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Potentials for cascading of recovered wood from building deconstruction—A case study for south-east Germany

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ABSTRACT

Increasing scarceness of primary raw materials leads to a heightened focus on secondary resources. Deposits from urban infrastructure, mainly the building stock, are a potential major source of secondary resources. However, reliable information concerning available volumes and qualities is lacking. We analyzed incorporated amounts of wood in the building stock of south-east Germany, and calculated resulting streams of recovered wood in order to quantify potentially available volumes for an environmentally beneficial cascading utilization of these secondary resources. By applying a new method using data from sample buildings in regard to the quantity and quality of incorporated wood and statistical data concerning the building stock, the stock of wood based materials in buildings and the recovered wood resulting from demolishing for the year 2011 were calculated.

We found that considerable amounts of recovered wood in suitable condition for a resource-efficient use in cascades can be expected to originate from the building stock: 25% of the recovered wood is suitable for re-use and 21% could be channeled into other high-value secondary applications.

These first initialized concepts of a cascading utilization of recovered wood should be further refined and extended to utilize the existing potential to its optimum.

1. Introduction

1.1. Problem statement

The *Europe 2020* publication of the European Commission states increasing resource efficiency as a major strategy for generating economic growth, to fight against climate change and limit the adverse environmental impacts of resource use (European Commission, 2010). The corresponding flagship initiative enumerates the re-use of valuable materials which would otherwise be wasted as a favorable measure in order to reduce the pressure on primary materials, such as raw wood from forests (European Commission, 2011).

On a national level, the German Government aspires to a doubling of resource productivity by the year 2020, compared to 1994 as a baseline (BMU, 2002, 2012).

In addition to focusing on resource efficiency, the finite nature and instability of fossil resources supply has led to a heightened awareness concerning the importance of renewable resources for an additional and more sustainable supply for both energy-related and material use.

This paper focuses on wood as a versatile renewable resource with a high potential relating to the mitigation of climate change: First, wood products act as a carbon pool during their lifetime. Second, these products can substitute for others produced from scarce and potentially more energy-intensive resources. Third, they can substitute for fossil fuels, when used for combustion with energy recovery after their service life (Werner et al., 2005; Richter, 2009).

In addition, however, also wood as a regrowing and thus renewable resource is not available infinitely with respect to volumes and regional availability. In recent years, an increasing competition for wood, intensified by rising prices for fossil fuels, can be detected (Schwarzbauer and Stern, 2010). To ensure a stable supply for multiple purposes and to meet the growing demands, the efficiency of the use of wood as a resource has to be enhanced and additional sources for wood have to be identified.

1.2. Cascading of wood – state of the art

A suitable means suggested both by science (Fraanje, 1997; Gärtner et al., 2012; Goverse et al., 2001; Haberl and Geissler, 2000; Lafleur and Fraanje, 1997; Sathre and Gustavsson, 2006; Sirkin and

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ten Houten, 1994; Werner et al., 2007) and legislative bodies (BMU, 2008, 2012) to achieve a more efficient resource use is the concept of cascading, meant as the sequential use of a certain resource for different purposes.

As described by Sirkin and ten Houten (1994), resource cascading is a method to enhance the efficiency of resource utilization by a sequential re-utilization of the same unit of a resource for multiple high-grade material applications followed by a final use for energy generation. Thereby, primary raw materials are saved and positive effects due to the substitution of finite materials by renewable resources can be increased (Gustavsson and Sathre, 2011).

To maximize the effects of a cascading utilization, secondary resources should be used in the application with the highest possible quality for which they are intrinsically suitable (Fraanje, 1997; Haberl and Geissler, 2000). For example, high quality recovered wood from the building sector in large dimensions and without contamination, such as solid beams, should first be used to produce timber of smaller dimensions, such as lamellas, which after a service time as flooring can be chipped and used in a second cascade step as particle- or fiberboards, and finally as an energy carrier, rather than being immediately used for energy production after the first product life as a beam (Fig. 1).

Previous studies have shown various benefits from cascading. Fraanje (1997) examined the effects on primary resource use by the cascading of pine wood in the Netherlands. He found that large savings of primary resources were possible and the time a resource is used could be extended considerably by cascading. Dornburg and Faaij (2005) compared cascading chains with wood from short rotation poplar, considering land use, CO_2 emission reduction and economic performance. They concluded that cascading has the potential to improve both CO_2 emission reductions per hectare and CO_2 mitigation costs of biomass usage. Sathre and Gustavsson (2006) analyzed the energy and carbon balances of cascade chains for recovered lumber with several post-recovery options such as particleboard production, re-use and burning for energy recovery. They compared the balances of cascaded products to the use of virgin wood and to the use of non-wood products. Cascading was found to have positive effects on the balances, especially due to a reduced demand for non-wood products when wood is cascaded and owing to energy savings by direct cascade effects. Gärtner et al. (2012, 2013) conducted Life Cycle Assessments (LCA) of different wood cascade chains. They concluded that generally the impact on the environment decreases with more cascade steps of using wood as a material resource before a final use for energy production.

However, most studies also discussed restrictions of the benefits of cascading. Sathre and Gustavsson (2006) concluded that benefits from cascading are minor, if virgin biomass were available yet remains unused due to cascading of recovered wood. However, this is not the case in the study area of Bavaria, despite a continuing increase of overall forest stocks. A considerable part of the increase of stocks is contained in small privately owned forests and a mobilization of these resources could not be achieved, despite great efforts over the last years. Furthermore, recovered wood today mainly substitutes virgin wood of lower quality as raw material for wood panel manufacturing (mainly particleboard). These assortments are also the main input for the growing wood use in domestic heating, which has led to rising raw wood prices and competition for these assortments between material use and use for energy production in recent years (Friedrich et al., 2012). An increase in the use of recovered wood by cascading would therefore alleviate this competition and prevent rising prices for manufactured wood products, which ultimately would lead to a partial displacement by non-wood products. This also is in accordance with the conclusion of Sathre and Gustavsson (2006) that a cascading use of recovered wood avoids the use of more energy intensive non-wood products, if forest resources are limited.

