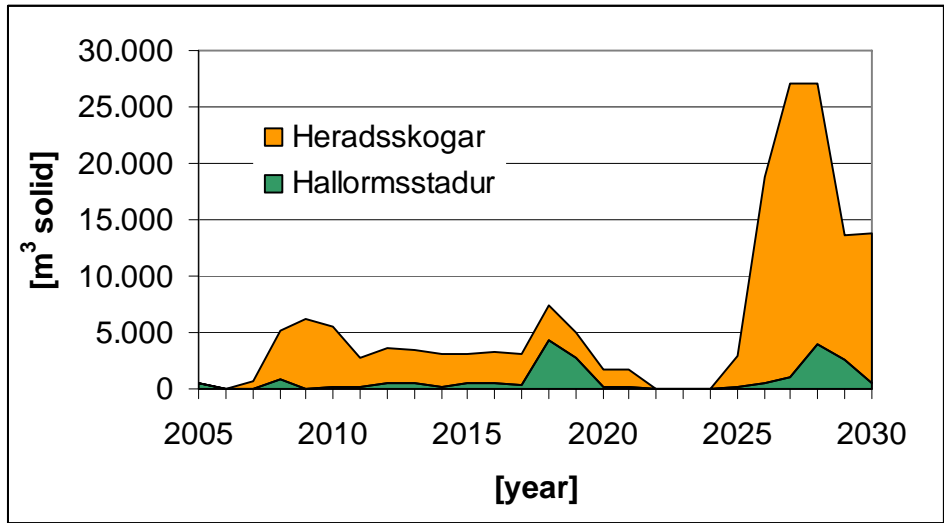
### **8.1 Available wood fuel resources 2005 - 2030**

Wood fuel resources are a function of the areas planted with Larch, the stand age and its productivity, and the thinning scenario and technologies chosen. Wood resources from thinning operations have been calculated for Hallormstadir and Heradsskogar separately for the years 2005 to 2030.

Figure 7 shows the total amounts of wood resources in solid m<sup>3</sup> for the two forests and for thinning scenario 1. It can be seen that the annually recoverable potentials highly depend on the areas planted 17 years earlier. The resources from the first thinning become exploited at around the year 2020, because future plantation in Heradsskogar has not been included in the model yet. A second thinning period commences in the year 2025, yielding volumes a magnitude higher than during the first thinning. This is because the specific yield is higher and because the afforested areas of Heradsskogar accumulate to considerable amounts. What also can be seen from the diagram is that Hallormstadir must rely on the delivery of wood chips from surrounding forests if the annual consumption is higher than 200-300 solid m<sup>3</sup> a year in the first 10 years.

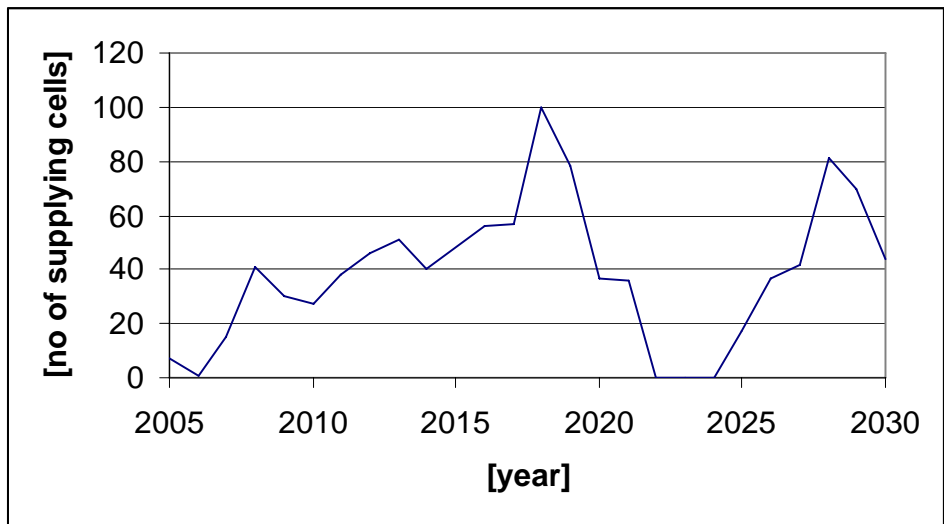
Finally, the figure also indicates that if thinning procedures could be moved 2-3 year in either direction, the resources available could be controlled in a way that would allow for more efficient utilisation of resources. This will be discussed later in detail.





