Ecological use of wood resources in Switzerland: an overview from the Swiss National Research Program (NRP) 66

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1. Overall project aims

Wood resources are scarce and can at the same time be used for many applications ranging from construction, components, pulp and paper, and chemicals to energy. In order to make optimal use of wood from the environmental perspective the project "*Ecological use of wood resources in Switzerland*", which is part of the Swiss National Research Program 66 (NRP66) (http://www.NRP66.ch) aims at identifying strategies for a sustainable management of wood resources in Switzerland.

To achieve this and provide results and recommendations relevant for policy making, decision makers in the wood industry and forest management, technology developers, as well as the scientific community, the project aims at:

1. **Modeling of wood value chains**: assessing current and future wood use scenarios by combining material flow analysis (MFA) and life cycle assessment (LCA) in a dynamic model of Swiss wood-based value chains (including cascade use, substituted products, policy incentives, etc.)
2. **Modeling buildings and the building sector**: highlighting ecological potentials of wood as a construction material for the future building stock and comparing it to other material, such as brick and concrete, while taking into account the interaction of energy and material use in the building stock.
3. **Technology assessment**: establishing process models of new technologies in the forestry and wood sectors in collaboration with other modules of NRP66 and providing capacity building and environmental hot-spot analyses
4. **Further development of impact assessment methodology**: improving current life cycle impact assessment (LCIA) methods to capture all major environmental impacts of associated with wood-based value chains

2. Modeling of wood value chains

Wood is a versatile material, which can serve many different functions such as material or energy use and as a consequence there are many different possible wood value chains. The challenge is to capture these possibilities in a model, which relies on the one hand on real data for the many different processes along the wood value chains (sophistication) and on the other hand finds a suitable level of abstraction in order to communicate the results and derive strategies (comprehensibility).

There are several **specific aims** to developing a model of wood value chains:
1. To **model wood flows**, e.g. "as they are in the real world" or "as they could be in the future"
2. To **evaluate environmental impacts** and benefits associated with these wood flows
3. To **identify environmentally optimal wood value chains** by using scenario analysis and optimization techniques and to provide policy recommendations

2.1. Methodology

In order to realize these different aims, the wood value chain modeling builds on different models and modeling techniques (as illustrated in Table 1). The **modeling of wood flows** aims principally at depicting either how wood is managed currently or in the future. The methodological framework for this is material flow analysis (MFA), which relies on mass balances of wood flows. This data is collected from different available studies and expert knowledge. Further, data reconciliation methods may be used where the collected flow data is contradictory, to ensure the mass balance throughout the system. Different wood use scenarios have been used in recent literature, e.g. (Hofer, Werner et al. 2007), and will be used in our model. New scenarios may additionally be defined together with different stakeholders.

The modeling of wood flows provides the basis for the **environmental evaluation of wood value chains**. Additionally to the MFA perspective all processes in the model will be associated with life cycle inventories, which are obtained from the ecoinvent database (Ecoinvent 2011) and the technology assessment (see 4). This enables a system-wide analysis of the environmental impacts associated with the modeled wood flows.

As the model is dynamic, carbon flows will also be modeled over time and a distinction will be made between biogenic and fossil carbon sources. A consistent methodological approach is currently being defined based on several recent publications, e.g. (Levasseur, Lesage et al. 2010; Cherubini, Bright et al. 2013).

The focus of the model is on the production and use of wood products within Switzerland. However, the environmental impacts of different harvesting and wood products manufacturing processes across the globe may vary significantly. Not considering the international trade of wood products increases therefore the uncertainty related to recommendations for an optimal wood use (Werner, Taverna et al. 2010). For this reason, we aim at linking our model for Switzerland to models of international wood trade as well as life cycle inventories for harvest and manufacturing practices in selected countries (the exact approach this needs to be identified as part of an ongoing PhD thesis).