Gärtner et al. (2013) detect possible constraints in the delay of the energy recovery step for several decades which would be caused by an extensive cascading of recovered wood. This may lead to the replacement of possible cleaner energy sources in the future, when the cascaded wood finally reaches its end-of-life. Nonetheless, those possible negative environmental effects are counterbalanced by the prolonged carbon storage in the wood due to cascading, thereby contributing to the mitigation of climate change. It is evident that a cascading utilization of wood is not to be favored uncritically. Yet, when taking into account legislative requirements and the situation in the study area regarding wood demand and availability, it seems a concept worth encouraging.

Currently, in Germany, cascading of wood as a strategy to extend the material lifetime has not yet been implemented sufficiently. Close to 80% of the total amount of recovered wood is incinerated, mainly in large-scale power plants with effective flue gas cleaning. Regarding the use of recovered wood as a secondary raw material, particleboard is the only noticeable industrial application

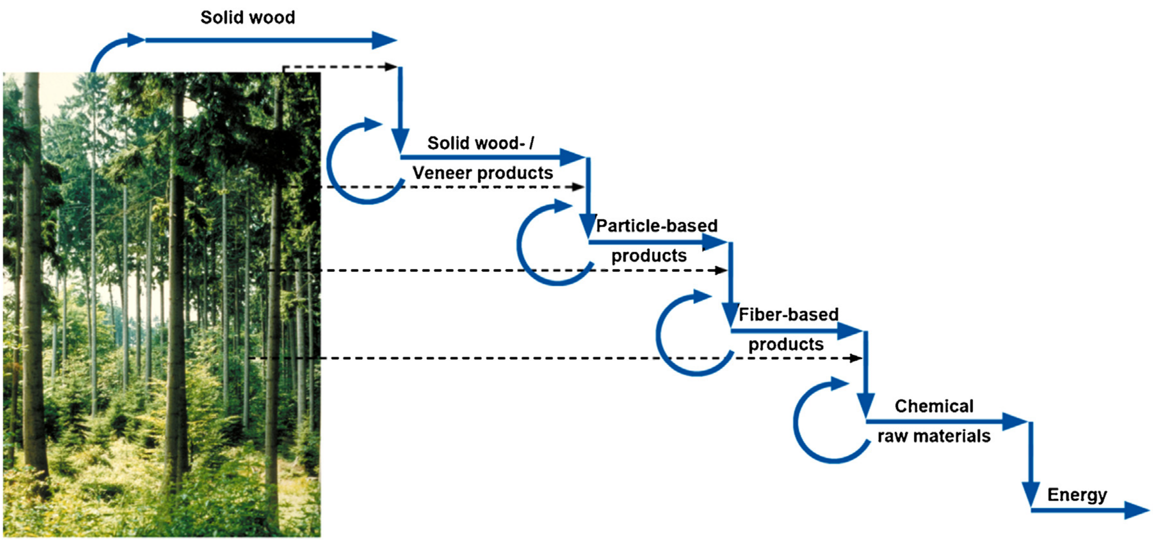

Fig. 1. Cascading use of wood to improve resource efficiency (based on EPEA, 2009).

Table 1
Quality classes of recovered wood according to the German Waste Wood Act (German Government, 2003).

Class	Description	Intended application
A I	Untreated or only mechanical treatment	Material use (energy possible)
A II	Glued or painted wood No halogen-organic compounds or preservatives	Material use (energy possible)
A III	Wood containing halogen-organic compounds; No preservatives	Energy use (material use only with prior processing)
A IV	Contaminated wood, including halogen-organic compounds No PCB	Energy use in large-scale combustion facilities
PCB	PCB treated wood	Non-hazardous disposal

(Friedrich et al., 2012; Mantau et al., 2012). Re-use is common in small amounts with old furniture. Other technically feasible applications, e.g. as input for other wood-based composites such as MDF (Medium Density Fiberboard) and OSB (Oriented Strand Board), or raw material for the pulp and paper production are not practiced, mainly due to only minor cost benefits, necessary technological process adaptations, and concerns of customers toward materials generated from “waste”.

1.3. *Recovered wood from building deconstruction – situation in Germany*

With declining stocks of primary resources, resources already incorporated in anthropogenic stocks will become increasingly important for a future resource supply (Müller, 2006). The building stock with both its mineral and organic components is one of the most important human-made reservoirs for secondary resources (Bringezu, 2012). Also for recovered wood as a secondary resource, the building sector, especially the deconstruction and demolishing of buildings, is essential. Previous studies concerning the recycling of building waste, including the wood fraction, already described the ecological benefits (Thormark, 2001; Coelho and Brito, 2012). However, no studies heretofore have applied the concept of cascading to building waste or a subsection of it.

For an effective cascading of recovered wood from building deconstruction, verified information relating to the expected amounts and the quality of the recovered wood is essential. Up to now, only little comprehensive, recent information is available on national or regional level. Studies with different methodological approaches were carried out for the Netherlands, Japan and the city of Vienna (Fraanje, 1999; Merl, 2007; Weng and Yashiro, 2003) and Kroth et al. (1991) assessed wood in the housing stock of Germany. Studies focusing on the overall material flow of the building stock are more common, though lacking more detailed information regarding the wood fraction (Baudirektion Kanton Zürich, 2010; Bringezu, 2012; Görg, 1997; Kloft et al., 1996; Kohler et al., 1999; Rubli and Schneider, 2007; Wittmer and Lichtensteiger, 2007). Yet, such information is crucial to assess the suitability of recovered wood for a use in cascades, as both the quantity and the quality determines its potential secondary use.