**Figure 7: Annual potential for wood resources from thinning operations. The first thinning after 17 years ends at around 2020, followed by a few years without scheduled thinnings and a second period of thinnings, which would create much higher amounts than earlier.**

For the assessment of the cost structure it is also important to analyse where the resources come from. In a later version of the model, a function will be added to allow drawing the boundaries of the “cost sheds” around a consumer location. In this version, however, the number of cells from which wood chips are available has been calculated year by year. This gives an idea on how distributed resources are, and on how many individual data points the statistics are based.



**Figure 8: Number of cells producing thinning resources, year by year. The number of cells is an indicator for supply diversity as well as statistical significance.**

Figure 8 shows the number of cells that can possibly supply wood to the demand location. Resource distribution is an indicator for supply diversity. A diverse supply is practically more stable, because a single failing supply unit means less need to find alternative supply. Likewise, a in a market situation it strengthens the position of the buyer to have many sellers to choose from. It can be seen that the supply diversity has to do with the number of cells that are mature in a given year.

The figure could also be produced for Hallormsstadur and Heradsskogar, separately. For Hallormsstadur the curve will be the approximate number of stands (of 1 ha size) to be thinned in that year. This would be valuable information for the forester. For Heradsskogar on the other hand, it means the number of farms being able to supply wood chips in a given year because Heradsskogar and Austurlandsskogar farms are treated as single cells. For the energy plant operator at Hallormsstadur it would be valuable to know how many possible suppliers there were in a given year, to assess supply safety and negotiate prices.

## ***8.2 Cost-supply analysis for a planned energy plant located at Hallormsstadur***

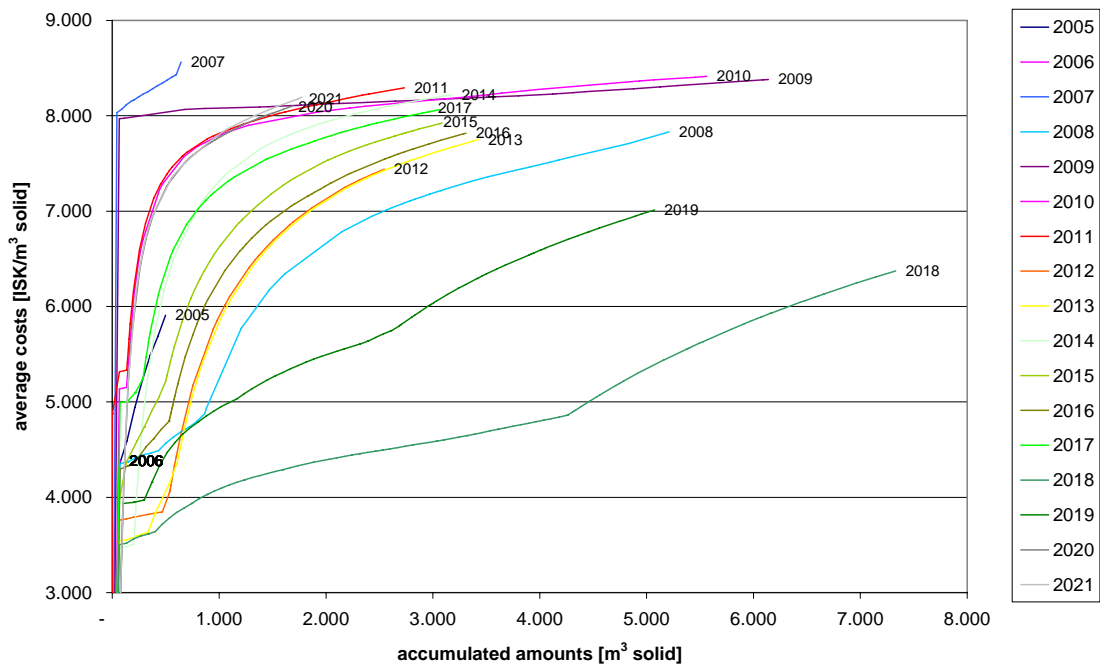
The costs of supplying a given location with a varying amount of wood fuel resources depends on the amounts of thinning residues and their location for the entire period. Cost supply curves have been produced for the years 2005 to 2021, see Figure 9.

The figure is complex and needs some explanation because so many data are included. First of all, the tendency of increasing costs with increasing demand at the Hallormsstadur location is clear. With every  $m^3$  that has to be brought in from further away, the costs increase with the distance. Also, there is a clear indication for a minimum cost, caused by the terminal time needed independent of the transport distance. The costs for a given amount of resources vary significantly year by year. The reason is that forest stands ready to be thinned are located in different areas every year. It follows that the variation of costs is induced by the pattern of afforestation.