Finally, we will not only assess different wood use scenarios but also aim at **identifying optimal wood use value chains** (e.g. certain use cascades) from the many possible ways of utilizing wood. In order to realize this, the entire model will be formulated as a system of linear equations. This is possible as also MFA and LCA can be expressed as systems of linear equations. As a consequence, we will be able to apply linear optimization techniques to determine optimal wood use scenarios over time (and possibly space) and under varying constraints. Examples for constraints are supply and demand (for the different scenarios), industrial capacities, stocks, policy measures or legal requirements. The objective of the optimization will be the minimization of environmental impacts. As LCA is usually dealing with multiple environmental impact categories, which cannot be directly compared (e.g. global warming and biodiversity loss), we will use multi-objective optimization or similar approaches to identify Pareto-optimal solutions for different environmental criteria at the same time.

Table 1: Different modeling objects and methods used in the wood value chain model

Modeling object	**Modeling method(s)**
Material flows (wood and wood products)	Material Flow Analysis (MFA) Data reconciliation
(Future) scenarios	Scenario development techniques
Life cycle inventories and associated environmental impacts	Life Cycle Assessment (LCA)
Carbon flows and stocks (dynamic and biogenic)	MFA / LCA (possibly with modifications)
Trade with other regions / countries	General / partial equilibrium or Input-Output Models
Material flows and the use of different parts of wood value chains under constraints	Mathematical optimization

The work has so far concentrated on developing a model structure that is compatible with these different modeling techniques and requirements and which is flexible enough to include new technologies in an efficient way into the model. A key element in this is a process-products matrix, which is similar to the matrices used in input-output (IO) modeling, MFA and LCA. However, in contrast to the matrices used in IO, MFA and LCA, it can be a rectangular matrix, describing the inputs and outputs of individual processes in the modeled system and thereby possibilities of linking these into a process system rather than a fixed linking of processes (such as in LCA, MFA and IO). This matrix is complemented by other matrices, e.g. for stocks, environmental impacts, and constraints. Within this system of matrices, information can be specified in a way that MFA, LCA and linear programming can be conducted at the same time.

2.2. Example of a simple wood value chain model

To **illustrate the above**, a **simple model** was constructed, which contained a material and an energy use of wood as well as alternative technologies (concrete house and fuel oil heating). The given technologies must fulfill the housing and space heat demands. The supply of roundwood was constrained and the initial stock of wood in the building sector was defined as 0. Two scenarios were calculated: a short term *scenario 1* for maximizing environmental benefits in the current period (Figure 1) and a long term *scenario 2* for maximizing environmental benefits over several periods (Figure 2). The two scenarios are equal except for the fact that in the second scenario, it was assumed that wood entering in the building sector in period 1 can be used as energy wood in the following period (demolition wood, in this case a period refers to several decades). Each process was associated with environmental impacts that were derived using LCA and ecoinvent datasets. The goal of the optimization was to fulfill the demands at the lowest possible environmental cost.

