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Dynamic building stock modelling: General algorithm and exemplification for Norway

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ABSTRACT

This paper presents a model based on dynamic material flow analysis, general in its principles and applied to the dwelling stock of Norway for exemplification. The algorithm at the core of the model is presented in the form of a pseudo-code and is described in detail. The driving force in the model is a population's need for housing and the necessary input are retrievable from national statistics on population, often dating back to around 1800, and its prognoses up to 2050 or beyond. Technical parameters such as the dwellings' lifetime and the renovation cycles are expressed by probability functions. Outputs of the model are the flows of construction, demolition and renovation; analysis of the renovation activity is given particular attention. The model shows how the renovation rates are a result of the need for maintenance of an ageing stock, and provides quantitative estimates of the present and future natural renovation rates, i.e. without specific incentives. The paper shows how to validate the model against statistics and other data sources, and how to use the model's future projections on construction, demolition and renovation activities in scenario based analyses of dwelling stocks' energy demand and greenhouse gases emissions.

1. Introduction

Buildings account for 40% of energy use in the EU [1] and for about one third of both energy use and greenhouse gases (GHG) emissions in OECD countries [2,3]. The building sector is therefore important for the mitigation of climate change. The EU roadmap to a low carbon economy sets a decarbonisation target for the building sector at 88–91% by 2050, compared to 1990 values [4,5].

When forecasting energy demand or GHG emissions from a dwelling stock it is important to use a good model for the development of the dwelling stock itself, i.e. total amount of dwellings or floor area, in addition to analysing possible changes in energy or GHG emission intensities, i.e. energy or emissions per square metre of floor area.

However, it is often found that policy roadmaps and other studies use rather detailed information on energy and emission intensities, whereas the development of the dwelling stock itself – in terms of number of dwellings or floor area – is modelled using simple assumptions such as fixed rates for construction, demolition and renovation [6–17]. Some study even seems not to consider changes in the stock composition at all [18]. Other studies make use of population forecasts to estimate the future need for dwellings, but make use of recent trends for estimating demolition and renovation activity [19–21]. Renovation rates are often assumed to increase rapidly and significantly in order to reach the energy efficiency goals for the stock. For example in Ref. [22] it is assumed that the average EU renovation rate, currently estimated at around 1%, will have to increase to more than 2.5% by 2020 and be stable thereafter in order to reach the EU 2050 roadmap decarbonisation target. Similarly, in Ref. [23] it is assumed that the renovation rate should step up to 2.3% or even 3.0% (depending on scenarios) already from 2015 in order to meet the EU policy goals by 2050.

All this may be regarded as static modelling, as opposed to dynamic dwelling stock modelling where future developments are mostly the consequence of past activities, the resulting effects of an ageing stock in need of maintenance and trends in underlying driving forces such as population development and standards of living.

A dynamic stock model was first developed by Müller [24] to analyse the Dutch dwelling stock. Based on dynamic Material Flow Analysis (MFA) principles and the underlying drivers in the dwelling stock system (population, floor area per capita, buildings' lifetime and material intensity per unit of floor area), the total floor

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area and materials demand were estimated for each year in the period 1900–2100. The floor area was modelled as the basic layer and the demand for materials as an additional layer. The demolition activity was estimated based on historical construction activity and a lifetime probability function, and the construction activity was calculated using mass balancing principles. Material flows were estimated using material intensities. The model was modified and applied to the Norwegian dwelling stock by Bergsdal et al. [25] and further developed by Sartori et al. [26] in order to model the renovation flows in an explicit way.

Similar dynamic dwelling stock models have also been used for studies of the Chinese dwelling stock [27–29]. Energy and carbon intensities were also introduced as additional layers of the models by Sandberg et al. [30,31] and by Pauliuk et al. [32]. The former analysed the long term development in energy demand and GHG emissions in the Norwegian dwelling stock; the latter studied transformations needed in the Norwegian dwelling stock to reach the 2 °C target. Further advances in the modelling consisted in segmenting the building stock in cohorts (construction periods) and building types Sandberg et al. [33,34].

The present methodology is based on the work previously done in the field, particularly on [26] though with some differences. In line to what first done in Ref. [33] the present work models the dynamics of the dwelling stock measured in number of dwellings rather than in floor area. This way one of the most uncertain input parameters, the average floor area per dwelling [25], is removed from the core of the model; while it remain simple to add it as an additional layer of the model in a later stage as it is done in Sandberg et al. [35]. Another difference is that the stock is divided in several cohorts.