Recovered wood as an additional source of wood is already used in Germany with estimated recovered annual amounts around 6.3 million tons (Mantau et al., 2012).

This volume represents the share of the total post-consumer wood which is collected separately. An additional approximately 3.1 million tons are combusted as part of the municipal waste, co-fired with coal or burned in small-scale furnaces in housing. Friedrich et al. (2012) state a total of 1.25 million tons of recovered wood for Bavaria in 2010.

Due to the implementation of a landfill ban regarding biomass based materials in 2003 and a rather strict legislation in regard to waste management, the recovered share of wood with at least one prior application can be seen as close to 100% in Germany. The *Act for Promoting Closed Substance Cycle Waste Management* (German Government, 2012) issued in 2012 regulates a five-step waste hierarchy, thereby implementing the concept of resource cascading on a legislative level. Which of the options of the hierarchy is to be favored depends on the quality of the recovered material. In general, the application highest in the pyramid which is suitable for a respective material has to be chosen.

In the case of recovered wood, the quality requirements to select the paths of either energy utilization, re-use or recycling are defined by the German Waste Wood Act from 2003 (German Government, 2003), which offers four different categories based on former treatment of the wood products with paints, preservatives, or other chemical substances (Table 1).

Studies focusing on the origin of recovered wood in Germany are rare. Lang (2004) states a share of 33% originating from the building sector. Other major contributors are packaging (14%) and wooden parts of municipal waste (31%). A study by the Bavarian Environmental Institute states the share of recovered wood from buildings as 44% (LFU, 2012).

1.4. *Objectives*

To enable a cascading use, information relating to the properties of the recovered wood is crucial, as it determines the possible secondary applications and helps to steer each part of the recovered wood stream to its optimal utilization.

The main influencing factors are type of the recovered wood (e.g. solid wood, engineered wooden products), size and volume, purity and composition of the wood with other materials (hybrid materials). Finally, the overall collected amount of a certain homogenous part of the recovered wood is also decisive, as most secondary utilizations require minimum volumes to be financially viable.

In order to determine the potential for the cascading of recovered wood, this paper aims to provide information concerning the following questions:

(1) What quantities of wood are embodied in the Bavarian building stock?
(2) Which building products are the biggest contributors to wood stock?
(3) What amounts of recovered wood can be expected to originate from the building stock per year?
(4) Which potentials for cascading of recovered wood, based on the quality of the wood in the building stock, can be expected?

The area of the case study presented in this paper is the Federal State of Bavaria in south-east Germany. As the biggest of the German federal states and representing a mixture of both rural and urban building structures, it is suitable for generating outcomes also potentially applicable to other areas. Furthermore, the statistical data concerning building stocks and activities available for

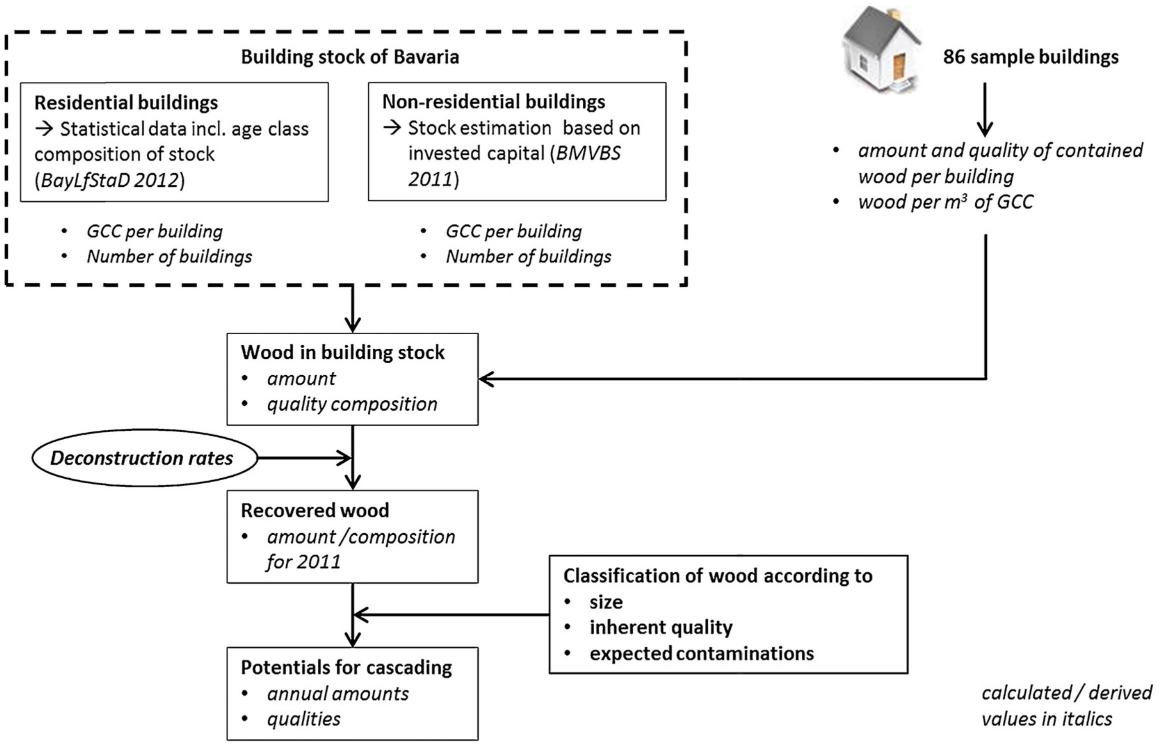

Fig. 2. Process of analysis of the wood in the Bavarian building stock by using sample buildings.

this region is consistent and sufficient for the purpose of this case study. We aim to evaluate the potentials for an optimal utilization of recovered wood from building deconstruction in Bavaria.