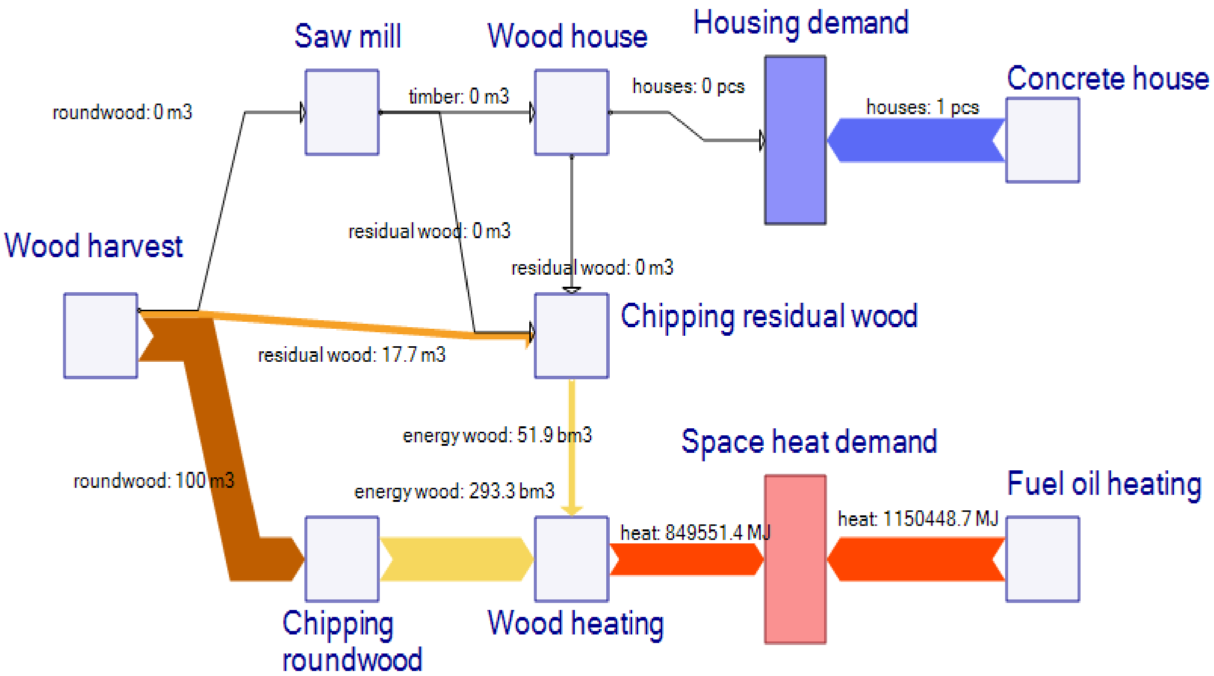

Figure 1 Optimal material flows resulting from a single-period optimization model for the above system, which maximizes short-term environmental benefits (scenario 1)

The results of this simple exercise show that while in the short term scenario (scenario 1, Figure 1) a direct energy use is preferable over a material use of wood, it is the other way around in a longer term scenario with multiple periods (scenario 2, Figure 2). Put simple, the mechanism works as follows: the direct, short term benefits from using wood to substitute materials are lower than the benefits of substituting fossil energy (in this example). However, wood used for material can be used for energy at its end-of-life (cascading), tipping the overall balance again, which is why scenario 2 yields higher environmental benefits. The presented model therefore contains a trade-off situation between benefits in the short or in the long term. Additionally, it shows that optimal solutions can be identified considering several modeling periods (which could e.g. also have different demands and different technological options present).

These results are intended to facilitate an understanding for the capabilities of the wood value chain model, which is currently still under development. The results should not be used as a basis for recommendations as the presented simple model is still far too simplistic and incomplete.

