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A mathematical model for infrastructure investments in the forest sector of coastal Norway

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ABSTRACT

Forestry in coastal Norway has traditionally been a marginal activity with a low annual harvest rate. However, the region is now faced with large areas of spruce plantations that will reach harvest maturity within the next 25 years. Due to the poor infrastructure in the region, the current challenge is to harvest the maturing spruce plantations at an acceptable cost. Hence, there is considerable interest both from the forest sector and politicians to invest in infrastructure that can provide the basis for profitable forest sector development in coastal Norway.

This paper presents a mathematical optimization model for timber transportation from stump to industry. The main decision variables are location of quays, upgrade of public road links, the length of new forest roads, and when the investments should happen. The main objective is to provide decision support for prioritization of infrastructure investments. The optimization model is combined with a dynamical forest resource model, providing details on available volumes and costs.

A case study for coastal Norway is presented and solved to optimality. The instance includes 10 counties comprising more than 200 municipalities with forest resources, 53 possible new quays for timber export and 916 public road links that also can be upgraded. Compared with a no investment case, the optimal solution improved the objective by 23%. The study shows that consistent, informative and good analyses can be performed to evaluate trade-offs, prioritization, time and order of investment, and cost saving potentials of infrastructure investments in the forest industry. The solution seems reasonable based on present infrastructure and state of the forest.

1. Introduction

The coastal parts of Norway consist of mountainous terrain with steep slopes, fjords and sparse road networks. In many parts of coastal Norway forestry have traditionally been a marginal activity with a low annual harvest rate (Fjeld et al., 2000). However, a large afforestation activity focused on spruce plantations was started in the 1950s. The spruce plantations thrive in the wet and mild coastal climate and have volume production per ha that surpasses that of the traditional forestry regions in the inland regions of Eastern Norway (Granhus et al., 2012). Given the afforestation history of the region with intense plantation establishment in the 1950 and 1960s the region is now faced with large areas of spruce that will reach harvest maturity within the next 25 years (Granhus et al., 2012). Hence, the region has the potential to strongly increase the annual harvest over the next decades.

Unfortunately, harvesting and transportation costs are in general high in the region. Coastal Norway is a fjord landscape with few shortcuts, and varying road quality. There is little tradition for forestry, and infrastructure related to forestry is poor compared to traditional forestry regions. In some parts of the Norwegian coast the average forest truck road density is as low as 4 m per hectare productive forest and the density of tractor roads is just under 10 m per hectare (Fjeld et al., 2000). This lack of forestry tradition may also be a reason why the fjords and sea to very little extent has been utilized for timber transport.

Coastal Norway includes 10 counties, comprising more than 200 municipalities (Illustrated in Fig. 3). The volume in Norway's coastal region has increased from 85 million m^3 in 1925 till 300 million m^3 in 2015 (Øyen, 2008). Due to the poor infrastructure in the region, the current challenge is to harvest the maturing spruce plantations at an acceptable cost of harvesting and transportation. Hence, there is considerable interest both from the forest sector and politicians to invest in infrastructure that can provide the basis for profitable forest sector development in coastal Norway.

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Table 1
Data sources for the forest map.

Data source	Priority	Method for production	Year	Forest area the in the merged map (km^2)	Reference
Forest management plans	1	Lidar with manual tree species classification	1997–2013	4000	
SR16	2	Photogrammetry with NFI plots as ground truth	2010	1600	Rahlf et al. (2017)
SATskog	3	Landsat kNN map	1999–2004	4000	Gjertsen (2007)
AR5 with average values	4	Field work and aerial photo interpretation	1966–	800	The Norwegian Mapping Authority (2016)

The basis for the presented paper is a method that will help support prioritization of potential infrastructure investments in coastal Norway in order to support the development of a large and profitable forest sector based on the maturing plantation forests. Potential investments include both roads and quays for shipping timber, where Coastal Norway has large advantages and potential due to the long coast line.

Many papers have been addressing problems related to operations research in forestry applications. For an overview of the area see D'Amours et al. (2008) and the more recent work of Rönnqvist et al. (2015). Applications range from short term operational problems during harvesting to long term strategic forest management problems.