2. Methods

2.1. Case study and research approach

The first part of the study focuses on calculating the volume of wood contained in the building stock of Bavaria in south-east Germany. Based on this quantification, amounts and quality of recovered wood originating from the demolishing of buildings were derived and used to determine the potential for different secondary applications of the wood part of building waste in Bavaria (Fig. 2).

A bottom-up approach based on data from the German Architects Association was applied. For 86 buildings constructed between 1948 and 2008, datasets specifying detailed summaries of all the used building materials were available, including interior furnishings such as staircases and doors. The type of materials is described in detail in these datasets, as they are normally used by the German Architects Association in a software tool to estimate the costs of building projects by comparing the planned object to already existing similar ones (BKI, 2011).

Based on these 86 model buildings, the volumes of wood in the housing stock of Bavaria were calculated by using statistical data of construction and demolishing of buildings provided by the Bavarian Statistical Office (BayLfStaD, 2012).

For the year 2011, amount and composition of recovered wood resulting from all demolishing of buildings were calculated. We determined the quality according to the categories of the German Waste Wood Act (Table 1) and analyzed the waste wood in regard to additional quality factors:

- The amount of rather large, formerly structurally used wooden elements which would potentially be suitable for re-use or other utilizations conserving the material integrity, and
- the share of solid wood without major contamination, which is a suitable secondary raw material for engineered wood products such as particleboards.

The potential for a use in cascades of these waste wood fractions was then determined, allowing the assessment of possibilities in Bavaria for improving resource efficiency by cascading.

2.2. Wood in the building stock

Each dataset contains a comprehensive list of all components embodied in the respective building on the level of single parts (i.e. beams, windows, floorings). Since only the surface area of the elements was given, average thicknesses were applied in order to calculate the volume.

The volume in cubic meters of the various building components was then summarized for each building, according to the methodology previously applied by Weber-Blaschke et al. (2006a,b). However, in contrast to this study, our work focuses only on the wood fraction of the building materials. Additionally, a more detailed analysis concerning the type and quality of the used wood was carried out in order to provide suitable information to quantify waste wood streams.

35 of the datasets were for residential buildings, both single-family dwellings and multi-family apartment buildings with up to 16 units. For non-residential buildings, 51 datasets were available, representing school, office and commercial as well as agricultural buildings.

For both groups of buildings, the average amount of each of the building product groups (doors, load-bearing structures, etc.) per cubic meter of gross cubic content (GCC) was calculated. By applying the number of buildings and the average gross cubic content per building, volumes of wood for the whole Bavarian building stock were calculated according to Formulae (1).

The term gross cubic content describes the volume enclosed by the building structure, including walls, roof and foundation slab.

It is a key figure in terms of financing of building activities and is calculated according to the German standard DIN 277 (German Institute for Standardization, 2005).

$$W_{stock} = W_{GCC} \times GCC \times n \tag{1}$$

with W_{stock} = wood contained in the stock [m^3]; W_{GCC} = average amount of wood per cubic meter of GCC derived from the sample buildings [m^3/m^3]; GCC = average gross cubic content per building [m^3]; n = number of buildings in the total stock.

Separate calculations were carried out for residential and non-residential buildings. In the case of residential buildings, the calculations were conducted separately for 7 building age classes. As the majority of the sample buildings were constructed later than 1975, correction factors of the wood per unit of GCC were derived from Kloft et al. (1996). Data availability was reasonably good for residential buildings. Numbers of annually constructed as well as deconstructed buildings were available (BayLfStaD, 2012). Thus, a calculation of the current number of buildings and their age composition could be carried out. The age classes reflect the change in building tradition over time. For example, buildings constructed before 1918 consist of nearly four times the amount of wood, compared to buildings constructed later than 1980 (Kloft et al., 1996).

Calculation of the stock based on statistical data was not possible for non-residential buildings, as data for the time before 1987 are lacking. Still, a recent study on behalf of the German Ministry of Construction (BMVBS, 2011) made an estimation of the stock of non-residential buildings in Germany based on statistical data and capital invested in building stock which we used as a basis for our calculations. To obtain the Bavarian share of the German total, numbers of inhabitants and the gross domestic product in Bavaria in relation to Germany were applied. The amount and composition of wood in the building stock was also calculated according to Formulae (1). However, no age class distribution could be made.

2.3. Recovered wood from building deconstruction

In order to quantify potential amounts for cascading, the annual stream of recovered wood from the building sector and its composition has to be calculated. In our study, the situation of the year 2011 was calculated, as deconstruction rates were fairly stable over the last years and the results of this exemplary year can be seen as representative for the present situation.

For both residential and non-residential buildings the number of demolished and deconstructed buildings per age class and year were available from the Bavarian Statistical Office (BayLfStaD, 2012). Consequently, deconstruction rates for each of the age classes could be calculated. By applying the average amounts of wooden building products derived from the sample buildings, the amount of recovered wood from the building sector was also calculated according to Formulae (2).

$$W_{rec} = WGCC \times GCC \times n \times d \tag{2}$$

with W_{rec} = recovered wood from building demolition [m^3]; d = annual deconstruction rate [% of total stock].

Again, these calculations were carried out separately per age class for residential buildings and as a total for non-residential buildings.

From the detailed information regarding the type, it is possible to derive the quality and intended use of all wooden materials available for the sample buildings, the quality class of the recovered wood to be expected in the future by decomposition of the buildings. A prerequisite for this was the classification of each wooden component of the building according to the four categories of the *German Waste Wood Act* (Table 1). As virtually no wood of class A I and A III accrues from the building stock, these classes were subsumed under the classes A II and A IV respectively. The amount of recovered wood per class in 2011 was calculated according to Formulae (2), using respective values of W_{GCC} for each of the two quality classes of recovered wood.