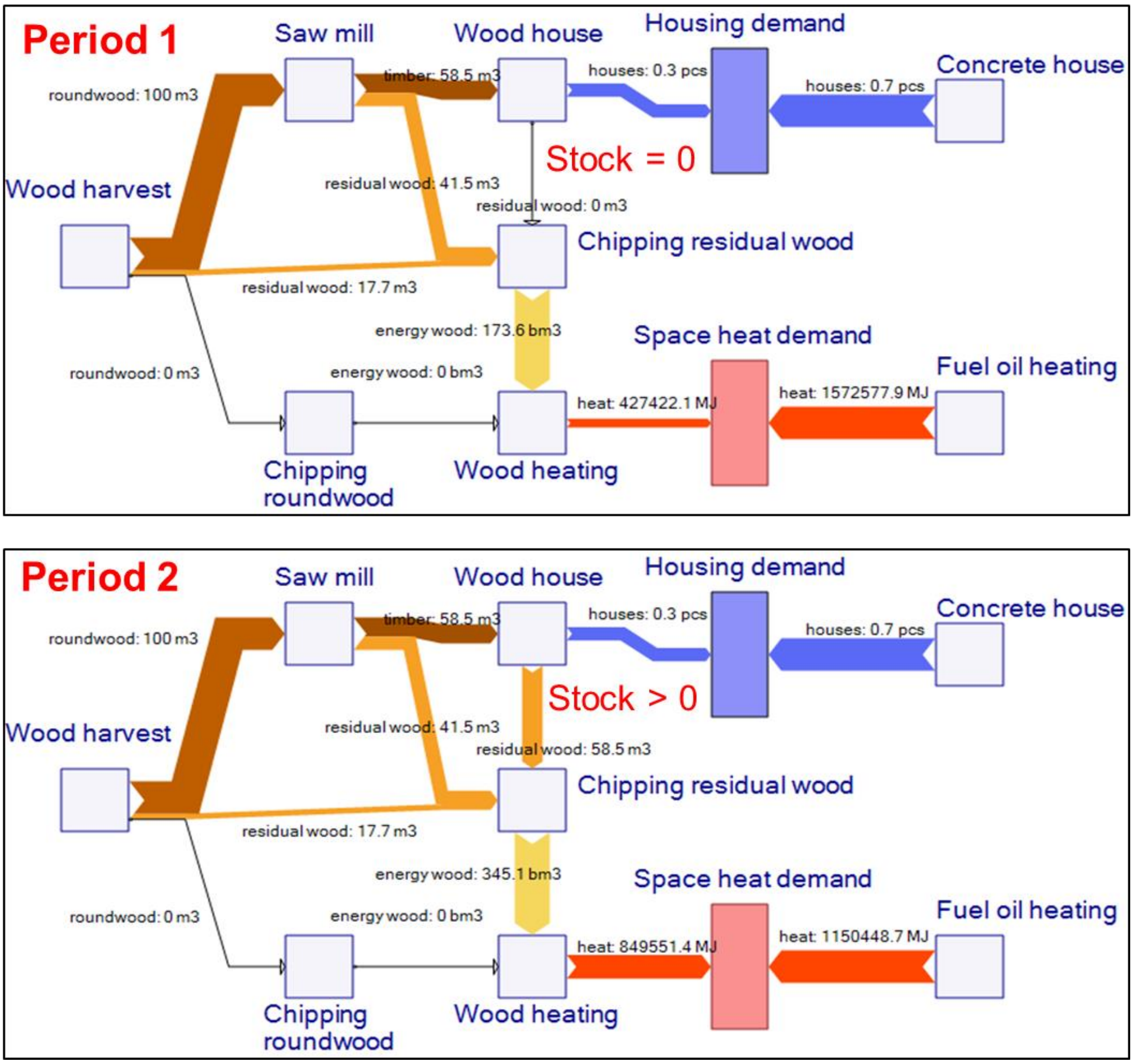

Figure 2 Optimal material flows resulting from a multi-period optimization model for the above systems, which maximizes long-term environmental benefits (scenario 2)

3. Modeling buildings and the building sector

This part of the project is investigated by the PhD student Niko Heeren. Its **specific aims** are to:

- Investigate life cycle impact of wooden buildings, including material / energy demand interaction
- Develop detailed models for the use of wood in the (future) building stock
- Study wood flows within the building sector
- Generate life cycle inventories for different representative buildings, which can be incorporated into the wood value chain model

Wood is traditionally a valuable resource for the construction industry. Its physical properties make it an ideal construction material: It has good structural qualities, relatively low weight, and is a thermal insulator.