Integrated approaches combining harvesting planning and logistics exist for several applications with Weintraub and Navon (1976) being one of the first examples. The Swedish situation has been considered in several papers (Henningsson et al., 2007; Karlsson et al., 2006) where forest road upgrading is a key aspect. With a very detailed representation of the road network and the harvesting areas, they face large scale mixed integer problems that cause computational challenges and must be solved with specialized solution approaches (Flisberg et al., 2014).

The current paper, while sharing aspects with previous applications, introduces several new elements into the integrated approach. The planning horizon of 25 years is longer than what is typically considered and allows the introduction of network design choices. This includes when and where to build new quays as well as the option of upgrading links in the public road network to allow larger trucks. We also include the effect of building new forest roads and explicitly model the associated harvesting cost reductions. The work builds on and extends the model presented in Nørstebøÿ and Johansen (2013).

The main objective is to provide decision support for prioritization of infrastructure investments. The study area is large (more than 200, 000 square kilometers), covering about 60% of Norway. The presented study consists of two components; A forest resource model providing information on resource availability and harvesting costs for a given forest road network. The second component is an optimization model that given the input from the forest resource model finds optimal harvesting, investments in forest roads, public road network bottlenecks, and quays for timber export, across time and space while maximizing profit.

In the following section, we describe the methodology developed in this study. Section 3 demonstrates the use of the model, describes the case study and discusses selected results and outlines wider perspectives. This leads to summarizing and concluding remarks in Section 4.

2. Methodology

We solve the problem outlined in Section 1 through four steps; (1) modelling forest resources and development over the time horizon, (2) modelling the transport network, (3) develop an optimization model for the system, and (4) application of the model to a case study, and discussion of the results, and how they can be used as decision support for infrastructure investments in forestry in coastal Norway.

In the following, we describe these steps in more detail.

2.1. *Modelling and mapping of forest resources*

As input into the optimization model, the forest resources were mapped and modelled through a six step procedure; (1) collection of information on existing and potential roads, (2) collection and merging of the best available forest data into a single resolution, (3) temporal harmonization and calibration of the forest data, (4) forecasting of the forest resources, (5) division of the forest resources into harvesting cost classes, and (6) summarizing of the forest resources by municipality.

(1) Collection of information on existing and potential roads
was carried out using the national road database and municipality forest road plans, respectively. In about half of the municipalities detailed plans (with variable quality and completeness) for potential new forest roads existed in digital form. All these plans were gathered into a single GIS layer with the existing roads.

(2) Collection and merging of the best available forest data into a single resolution
was done using four different sources (Table 1). For areas where more than one data source was available, the data source with the assumed highest accuracy was utilized (highest priority in Table 1).
Once the data source with the highest priority was identified for the full study region, the data was resampled to 16 by 16 m pixel map (which is the original resolution and format of SR16 in Table 1).

(3) Temporal harmonization and calibration of the forest data
was necessary, as the forest information originated from different years and data sources (Table 1). Initially data set specific biases in SR16 and SAT-skog were identified by comparison in areas overlapping (high quality) forestry plan maps, and corrections were made to some strata. In particular the volume on high site index was underestimated in SAT-skog, and the stand age tended toward mean values. The next step was to standardize all data sources to the base year (2015) which was done in two steps, first the standing timber volume of all pixels were forecasted to the base year using simple lookup tables, as described in Antón-Fernándes and Astrup (2012), with age and site index as index variables and the actual increments based on Norwegian NFI data (Tomter et al., 2010). Finally, the standing volume in each region was calibrated to match the official statistics from the National Forest Inventory (NFI) (Tomter et al., 2010) at the base year. The calibration was done in order to reduce bias that had occurred during the forecasting and merging of datasets.

(4) Forecasting of the forest resources
was done using the previously described simple lookup tables. From the base year the forest volume was incremented (year by year) as a function of site index and age. Thus, both volume and area of mature forest would increase. The growth of aged forest stop at a limit, but harvesting was not modelled here (it is decided in the investment model (2.3)). The status at the end of each 5-year period was stored as separate maps and volumes, and used in the cost calculations.