Mainly two factors determine the potential recovered wood quality: First, the inherent properties of the wood or wooden material used to construct the building are decisive. Especially materials combined permanently with the wood, such as plastic overlays, glues, adhesives or paints are to be mentioned here. Second, influences on the quality taking place during maintenance and repair over the service life of the wood, i.e. subsequent treatment with preservatives and paints have to be taken into account. In our study, we assumed that the wood products were treated only with the necessary minimum of additives: Only if safety standards would require the treatment with preservatives or paint, was a downgrading into the respective lower waste wood class applied. Consequently the amounts of clean and untreated wood we calculated represent an optimum situation in regard to recycling of recovered wood. In reality higher shares of contaminated wood may occur. Wood from load-bearing structures such as roof beams was graded into class A IV according to legal stipulations, despite this wood in reality partially not being treated with preservatives.

2.4. Potential for cascading recovered wood

Besides a classification and quantification of wood in the building stock, the assessment and evaluation of potential for cascading recovered wood was a major goal of our study.

To enable cascading, each part of the recovered wood stream has to be assigned to an appropriate secondary use, depending on its quality. To assess potential amounts for the different secondary use options, which constitute the recovered wood cascade, the wooden building products were categorized: First, according to their application in the building (load-bearing structures, doors, windows, flooring, stairs, boards etc.) and second, in regard to their inherent properties. Together, they define possible secondary use options. In the latter, the amounts of structural components possibly suitable for re-use and the fraction of solid wood products were determined.

In each case, current stocks and amounts to be expected in the recovered wood stream per year were calculated, applying the described methodology.

3. Results and discussion

3.1. Wood in the sample buildings

Values of wood content were calculated for each of the 86 sample buildings. They varied considerably, due to the size of the buildings, different construction methods and differing choices with interior fittings and windows (Fig. 3).

The representativeness of the sample buildings in regard to the building stock in general can be assessed by the following characteristic values: (1) the share of wooden buildings in the total building stock, since those buildings incorporate a considerably higher amount of wood per unit of gross cubic content compared to conventional buildings (Kroth et al., 1991), and (2) the average GCC, as it directly influences the calculation of the total amount of wood in the stock when operating with statistical building data.

In a study for the German Ministry of Construction, Diefenbach et al. (2010) report a share of 7.2% for wooden residential buildings in the stock of southern Germany. In our sample, 2 out of 35 residential buildings were wood constructions (6%), representing the actual share fairly well. Diefenbach et al. (2010) present no data for the share of wooden non-residential buildings in Germany. However, it can be expected to be considerably lower than the number

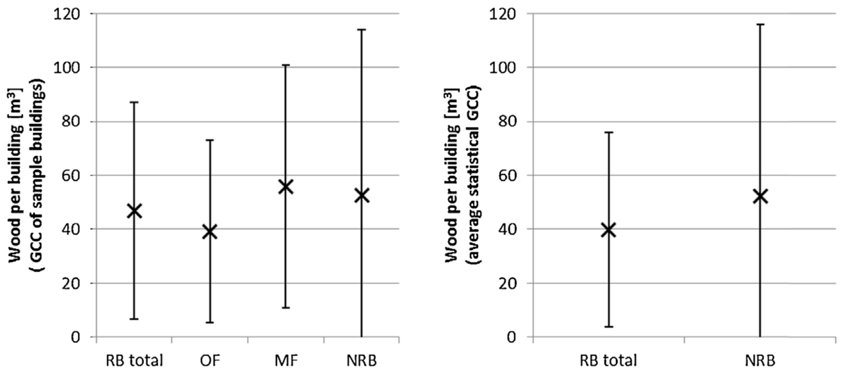

Fig. 3. Mean values and standard deviation of wood in the sample buildings (BKI, 2011); left: amounts calculated with gross cubic content of sample buildings; right: amounts calculated with statistical Bavarian average of gross cubic content (see text), no separate values for OF and MF available (RB total: residential buildings total; OF/MF: One-/multi-family buildings; NRB: non-residential buildings).

Table 2
Characteristic parameters of the sample buildings used to determine wood in the building stock of Bavaria. Data from BKI (2011) (GCC: gross cubic content).

	Residential buildings			Non-residential buildings
	Total	Single-family	Multi-family	
Number of sample buildings	35	19	16	51
Year of construction (from-to)	1948–2009	1948–2009	1989–2008	1989–2008
Average GCC [m^3]				
of sample buildings	2317	913	3983	11,187
Bavarian average	1169	–	–	4112
Wooden buildings	2	2	0	0

for residential buildings. In our sample 2% of those buildings were wood constructions, confirming this assumption.

The second characteristic value, the average GCC per building, shows a considerable difference between the statistical value for Bavaria and the average value of our building sample. Therefore, for calculating the amounts of wood in the total building stock, the average Bavarian GCC was used, instead of the average one of the sample buildings, as the latter is considerably higher both with residential and non-residential buildings (see Fig. 3 and Table 2).

A reason for this discrepancy might be that architects can choose if they input one of their building projects into the planning tool we derived our data from (BKI, 2011). It can be assumed that they do this more often with high value buildings, which normally also have a higher than average GCC. Another reason may be the high number of multi-unit houses in our sample buildings, which increases the overall average GCC. To obtain an accurate overall value of incorporated wood, we assumed all buildings to have the average Bavarian GCC, however, with differing amounts of wood contained per cubic meter of GCC, as derived from the sample buildings.

3.2. *Wood in the building stock*

The quantitative and qualitative assessment of wood in the Bavarian building stock was one major goal of the study. The Bavarian building stock is dominated by residential buildings. Although non-residential buildings account for nearly one third of the overall gross cubic content (GCC) of the Bavarian building stock (Table 3), residential buildings contribute over 90% of the wood contained

Table 3
Description of the Bavarian building stock in 2011 (Column 1–4: data from BayLfStaD, 2012 and derived values; Columns 5 + 6: own calculations based on sample buildings and statistical data).