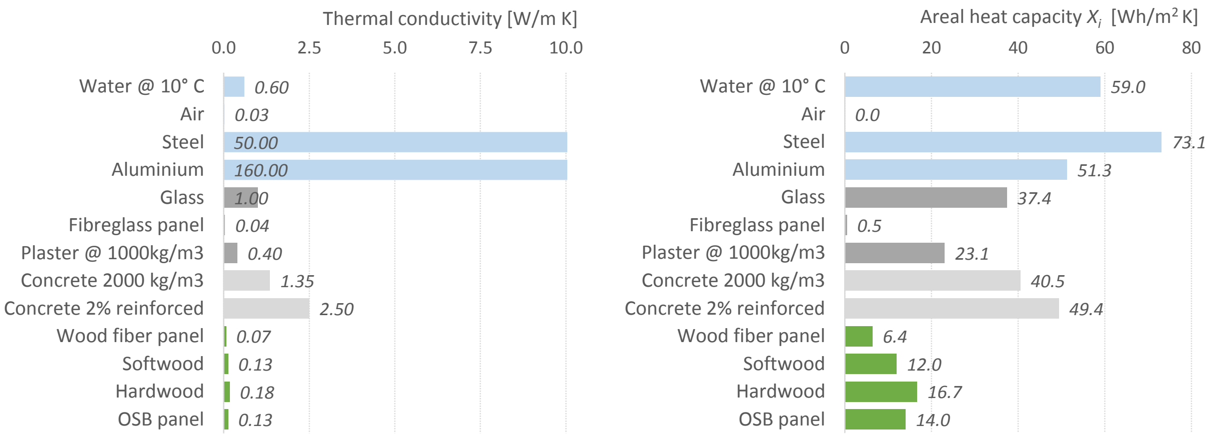

Figure 3 Thermal conductivity (left) and areal heat capacity (right) of wood. Wood is a good thermal insulator, but has a reduced capacity to store heat, when compared with brick or concrete. Data: EN 12524, areal heat capacity X_i calculated based on ISO 13786 (d=15cm, T=24h, $R_{si/se}$=0.0).

Despite these favorable properties, wood is currently not widely used for buildings. This has a wide range of reasons. This part of the NRP66 project focuses on the ecological aspects of wood as a construction material and compares it with other materials. The aim is to investigate the overall ecological competitiveness of wood, compared to other construction material and providing arguments for the discussion on sustainability of future construction materials. That includes the following studies: a. thermal inertia of construction material, b. life cycle impact of material and operating energy, and c. large-scale and cascade use in building stock.

3.1. Thermal inertia modeling

As illustrated in Figure 3, wood has a reduced capacity to store thermal energy, compared to brick or concrete. Previous publications (Aste, Angelotti et al. 2009; Dodoo, Gustavsson et al. 2012) find different figures on the resulting effect on space heat or cooling energy demand of buildings. Accordingly also indoor comfort is affected, since overheating periods are more likely in buildings with low thermal inertia (Aeschbacher, Bartlomé et al. 2011).

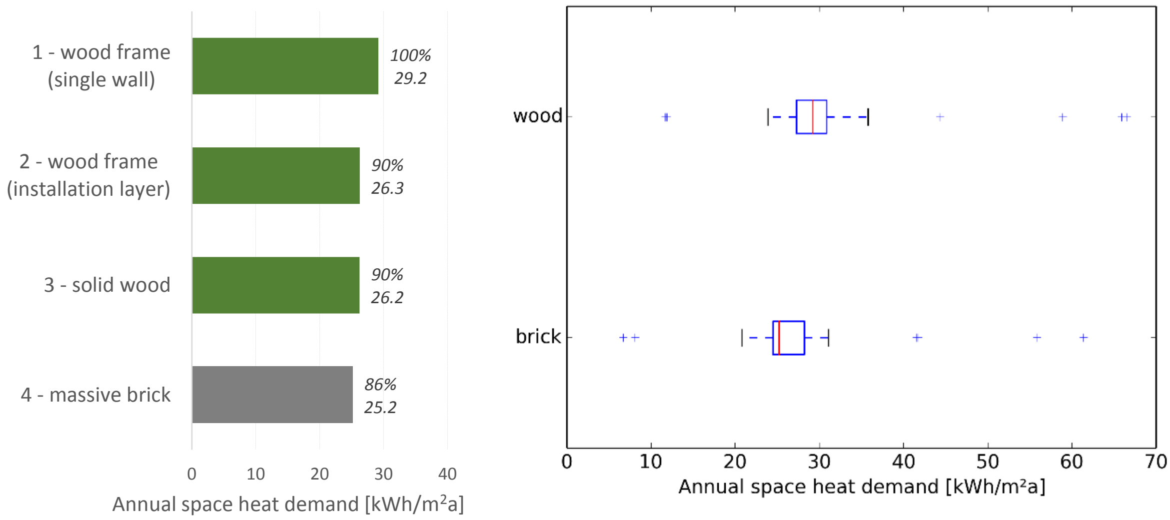

Figure 4 Preliminary simulation results of typical single-family home with wooden (green) and massive (grey) construction. Depending on the scenario and sensitivity, annual space heat demand of wooden buildings is 4-20% higher.