The diagram also gives a clear hint on the additional costs for transporting resources from Heradsskogar, as some of the curves show a bend. This bend is located where the Hallormsstadur resources become exhausted and additional resources have to be hauled from further away.

As this analysis has only been carried out for one location yet, most of the cost curves have the same shape because the location of the demand is the same.

The costs for a consumption of wood fuels in the order of 500 to 2,000  $m^3$  solid per year vary by a factor 2, from about 4,000 to 8,000 ISK/ $m^3$  solid. Most cost curves seem to follow the same pattern of some logarithmic increase, where the cost increase most for the small amounts, while flattening out the higher the amounts grow. Some curves are very flat with only little increase for amounts over 1,000 – 1,500  $m^3$ . The curves for those years where only few resources are available do not look very “nice” because they have been based on very few data points only.

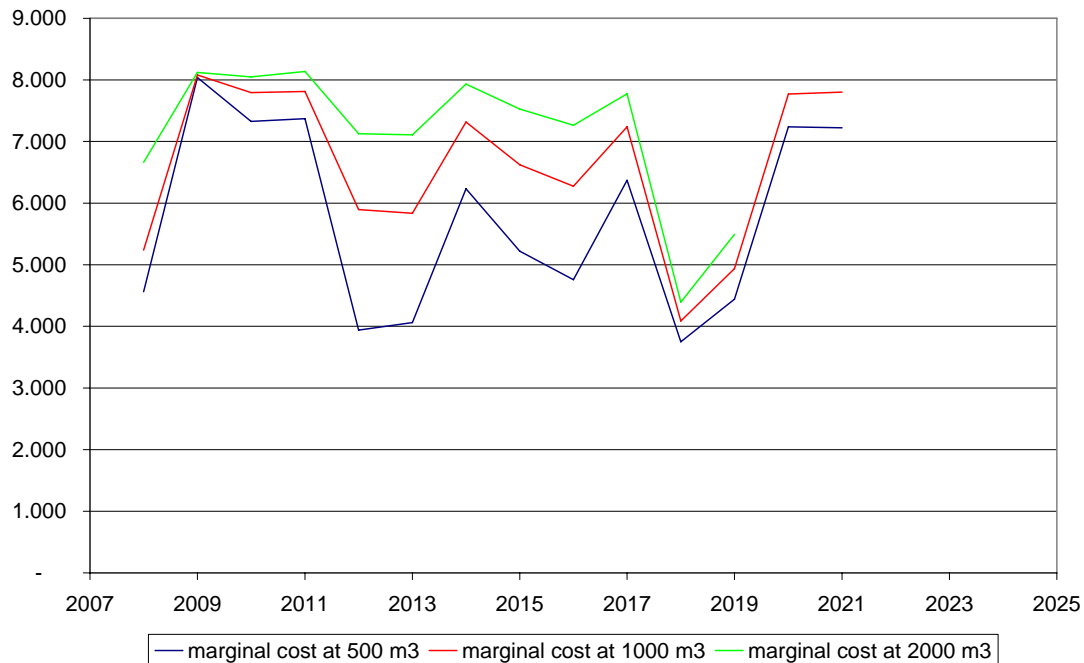


**Figure 9: Cost-supply curves for the Hallormsstadur location and for wood resources from Hallormsstadur and Heradsskogar forests. There is a clear tendency of increased costs for increasing amounts. A few years are outliers because of few available resources. A bend in the curves indicates the increase of costs when resources have to be imported from Heradsskogar.**

From the cost supply curves another form of diagram can be produced, where the marginal costs for supplying a given amount is shown year by year. This has been done for the period between 2008 and 2021, where supply was available and costs were representative (no outliers). Figure 10 shows the marginal costs of supply for 500, 1 000 and 2 000 m<sup>3</sup> solid annually for the Hallormsstadur location. As already shown with the cost-supply curves, the specific fuel supply costs increase with the annual demand. What can be seen from this figure, however, is that a smaller demand also means a greater variation of costs from year to year.

