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Sensitivity analysis in long-term dynamic building stock modeling—Exploring the importance of uncertainty of input parameters in Norwegian segmented dwelling stock model

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ABSTRACT

Models describing long-term development in energy consumption or greenhouse gas emissions from building stocks commonly model the underlying development in the building stock's size and composition using simple, linear trends. Uncertainty is rarely discussed. This study explores the importance of uncertainty in input parameters in a dynamic model for the Norwegian dwelling stock that is presented in a recent publication and provides valuable insights in expected future quantities of renovation activity and how different segments of the stock are subject to renovation. By use of a sensitivity analysis and a scenario analysis the present study focuses on how uncertainty in model input parameters affect the modeling results and the robustness of results and conclusions. The sensitivity analysis did not lead to unexpected changes in results, and showed the dynamic model being mostly sensitive to changes in population and dwellings' lifetime. Further scenarios with extreme input values for population and dwellings' lifetime were considered in order to investigate the consequences of low and high renovation options. Results prove that previous main conclusions still hold: renovation rates at levels necessary to achieve policy targets in energy and emission savings seem unrealistic to be achieved when modeling the 'natural' need for renovation.

1. Introduction

Models describing long-term development in building stocks are commonly used as a basis for estimating long-term changes in energy consumption, greenhouse gas emissions, material demand and waste flows from building stocks. Standard linear models assume fixed rates for annual construction, demolition and renovation activities, based on recent trends or political goals (e.g. [1–4]). However, in a long-term perspective such activities are highly dynamic, depending upon changing external drivers and changing age composition of the building stocks. Dynamic building stock models will better account for such changes and introduce additional input parameters to describe the future expected building stock characteristics, compared to standard linear models.

When using building stock models as basis for analyses of energy demand, emissions or material flows, the results of the building stock model itself are commonly hardly described (e.g. [5,6]), although they are highly important for the final results of the analysis. All models trying to describe future development have uncertainty in the input parameters. It is therefore crucial to try to understand the importance of the uncertainty: how does it affect the final results and how robust are the conclusions of a study?

Long-term modeling is of course subject to uncertainty in assumptions and input parameters. Such uncertainties include external drivers and factors, like socio-economic, demographic and regulatory factors, as well as stock-internal factors, such as stock size and composition, technologies applied over time, ageing structure and building lifetimes/mortality and renovation cycles. High uncertainty in important parameters should be avoided, as this may destroy the quality of the model and the robustness of results, conclusions and recommendations.

To the knowledge of the authors, there is no standard building stock model that includes any kind of uncertainty analysis of the stock-internal factors or the results of the building stock model

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itself. Some studies, however, include uncertainty analyses or scenario analyses on the assumed renovation rates [6,7], concluding that the energy savings in the stock highly depend on the assumed renovation rates.

Other studies, e.g. Booth et al. [8] and Booth and Choudhary [9] study the uncertainty of proposed energy consumption and energy savings potential of predicted retrofit measures in bottom-up housing stock models. Famuyibo et al. [10] use a statistical analysis for reducing the uncertainty in energy demand when developing archetypes for domestic dwellings. Kavgic et al. [11] study the uncertainty in energy consumption as well as in corresponding greenhouse gas emissions in a housing stock model. They conclude that the uncertainty in stock model predictions can be large and demonstrate the importance of sensitivity analyses to support model estimates.

A dynamic dwelling stock model using time series in underlying drivers, such as population and average number of persons per dwelling, has previously proven useful when analyzing the long-term development of dwelling stock demand, construction, demolition and renovation activities [12–14], of material demand and waste flows [12,13], of energy demand and greenhouse gas emissions [15,16,17] and of earthquake vulnerability [18]. The latest development of such modeling is Sandberg et al.'s [19] segmentation of the dwelling stock in dwelling types and construction periods. Stock segmentation is a powerful modeling approach since it allows for allocating different characteristics to each of the different building types and age cohorts (construction periods), which is necessary to capture the large differences in building traditions and technology over time. It also offers the opportunity to examine how selected type/age segments develop over time. The latter is indeed important when studying energy consumption and greenhouse gas emissions from building stocks over time, for instance in response to different refurbishment strategies in the past or in future.