The issue of thermal inertia is investigated by parametric simulation of representative Swiss buildings. That means thermal behavior of a typical single-family homes, offices, etc. is studied for a typical wooden and also a typical heavy-weight (e. g. concrete) construction. We use a sophisticated dynamic thermal simulation software (EnergyPlus v8.0) in order to derive hourly indoor temperature, heat demand, and cooling demand. By modifying numerous input parameters, such as climate, ventilation strategy, window ratio, U-value, the most influential parameters, affecting thermal performance of wooden buildings are identified. This will also highlight mitigation strategies and design guidelines for compensating the reduced thermal inertia. Such strategies could be the use of phase-change materials (PCM), adapted shading, etc.

3.2. Life cycle impact of material and operating energy

Energy demand of a building represents only part of its overall environmental impact. Also for construction, maintenance, and demolition energy and material are required. This is often referred to as the embodied or grey energy of a building. Several studies have shown, that this component may become comparatively important as a building's energy consumption for space heating energy during the entire lifecycle of the building (Sartori and Hestnes 2007; Ramesh, Prakash et al. 2010). This is particularly true for energy efficient buildings, since their share in operating energy is lower. As illustrated in Figure 5, typically the embodied energy of wooden constructions, compared to massive constructions is significantly lower.

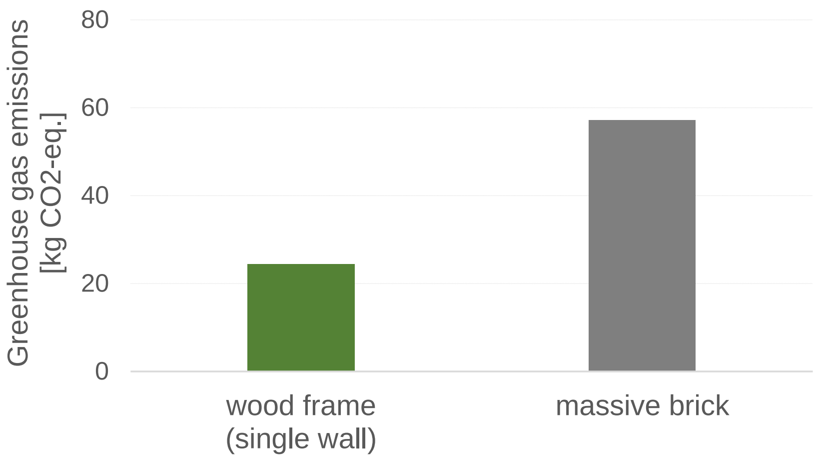

Figure 5 Greenhouse gas emissions for 1m^2 exterior wall (production only, i.e. no maintenance, recycling, or disposal included). Data: ecoinvent v2.2

Therefore, the results for energy demand, illustrated in the previous paragraph, will be extrapolated to a life cycle analysis of the studied buildings. The question is, if (looking at the entire life cycle) wooden buildings are able to compensate for their slightly increased heat energy demand.

3.3. Wood use in the building stock

The previous two analyses will investigate the impact of using wood as a construction material on energy demand and embodied energy. However, these findings are only true for particular cases and the significance for the Swiss building stock is unknown. In order to investigate that, a larger scale needs to be considered. Therefore, the previous results will serve as input to a building stock model (Heeren, Jakob et al. 2013). This will be a prospective, bottom-up model, which includes embodied energy of construction material, renovation cycles, and individual energy demand of buildings. Including these aspects of the construction sector, it is possible to consider different scenarios for future construction material use and energy efficiency of buildings and determine the respective impact.