Construction period of residential buildings	1	2	3	4	5	6
	Number of buildings	Buildings distribution over age classes [%]	Average GCC per building [a] [m^3]	Gross cubic content of stock [10^6 m^3]	Wood contained in stock [10^6 m^3]	Distribution of wood over age classes [%]
Before 1900	319,050	11	1089	347.4	27.5	28
1901–1918	100,012	3	1089	108.9	8.6	9
1919–1948	311,300	11	1195	372.0	6.4	7
1949–1962	551,117	19	1147	632.1	9.1	9
1963–1970	413,909	14	1147	474.9	6.8	7
1971–1980	511,359	17	1169	597.5	12.1	13
1981–2011	748,104	25	1230	920.1	18.6	19
Residential buildings	2,954,850 (88%)	–	1169	3453.0 (67%)	89.2	92
Non-residential buildings	406,174 (12%)	–	4112	1670.3 (33%)	7.9	8
Building stock total	3,361,024 (100%)	100%	–	5123.3 (100%)	97.1	100%

[a] Values until 1948 from IWU (2005); 1949–2011 from BayLfStaD (2011).

Table 4
Wood in buildings – comparison of studies (shell: shell construction; GCC: Gross Cubic Content).

Author	Own calculations				Kroth et al.	BDZ	Fraanje	Weber-Blaschke et al.
Year	–				1991	2009	1999	2006a,b
Year of data	2011				1990	2009	1996	2003
Region/country	Bavaria				Bavaria	Germany	Netherlands	Bavaria
	[m^3/building]		[m^3/1000 m^3 GCC]		[m^3/1000 m^3 GCC]		[m^3/building]	
	Total	Shell	Total	Shell				
Residential buildings	30.2	21.1	25.8	18.0	21.0		3.4	37
Non-residential buildings	19.4	12.7	4.7	3.1	12.0	5.4	–	–
Building stock	28.9	20.1	18.9	13.2	–	–	–	–

in the total stock. This is due to the fact that residential buildings embody roughly 1.5 times the amount of wood compared to non-residential buildings. Per unit of GCC, the rates differ even more (Table 4).

Thus, especially residential buildings are crucial to an effective recovery of wood and the possibilities for a secondary use.

The majority of the wood is part of the shell construction, mainly in roof structures, walls and ceilings. For an effective recovery of wood used in buildings, a focus has to be put on those parts of the construction that merit the highest salvageable amounts.

Kroth et al. (1991) derived an average amount of wood of 21 m^3 per 1000 m^3 of GCC for residential buildings in southern Germany for the year 1990. Comparing these numbers to our findings, a substantial increase in wood in the residential building stock over the last 21 years could be assumed. However, as the applied methodologies are not comparable, such a conclusion is not soundly based. Weber-Blaschke et al. (2006a) stated an amount of 16 kg per m^3 of GCC, which equals approximately 37 m^3 of wood per residential building in Bavaria in 2003.

Kroth et al. (1991) found average amounts of 12 m^3 per 1000 m^3 of GCC for non-residential buildings, with numbers for different building types ranging from 6 to 16 m^3 per 1000 m^3 of GCC. Here, our calculated amounts are considerably lower. Another study carried out by the German Cement Industry Association (BDZ, 2009) found an average amount of 5.4 m^3 per 1000 m^3 of GCC for non-residential buildings newly constructed in Germany in 2009.

For the Netherlands, Fraanje (1999) indicated an average of 3.4 m^3 for a typical one-family dwelling in 1996. In contrast to our study, it did not take into account wood for the construction of inner walls and ceilings, skirting and roof lathing and a number of indoor finishings, which may partly explain the considerable difference of the estimated amounts compared to our findings and those of Kroth et al. (1991).

Müller (2006) states an average of 3 tons per capita in the Dutch housing stock. Weber-Blaschke et al. (2006a) indicates 2.4 tons per capita. We calculated an amount of 3.8 tons per capita in 2011 in Bavaria.

When assessing wood in stock and its potential for secondary use, not only the amount but also the composition with respect to size and potential mechanical damage or chemical contamination is critical. To evaluate the risk of contamination of recovered wood, the type of wood and its use in construction are the determining factors. Consequently, the wooden share of the sample building was categorized into different building product groups (Table 5). The major part is made up of load-bearing structures (34%). Slightly over 60% of this category is made up of beams and rafters in roof construction, which can easily be salvaged by thorough deconstruction and therefore represent an important potential for future re-use or other high-quality secondary applications.

Wood frame constructions, which are mainly utilized as construction elements for contemporary wooden buildings, currently contribute 8% to the total stock and can be expected to be of increasing importance in the future. The wall forming frames constitute studs and are covered with panels such as Oriented Strand Boards. As they are generally a composition of wood and other materials such as plastic sheetings and insulation materials, they will require a special deconstruction in order to make the wooden components available for material recycling. Therefore we list them separately, despite also being a load bearing structure.

Glulam structures have become increasingly important as structural components over the last decades in construction, as they allow a wider variety in form and show higher strength parameters with smaller dimensions. Our data did not allow estimations for all age classes, due to the uneven age distribution of the sample buildings. However, with buildings of the youngest class (1981–2011) a share of close to 19% of the total incorporated wood are glue laminated products, both in form of panels or beams. In 1957, Germany produced a total of 5000 m^3 of glue laminated wood (Wiegand, 2012). This marginal number, compared to the current annual production volume of close to 500,000 m^3, allows the conclusion that

Table 5
Contribution of different building products to the wood embodied in the Bavarian building stock in 2011.