The input parameters used in the model in the study by Sandberg et al. [19] are (1) socio-economic and demographic factors influencing the demand for dwellings, population, the number of persons per dwelling and the share of the population living in each dwelling type, as well as (2) technical indicators influencing the dwelling stock itself, buildings' lifetime and renovation intervals, including their respective probability functions. Further applications using the segmented dynamic dwelling stock model for modeling future energy demand will additionally require input parameters like average floor area, average energy demand and expected future development in energy standard of new and renovated buildings.

According to the energy performance of buildings directive [20], energy-efficiency measures should be included when buildings are going through deep renovation in any case. Sandberg et al. [19] demonstrated which building stock segments that are most likely to dominate the renovation activity in the coming decades. Further they concluded that renovation activity resulting from the building stock's need for maintenance due to the age composition of the stock is expected to increase in the future, deep renovation to a level of about 1.5% in 2050. This is still far below renovation levels assumed in scenario studies, political action plans and roadmaps, which are commonly in the range of 2.5–3% by 2030 (e.g. [6,21]). The main objective of the present paper is to study the importance of uncertainties in input parameters in the dynamic segmented dwelling stock model from Sandberg et al. [19] and how uncertainties influence modeling results and robustness of conclusions.

The uncertainty of input parameters in fairly similar types of dynamic dwelling stock models is somewhat covered in other studies [12–14,18]. Their main findings are that even when varying the input parameters, the presented scenarios show rather robust in their general trends, and that lifetime is an input parameter of high uncertainty and of high sensitivity to the resulting activities in the system. Gallardo et al. [18] apply a dynamic model on a case study of earthquake damage of Chilean dwellings, and conclude that even though the uncertainty of input parameters affect the results, the main conclusions of their study are not changed. Sandberg et al. [16] varied energy need per square meter in their model, and concluded that results were by far more sensitive to changes in the efficiency of the heating system than to changes in intensities for embodied energy and appliances.

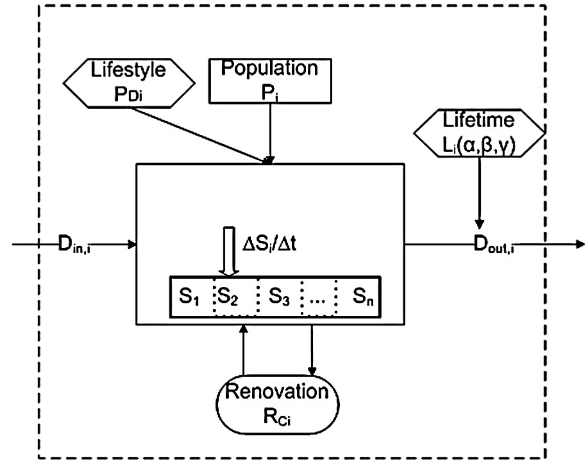

Fig. 1. Conceptual outline of the segmented dynamic dwelling stock model.

Since there is still a limited number of building stock dynamic studies published, and since they did not include in-depth analyses of modeling uncertainties, there is yet much to learn on this topic. The present study is a sensitivity analysis for the dynamic segmented dwelling stock model applied for Norway, described in Sandberg et al. [19]. The aims of the paper, therefore, are to:

- Investigate the uncertainty in stock-internal parameters of the dynamic Norwegian dwelling stock model [19] and identify their importance on the results of the model.
- Demonstrate the importance of the uncertainties on the final results of model in two additional scenarios.
- Study if political targets regarding future renovation rates are likely to be reached given the ranges of possible renovation rates that are resulting from the scenario analysis.

2. Methodology

2.1. Model description

The dwelling stock is segmented in dwelling types and age cohorts. For all years the model aims at describing the development in annual dwelling stock demand and the annual construction, demolition and renovation activity, in each segment. The conceptual outline of the segmented dynamic dwelling stock model applied by Sandberg et al. [19] is shown in Fig. 1. The core of the model is the population's need to reside: each year the population P is divided by the average number of persons per dwelling P_D to estimate the total demand for dwellings, as shown in Eq. (1). The index i in Fig. 1 and Eq. (1) indicates the input parameters, dwelling stock demand and activities in segment i of the stock.

$$S_i(t) = \frac{P_i(t)}{P_{Di}(t)} \quad (1)$$

Further, a demolition probability function DEM is used to estimate the demolition activity. Each year, the number of dwellings demolished $D_{out,i}(t)$ is estimated based on historical construction activity and the probability of a dwelling to be demolished a certain