Furthermore it is possible to carry out a mass flow analysis (MFA) of the building stock, thus consider cascade use of materials. This is particularly important for wood as a construction material, since it can undergo several life cycles, such as reuse, downcycling (e.g. cellulose as insulation material) or thermal use (e.g. wood pellets).

Combining these analyses gives a comprehensive picture of the environmental impact of the current and future Swiss building sector. By comparing scenarios with increased future wood use, reduction potentials in the building stock's environmental impact can be identified. The results allow concluding according recommendations for policy makers and other stakeholders. The results and inventories of the building sector model will be integrated into the wood value chain model, illustrated in the previous chapter.

4. Technology assessment

The **specific aims** of the technology assessment are to:

- support other modules in LCA and technology improvement
- provide a web-based LCA tool with customized interface for data entry
- perform life cycle assessment of technologies from partner projects
- incorporate the technologies in the wood value chain model

A web-based LCA software tool with a user-friendly interface has been developed by our project partner Aveny GmbH[1] and made available to all project partners of NRP66 (technologies developed in the modules 2-5 of the project). The simplified interface, designed for non-LCA experts, facilitates understanding of the modeling and outcome and allows the technology providers to conduct case studies of their own. The LCA tool also includes advanced features like Monte Carlo-based uncertainty calculations.

To ensure a proper environmental hotspot analysis within the other modules, all partners of projects within NRP66 need a basic and common understanding of how to perform an LCA. Therefore, an LCA training workshop was held in 2012 and a written guideline on the LCA framework conditions and data collection has been developed to ensure consistency across all NRP66 projects.

Several technologies from the NRP project partners are currently being investigated, including technologies for material / building, chemical and energy use. LCA results are expected for 2014 and the technologies will be included in the wood value chain model.

5. Further development of impact assessment methodology

The **specific aims** of the further development of impact assessment methodology are to:

- Develop impact assessment methods to address impacts particularly relevant to forestry and the wood value chain
- For the time being, the focus has been laid on indoor emissions from wood products and impacts from land use and associated biodiversity losses
- Apply the developed impact assessment methods in the wood value chain model (if possible given data availability)

5.1. Methodology to assess human health impacts due to indoor wood emissions

Wood is known to contain and emit Volatile Organic Compounds (VOCs) which can be demonstrated by the fact that wood has a characteristic odor. Wood products for the building- and furniture industry are often a combination of wood and the materials added e.g. adhesive. Emissions from solid wood are mostly terpenes and aldehydes. When glue is added to the wooden material, other compounds as formaldehyde and aromatic hydrocarbons may be emitted from the wood-based material. Exposures to formaldehyde are of concern because formaldehyde is a potent sensory irritant and is classified as a probable human carcinogen. Higher molecular weight aldehydes can produce objectionable odors at low concentrations. The odor thresholds for hexanal and other aldehydes are often exceeded in new houses and may remain elevated for months after construction.

[1] http://www.aveny.ch/

Terpene hydrocarbons are of potential concern because they react with ozone to produce ultrafine particles. Animal studies also indicate that strong sensory irritants are formed by terpene–ozone reactions. Wood and composite, and engineered wood products are the likely major sources of aldehydes and terpene hydrocarbons in new houses (Hodgson, Beal et al. 2002).

However, the life cycle assessment (LCA) studies, conducted on wooden products, generally neglect these use-phase impacts and therefore underestimate the product's total environmental impact. The goal of this NRP66 project is to develop a methodology to quantify these impacts and apply it within the overall LCA based evaluation of wood products (modules 1&2). The methodology development consists of 4 steps:

1. Source Testing: Chamber studies conducted in accordance with ISO 16000 guidelines aim to quantify the emission factors (µg/m^2/h) of different products under controlled chamber conditions such as ventilation rate, known loading rate (area of exposed product per unit volume of chamber) etc. The outcome of these chamber studies is a time vs. concentration plot, which illustrates how the emissions vary over time. In general, there is fast exponential decrease in rate of emissions during the first week and then a slow exponential decrease. Eventually it reaches a profile resembling a pseudo steady state concentration. Typically the emissions decrease to 50% of their initial value during the first six months. We have collected such product emission data from 70 different published studies around the globe and compiled them into a database resulting in emission data for more than 100 different types of wood products used in various indoor settings. Some studies only provide the steady-state concentration for a particular product whereas others provide rate of decrease in emission factor over a period of time. As the product testing is an expensive task, the monitoring is done only for 3-4 weeks (28 days). A decay model is generally fitted to this 28 day data in order to be able to predict the long term emission behavior.