	Total stock		Potential waste wood qualities			
			A I + II		A III + IV	
	[10^6 m^3]	[% of total stock]	[10^6 m^3]	[% of product]	[10^6 m^3]	[% of product]
Load-bearing structures	33.3	34	5.4	16	28.0	84
Boards and planks	27.7	29	15.2	55	12.6	45
Wood frame constructions (walls and roofs)	7.9	8	2.9	37	5.0	63
Plates and panels	7.8	8	4.4	57	3.4	43
(Roof) battens	5.2	5	2.8	54	2.4	46
Square timber	1.0	1	0.9	88	0.1	12
Doors	6.7	7	4.5	68	2.1	32
Staircases	0.7	1	0.7	100	0.0	0
Flooring	3.6	4	3.6	99	0.0	1
Windows	1.4	1	0.1	11	1.2	89
Others	1.8	2	1.4	78	0.4	22
Total	97.1	100	41.8	43	55.2	57

Table 6
Recovered wood stream from building deconstruction in Bavaria for the year 2011.

Construction period of residential buildings	Number of demolished buildings in 2011	Deconstruction rate [%]	Gross cubic content demolished [m^3]	Waste wood [m^3]	Quality distribution of waste wood [m^3]	
					Classes A I + II	Classes A III + IV
Before 1900	104	0.03	113,256	8978	3843	5135
1901–1918	145	0.14	157,905	12,518	5358	7160
1919–1948	150	0.05	179,250	3100	1327	1773
1949–1962	315	0.06	361,305	5208	2229	2979
1963–1970	93	0.02	106,703	1538	658	880
1971–1980	54	0.01	63,102	1273	545	728
1981–2011	31	0.00	38,127	769	329	440
Residential buildings	892	0.03	1,042,386	33,385 (100%)	14,290 (43%)	19,094 (57%)
Non-residential buildings total	1211	0.30	4,979,980	23,453 (100%)	10,912 (47%)	12,541 (53%)
Building stock total	2103	0.06	6,022,365	56,838 (100%)	25,202 (44%)	31,635 (56%)

the amounts of this wood product type in buildings constructed earlier than the 1970s can be expected to be negligible.

3.3. *Recovered wood from building deconstruction*

For assessing possibilities for high-quality secondary applications of recovered wood from building deconstruction, reliable information concerning amounts and qualities is essential. By applying statistical deconstruction numbers, the recovered wood stream resulting in 2011 was quantified and evaluated in order to derive representative information.

The overall deconstruction rate in 2011 of 0.06% of the building stock led to an amount of roughly 57,000 m^3 of recovered wood in Bavaria, which equals 28,000 t (Table 6).

Only the classes A I and A II, which make up less than half of the amount, are potentially suitable for a secondary material use under current legal guidelines, which prohibit the re-use of recovered wood from load-bearing structures and recycling for a secondary high-value application such as the production of boards or planks.

Friedrich et al. (2012) reported an annual total amount of 1.25 million tons of recovered wood for Bavaria in 2010. Assuming a share of 33% originating from the building sector (Lang, 2004), roughly 410,000 t could be expected, which is more than 14 times higher than our calculated amounts. A possible explanation for this discrepancy could be that the official deconstruction statistics are assumed to be underestimating the numbers considerably. A study by Sautter (2004), whose contents are presented more in detail in Section 3.5, showed a four times higher real deconstruction rate compared to the statistical recorded one. Assuming this trend to also be applicable to Bavaria, the calculated amount would increase up to 112,000 t annually, which is still nearly four times less than the amounts derived from Friedrich et al. (2012).

However, another factor to be taken into account is the fact that our study only encompasses recovered wood from the deconstruction of buildings. Yet, the reported amounts of recovered wood from the building sector generally also includes wood originating from the construction of buildings, such as formwork and packaging. Kroth et al. (1991) calculated an average of 0.7 t of recovered wood accruing per newly constructed 1000 m^3 of GCC. Weber-Blaschke and Faulstich (2005) confirm this amount as they state 0.75 t per 1000 m^3 of GCC for buildings erected between 1978 and 1999. Sianchuk et al. (2012) state a number of 1.9 t of wooden building waste per building for the US in 2009. In 2011, new buildings with a total of 68 million m^3 GCC were constructed in Bavaria (BayLfStaD, 2012), thereby producing roughly 51,000 t of additional recovered wood.

Our methodology did not allow the calculation of the volume of recovered wood from building components which are renewed during the life span of a building. Those mainly consist of windows, doors, stairs, flooring, panels and plates. Together they account for 20.2 million m^3 of the wood in the current stock (Table 5). The average age of the buildings deconstructed in Bavaria in 2011 was 63 years. When assuming one exchange of each of those building products per average building life time, roughly 321,000 m^3 or 160,000 t respectively of waste wood will be generated by these minor renovations per year.

Wood from deconstruction, building waste and wood from minor renovations together would sum up to 323,000 t of annually recovered wood. Further investigation is needed to determine the exact share from minor renovations.

3.4. *Potential amounts for cascading*

Effective cascading requires recovered wood of good quality, i.e. clean, homogenous and in usable dimensions. An entry of the recovered wood at a high level of the cascade chain allows several following steps, since the quality of the wood generally decreases with each step. Previous research has shown that the number of possible cascade steps directly influences the ecological benefits of cascading (Fraanje, 1997; Gärtner et al., 2013). In order to determine potential amounts for a high quality cascading utilization of recovered wood, two suitable types of recovered wood were determined and their amounts calculated.

The first group of suitable recovered wood consists of rather large, formerly structurally used wooden parts. This share mainly originates from roof structures or wooden ceilings. Roughly one quarter of the total recovered wood (25%) can be classified in this group (Table 7). Possible secondary utilizations could be a re-use as part of a load-bearing structure, an application in interior design or the manufacturing of boards and planks. However, with the current legal situation in Germany, the re-use of this wood in load-bearing

Table 7
Potential amounts for cascading utilization of recovered wood from building deconstruction in Bavaria in 2011. Percentages refer in each case to the total amount of recovered wood of 56,838 m^3 as presented in Table 6.

