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Environmentally optimal wood use in Switzerland—Investigating the relevance of material cascades

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ABSTRACT

This study assesses the environmentally optimal wood utilisation patterns under varying wood cascading options, using the example of Switzerland. Cascading is the use of the same wood unit in multiple, successive product cycles. To consider aspects relevant at the system level (e.g. stocks/flows, demand/supply constraints) as well as at the product level (e.g. process inventories), we present a model that combines material flow analysis (MFA), life cycle assessment (LCA) and mathematical optimisation to identify environmentally optimal wood use scenarios concerning climate change and particulate matter formation. We separately include the temporal dynamics of biogenic carbon flows, i.e. carbon uptake, storage and subsequent release, which may have a considerable influence on the climate change performance of wood products.

Results indicate that multiple cascading (mC) of wood can decrease environmental impacts: total systemic impact reductions over the modelled 200-year time horizon compared to single cascading (i.e. all waste wood is directly incinerated), are between 35–59 Mt CO_2-eq. and 43–63 kt PM10-eq. Driving factors for the environmental impact of future wood use scenarios are: waste wood processing efficiency, wood storage effects (in case of biogenic carbon accounting), and available cascading options. Particularly, high quality wood cascade of wooden beams is a promising recycling path for reducing environmental impacts.

We conclude that by implementing wood cascading, future Swiss wood utilisation can be further improved in terms of environmental impact. The tool combination of dynamic MFA, LCA and optimisation proved to be suitable to identify environmentally optimal scenarios for a complex value chain.

1. Introduction

Wood serves as a raw material for a wide range of products and may also be used for energy purposes. It is therefore of particular interest to define national strategies for wood's efficient and ecological use (Werner et al., 2010; Mantau, 2014; FOEN et al., 2014). Due to its versatility, wood can substitute fossil energy carriers as well as conventional building materials such as concrete, steel and brick. As wood-based products are often found to have lower environmental impacts than functionally equivalent products from fossil or mineral sources, an increased use of wood might lead to substitution benefits (Werner et al., 2005; Gustavsson et al., 2006; Sathre and O'Connor, 2010). In addition, long-lived wood products act as a carbon stock during their service life and therefore contribute to the mitigation of climate change (Taverna et al., 2007; Werner et al., 2010; Cintas et al., 2015; Jasinevicius et al., 2016).

After Sirkin and ten Houten (1994), introduced the resource cascade concept, several recent studies have dealt with the potential benefits of cascading uses of wood, i.e. for multiple successive product cycles, first for material uses (typically with decreasing quality requirements) and finally for energy. Sathre and Gustavsson (2006) analysed energy and carbon balances of various wood cascade chains under different post-recovery options by considering direct cascade effects, substitution effects and land use effects. The authors concluded that wood cascading leads to carbon and energy balance benefits, predominantly through land use and substitution effects. Höglmeier et al. (2013) assessed cascading potentials of recovered wood from building deconstruction in Southern Germany and found considerable amounts of recovered wood in suitable condition. In a subsequent study, Höglmeier et al. (2015) then performed a systemic LCA-based optimisation of wood utilisation in the same region. Environmental benefits of cascading were determined for all the environmental impact categories considered, most notably for particulate matter formation and land occupation. However, particle board is the only recycling option of post-consumer wood included in the study. Also, temporal aspects regarding carbon emissions and storage are not considered.

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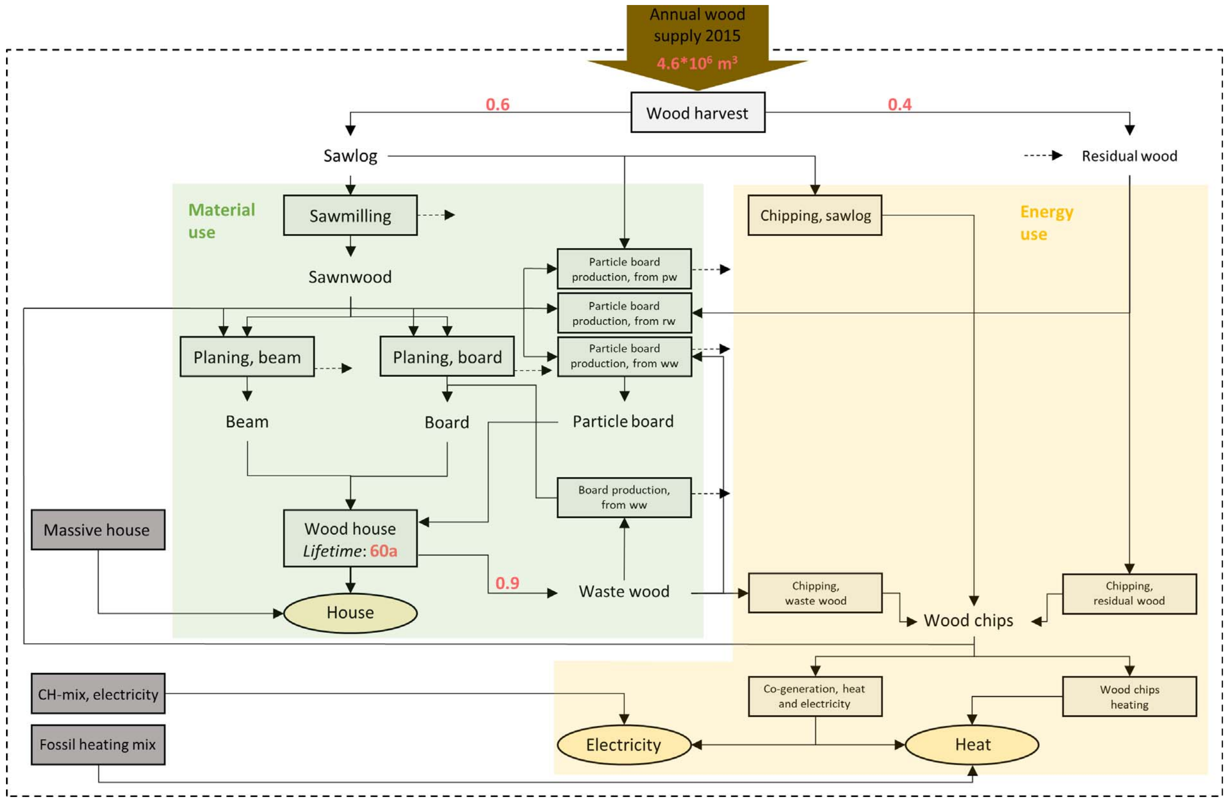