These emission results are then compared with the criteria developed by environmental agencies and a decision is made whether the product is suitable for indoor use or not. An example of this is the Nordic Eco labeling scheme for building, decoration and furniture panels, where formaldehyde emissions must be below 0.065 mg/m^3, when measured after 28 days with the M1 testing protocol.

2. Source Modeling: From the literature research, we have selected 10 different empirical decay models. The simplest of the decay models is a first order type (2 parameters), where it is assumed that the emission continues to decay exponentially throughout the products life. These models are first calibrated using the chamber data and model coefficients are determined (non-linear regression). Other models used are constant emission; dual first order (in series); n-order decay; second order decay; third order decay; 2.5 order decay; power law decay and time log decay. The model, which fits the experimental data the best (i.e. highest R^2), is chosen to represent the long term emission behavior of the particular product. There are some physical based models available as well. These rely on processes, such as diffusion & mass transfer, and are used to predict emissions from a particular product utilizing experimental data and material properties.

3. Fate and Exposure Modeling: A homogeneously mixed one-box model will be used to model indoor exposure. The model is connected to the surroundings through ventilation. Inhalation is assumed to be the most significant exposure pathway, thus excluding dermal contact and ingestion from the assessment. To estimate the impact on human health, we must know how much of the total emitted mass of pollutants is inhaled by human beings. This ratio is defined as the intake fraction and is a function of room volume, ventilation rate, inhalation rate, and exposure time.

4. Effect Modeling: Human health effect factors for inhalation of the specific substance are imported from the USEtox database (Rosenbaum, Bachmann et al. 2008). These effect factors relate the quantity taken in by the population to the probability of adverse effects (or potential risk) of the chemical in humans. Finally, the use stage health impacts are calculated by multiplying total mass emitted with the corresponding intake fraction and effect factor.

Preliminary results are currently being produced for various wood based panels used indoors like particleboard, medium density fibreboard (MDF), plywood and oriented strandboard (OSB).

5.2. Methodology to assess biodiversity impacts due to forest management activities

Past and present pressures on forest resources have led to a drastic decrease in the surface area of unmanaged forests in the world. Changes in forest structure, composition, and dynamics inevitably lead to changes in the biodiversity of forest-dwelling species. During the last decades, global biodiversity loss has become a major environmental concern. One of the main drivers of current and projected future biodiversity loss is habitat change due to land use. Within research on life cycle impact assessment (LCIA), attempts have been made to quantify the impacts of land use and other important drivers of biodiversity loss, such as climate change and pollution (for a review, see Curran et al. (2011)). Several approaches on how to quantify land use-related biodiversity impacts have been proposed (De Baan, Alkemade et al. 2013).

A preliminary literature search has been carried out containing data and different methods related to biodiversity assessment and forestry operations. The goal is to quantify changes in biodiversity resulting from forest management activities and integrate these impacts in LCA of wood products.

6. Summary

The project "*Ecological use of wood resources in Switzerland*", which is a part of the Swiss National Research Program 66, aims at providing further knowledge and recommendations for different stakeholders on how to manage the use of wood resources at different levels. These range from bird's eye perspective comparisons of entire wood value chains to specific and more detailed recommendations at the technology level, e.g. for wood buildings or other technologies developed within the NRP 66. In addition the project aims at improving the environmental impact assessment methods that are used as a basis of for life cycle assessments of wood based products and technologies. Final results can be expected in the years 2014 and 2015.

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