2008 - 2018  
 Average costs, [ISK/m<sup>3</sup> solid]  
 Standard deviation

**Table 2: Average costs and the standard deviation of costs for the period 2008 to 2018 for 500, 1 000 and 2 000 m<sup>3</sup> wood resources delivered to Hallormsstadur forest station. The average costs as well as their variation grow with increasing demand.**



**Figure 10: Marginal costs for supplying 500, 1 000 and 2 000 m3 annually to Hallormsstadur forest station. The higher the demand, the higher the costs, as also can be concluded from the cost-supply curves. When it comes to the influence of resource availability year by year, a smaller demand means a relatively higher sensitivity to costs.**

All in all, the level of the costs calculated with this version of the model has to be checked against real conditions. A few model adjustments are required. So far, travel distance only counts as single distance. The distance travelled is actually twice the lead distance between forest and location of demand. Secondly, the estimated terminal time needed to load and unload is rather low at 15 minutes for the forwarding process. The fixed costs of road transport, also including terminal time, have been set to zero in this version to have a clearer image of the influence of the distance factor. Finally, wood chipping and storage costs are not included in this model because data were missing. As these factors are location-independent, however, they could just be added as a factor of volumes.

### **8.3 Sensitivity analysis**

A sensitivity analysis on various factors is going to be carried out in the final phase of the feasibility study, when the model results are agreed upon in the project group.

### **8.4 Applicability of the model**

This chapter summarises the experiences made with the use of the model. Special attention is going to be on the use by other project partners.

## **9 Perspectives and recommendations for further development**

### ***9.1 Recommendations on data improvement***

Many data used for the project have major insufficiencies and errors. Of course these can not be taken care of at once and without careful planning. There are however a few data sets that could be improved with no big effort.

#### **Hallormsstadur forest maps**

Despite being the best available forest maps for the area, there seem to be a few things, which could be improved to achieve better results. First of all it should be considered to update the data for the stands containing Larch. Some of them lack data about the age; an estimated age would be much better than no data at all. Also the map could contain unmapped Larch stands, which also could be added without much effort.

An improved thinning residue model could be achieved with specific site index or growth curves. This would require the registration of the breast height diameter for the stands.

## 10 Conclusions

A forest to energy cost chain model was developed in a geographical fashion with spatially explicit locations of forests, conversion plants as well as energy demand. Forest production was modelled geographically using existing forest growth functions and available stand information. Distances between these locations across the available transport infrastructure, as well as the incremental costs were modelled using continuous cost surfaces. A combination of resources and costs results in spatial supply curves valid for a specific location.

The preliminary nature of forest resource estimation, forest growth modelling, and the assessment of costs associated to thinning, felling, in forest and road transport, chipping and other processes such as storage in Iceland make the development and application of spatial cost-chain model an uncertain business. The final findings and results of this study should be used to point out the necessity of the collection of better input data, as well as the high risk associated to enterprises of this kind.

The study was terminated because the flow of information between those project partners involved with the collection of actually experienced costs and wood resources turned out to be inefficient. There are therefore no further conclusions to make.

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## **Appendix 1: GRASP model operation**

### ***Copyright information***

The GRASP (Geographical Resource Assessment, Supply and Processes) model and its version for Iceland are copyright protected and the intellectual property of the author Bernd Möller (berndm@plan.aau.dk). The model must not be used outside the Northern WoodHeat project without asking the author for permission. Without the consent of the author the GRASP model, including the ArcGIS Toolbox and the model data, must not be given to people who are not affiliated with institutions that participate in the Northern WoodHeat project. The GRASP model, its methodology, design or results may not be published without consent from the author, who shall give proper scientific reference to published work and who may request co-authorship in scientific articles. The author has no responsibility for the results produced with the model and is not liable for errors in the model code, the input data, or other sources. The author is, however, thankful for reporting errors and suggesting improvements.

### ***Introduction***

The GRASP model is implemented using ArcGIS Model Builder. All models are hard-wired to Shape themes and Grids on certain hard disk locations in a folder on the c:-drive called NWH-GIS. If data are deleted or moved the models may stop to function. The model code is written in a Toolbox called GRASP Ice 1.x, which includes all models required to carry out the calculations mentioned in this report. The models can be edited as they are open-source, uncompiled scripts. Utmost care must be taken if the models shall be run from edit mode. Inexperienced users should run the models by double-clicking the model icons. In case alterations shall be made, it is highly recommended to copy and rename the Toolbox file.

### ***Requirements***

To run the models, ArcGIS version 9.0 with service pack 3 and Spatial Analyst is required. The models run on a pc with a Pentium III, 600 MHz processor and 320 MByte RAM, but a faster computer will speed up the computations considerably. The model needs up to 1 GByte space on the hard disk.

### ***Running the model***

The models need to be run in a certain order. Some of the more basic submodels produce data that are used in succeeding models....