Fig. 1. Schematic overview of the wood flow model and associated assumptions (in red, Sections 2.1.1–2.1.3) as well as non-wooden substitution modules (rectangular grey boxes, Section 2.1.5). Yellow ellipses represent product demand (Section 2.1.4). Intermediate products are displayed as labelled arrows. Dotted arrows represent wood processing residues. Further (non-wood) material flows entailed by the corresponding LCA processes are provided in the *Supplementary data*.

The method chosen by most studies to assess environmental impacts of wood processing and wood products is life cycle assessment (LCA) (Werner and Richter, 2007; Rüter and Diederichs, 2012; Sathre and González-García, 2014; Cambero et al., 2015). Klein et al. (2015) reviewed LCA studies of wood production and utilisation published in the past 20 years and concluded that, despite significant differences in the results, LCA is a well-established methodology to assess environmental impacts of the wood value chain.

However, assuming wood as carbon neutral may be problematic, as highlighted in the 5th IPCC report (Myhre, 2013). Brandão et al. (2012) reviewed six methods accounting for the potential climate impacts of carbon sequestration and temporary storage or release of biogenic carbon in LCA and carbon footprinting (CF) and identified that possible benefits depend on the time horizon and thus include value judgements. Cherubini et al. (2011) introduced a method to calculate the contribution of biogenic carbon emissions to global warming based on the timing of emissions, the sequestration of the forest, and the atmospheric CO_2 decay. The authors show that the temporal dynamics of carbon uptake in the forest, subsequent storage and eventual release through wood combustion strongly influence the global warming performance of wood products. Guest et al. (2013a) extended Cherubini's emission factors by including carbon storage benefits in case the harvested wood remains stored in products over a longer time period before its eventual combustion. Both studies proposed that these emission factors could be applied in LCA studies. Other studies assessing climate effects of increased bioenergy use underline that results strongly depend on biomass species, local forest management and local climate variables (Cherubini et al., 2012; Cintas et al., 2015). Yet, the potential climate effect of biogenic carbon is rarely accounted for in LCA-studies assessing the impacts of wood utilisation patterns (Werner and Richter, 2007; Höglmeier et al., 2015; Thonemann and Schumann, 2017).

Despite being a renewable resource, wood availability at any given time is limited. A systemic approach is thus needed to identify optimal wood allocation amongst competing uses. Therefore, this explorative study combines a dynamic material flow model containing flows and stocks of the most important wood use options for the case of Switzerland with an LCA-based optimisation problem formulation including process inventories and life cycle impact assessment (LCIA). We hereby account for aspects relevant at the system level such as stocks and flows, detailed process models and environmental impact assessment as well as constraints to identify environmentally optimal utilisation patterns. In addition, the temporal scope of the model enables for assessing the dynamics of biogenic CO_2 emissions, including storage effects of long-lived wood products, in the context of multiple successive product applications (cascade uses). This study discusses optimal wood utilisation patterns obtained under different constraints and provides insight into the most sensitive parameters for an environmentally optimised wood use in Switzerland.

2. Method and approach

To address the aforementioned research objectives, we combine three tools: dynamic material flow analysis (MFA), life cycle assessment (LCA), and mathematical optimisation. A high-level dynamic MFA model depicts archetypes of the most important wood use options in Switzerland and describes the material input and output flows of the related processes (here denoted *modules*). To calculate the environmental burdens associated with these MFA processes, we apply the modular LCA approach of Steubing et al. (2016), where several LCA processes can be combined into modules, reflecting the broader level of abstraction often found in MFA models. The product flows to and from each module, as well as its environmental impact, are stored in a spreadsheet-based module-product matrix. This matrix is then used within an optimisation model to identify environmentally optimal wood use options. This allows us to calculate the total environmental impact of the system over the modelled time horizon for different LCIA