This paper presents a detailed mathematical description of the dwelling stock model, showing the algorithm at the core of the model in a pseudo-code. The purpose of making the model's algorithm openly available is to provide a sound and transparent basis for applying the model in other studies and to the national dwelling stocks of other countries.

The model presented herein is general in its principles and is applied to the dwelling stock of Norway just for exemplification. This model is applied to 11 European countries in Ref. [36], where the resulting renovation rates towards 2050 are in the range of 0.6–1.6%; substantially below the level of 2.3–3.0% that should be attained already by 2020 in order to achieve the EU 2050 roadmap decarbonisation target for the building sector according to [22,23].

The model can serve as the basis for a range of applications, such as the analyses of energy use and greenhouse gas emissions, material demand and waste flows as well as market opportunities for component substitution. Many energy efficiency measures are cost efficient only if performed when a building is undergoing a deep renovation in any case. The present model aims at describing what renovation rates can be expected based on the characteristics of the dwelling stock and its need for maintenance.

The present paper does not include an energy demand or GHG emission analysis per se, as this requires a large amount of additional data and calculations. Such a study is presented in Ref. [35] where additional layers of floor area and energy intensity are added to this model in order to analyse the historical development of the energy demand in the dwelling stock of Norway from 1960 to 2015 and study phenomena and causes behind it. The following step, which is left for future work, would be to use the estimates of future construction, renovation and demolition flows from this model in order to investigate possible scenarios for the evolution of energy demand and GHG emissions from the Norwegian dwelling stock towards 2050.

2. Methodology

Dynamic Material Flow Analysis (MFA) is the methodology at the basis of the model presented here for studying the long term development of a dwelling stock. The driving force in the model is a population's need for housing and the necessary input are retrievable from national statistics on population, often dating back to around 1900 and earlier, and its prognoses up to 2100. Technical parameters such as buildings' lifetime and the frequency of renovations are expressed by means of probability functions. Outputs of the model are the flows of construction, demolition and renovation for the total dwelling stock and for each of the cohorts. Results from a detailed dynamic model like this can be used to estimate the natural turn-over and renovation rates in the dwelling stock, under different assumptions on the renovation cycle.

2.1. Mathematical model

A schematic representation of the model is given in Fig. 1, which shows how input data series (population, P, and Persons/dwelling, P_D) and parameters (demolition function, p_{DEM}, and renovation functions, p_{REN}) are combined, by means of equations, to generate output time series. The model's output time series are the flows of new construction, D_{new}, demolition, D_{dem}, and renovation, D_{ren}, activities. Several renovation functions may be considered, each with a different renovation cycle, e.g. 20, 30 and 40 years, referring to different types of renovation activities, such as replacement of equipment, envelope elements and full renovation, respectively. That explains using the plural when referring to the renovation activity, though in the following equations only one renovation flow is considered, for simplicity and readability reasons.

The equation set is explained below and the number in parenthesis in Fig. 1 is the number of the corresponding equation. Bold shapes in Fig. 1 represent variables that are obtained in an iterative process; see algorithm in Appendix .

A simpler visualization of the model's structure is given in Fig. 2 that emphasizes the connections between inputs, stock and flows while overlooking the actual equations linking the variables. It is useful to introduce this conceptual representation here since it is the same type as used in Ref. [35] (with additional layers) and [36], which are both presented in this issue and based on the model explained here.

2.1.1. Equation set

Convolution is a mathematical operator between two functions f and g, denoted as $f*g$, that expresses the amount of overlap resulting as one function is shifted over the other. The convolution between f and g in the discrete domain is formally written as:

$$(f * g)(n) = \sum_m f(m) \cdot g(n-m) \qquad (0)$$

Table 1 shows the equations used in the model. Eq. (1) is performed on the whole input data series; Eqs. (4) and (5) refer to input parameters (not time series). Eqs. (2), (3) and (6) refer to input and

Table 1
The model's set of equations.

$S_D = P/P_D$	(1)
$\Delta S_D(i) = S(i) - S(i-1) = D_{new}(i) - D_{dem}(i)$	(2)
$D_{dem}(i) = D_0(i) + (p_{DEM} * D_{new})(i)$	(3)
$L = 1 - CDM(p_{DEM})$	(4)
$p_{REN\_cycle} = \sum_{k=1}^{K} p_{REN}(k) \cdot L(\tau)$	(5)
$D_{ren}(i) = R_0(i) + (p_{REN\_cycle} * D_{new})(i)$	(6)