	Structural components suitable for re-use [m^3]	Solid wood [m^3]
Residential buildings	7016 (10%)	7072 (16%)
Non-residential buildings	6948 (16%)	4954 (11%)
Building stock total	13,964 (25%)	12,026 (21%)

structures is not allowed, as the German Waste Wood Act (German Government, 2003) classifies this wood in class A IV, which disqualifies the wood for other applications than energy production. Nevertheless, also these amounts are included in the calculations as they are potentially valuable input resources for cascading. The overall cascading potential (Table 7) is therefore higher than the total amount of class A II wood (Table 6). For an effective use of this considerable resource amount and in the light of improving sorting technologies for recovered wood, this strict regulation ought to be reconsidered.

Another factor determining the potential of recovered wood from building deconstruction for cascading utilization is the share of solid wood without major contamination (class A I + II), which is a suitable raw material for engineered wood products such as particleboards or even OSB and other high-quality products. We found that 21% of the recovered wood from building deconstruction in Bavaria meets these requirements (Table 7). The quality requirements for particleboard also allow for waste wood fractions consisting of engineered wood products to be used as input, which increases the potentially available amount to 44% of the total recovered wood (Classes I + II; Table 6).

As mentioned in Section 2.3, we assumed minimum contamination during the service life of the wooden building components. Currently, the actual share of non-contaminated solid wood from dismantling can be assumed to be lower than the amounts calculated by applying this assumption. Yet, with a rising awareness of the problems associated with chemicals and preservatives in wood, an achievement of this share in recovered wood streams from buildings can be seen as probable. Problems generally occur twofold: In both the production and use phase of impregnated wood and wooden products can the applied chemicals such as chromium and copper or substances such as creosote cause serious harm to human health. Additionally, the end-of-life options for impregnated wood are restricted, since an incineration with effective flue gas cleaning often is the only viable option. The Biocidal Products Directive (98/8/EC) of the EU, issued in 2000, accommodates these facts by requiring the authorization of a wide range of biocide products, which previously could be applied without authorization.

In the study area, the development toward constructive instead of chemical wood protection will be further encouraged by a current change of the standard DIN 68800, which rescinded the mandatory treatment of certain wooden building parts with preservatives and generally emphasizes a reticent application of chemical wood treatment.

3.5. *Relevance of recovered wood from deconstruction for a cascading utilization*

To determine the relevance of recovered wood from building deconstruction for cascading utilization, we additionally conducted a scenario analysis by applying different deconstruction rates and comparing the resulting amounts of recovered wood to the annual input of virgin wood in the wood products manufacturing industry in Bavaria. Scenario A depicts the current deconstruction rate of 0.06%, as derived from statistical data (BayLfStaD, 2012). Scenario B assumes a four times higher rate, in accordance with a study of Sautter (2004), carried out for the neighboring state of Hesse in Germany. It showed a four times higher real deconstruction rate compared to the statistical recorded one. Scenario C assumes a building lifetime of 80 years, as given by IEMB (2006), to be the technical lifetime of brick buildings in Germany. Finally, in scenario D, the average building lifetime is assumed to be 50 years, in accordance with most Life Cycle Assessments (LCA) of buildings, especially in the German Building Certification Scheme DGNB (Lemaitre, 2011).

Particleboard is the most important utilization of recovered wood as a secondary material in Bavaria. Due to given requirements regarding size, moisture and color of the applied wood chips, recovered wood is suitable when applying a thorough sorting beforehand. Furthermore, particleboard is the only industrially manufactured wood product of significance in Bavaria in regard to production volume. According to Friedrich et al. (2012) a raw material input of approximately 750,000 t of wood was required in 2011 in Bavarian production sites. Since it can be assumed that in 2011 already 33% of this amount was constituted by recovered wood (EPF, 2012), only 500,000 t of virgin wood were utilized. This amount of virgin wood could further be reduced by using recovered wood from building deconstruction, if the concept of cascading were widely applied. Due to legal guidelines and quality standards, only recovered wood of the quality classes I and II (Table 1) is eligible for particleboard production.

When applying the statistical recorded deconstruction rate of 0.06% as in scenario A, slightly less than 13,000 t of suitable secondary raw material will be available per year (Table 8). This amount could replace only 3% of the total annual demand of 500,000 t. Assuming the findings of Sautter (2004) to be applicable for Bavaria, a resulting deconstruction rate of 0.25% would lead to a potential contribution of 10% (Scenario B, Table 8). Scenarios C and D are based on different average building lifetimes, in accordance with IEMB (2006) and LCA principles in building certification (Lemaitre, 2011). Both scenarios lead to a substantial increase in recovered wood from deconstruction, enabling considerable substitution of recovered wood for primary wood in particleboard production in Germany.

However, deconstruction rates have been gradually declining in Bavaria since a peak at the beginning of the 1990s for both residential and non-residential buildings. A rise to a magnitude seriously influencing the available amounts of recovered wood as shown in Scenarios C and D is therefore not to be expected in the near future. Furthermore, despite its being technically feasible and already established in other European countries such as Italy, Great Britain and France, using higher amounts of waste wood in particleboard production seems to meet a certain resistance both

Table 8
Scenario analysis of different deconstruction rates, resulting amounts of recovered wood and their potential contribution to cascading utilization in particleboard production in Bavaria. Percentages refer to the total annual input of virgin wood in particleboard production in Bavaria (500,000 t).

	Scenario	Deconstruction rate [%]	Resulting waste wood [1000 t]	Suitable for particleboard production (Class I + II) [1000 t]	Possible contribution as cascading resource [%]
A	Statistical rate	0.06	28	13	3
B	Assumed real rate (Sautter, 2004)	0.25	118	52	10
C	Building lifetime of 80 years	1.25	592	261	52
D	Building lifetime of 50 years	2.00	947	417	83

by customers and producers in Germany. Some reasons may be a reluctance to purchase products manufactured out of “waste” on the part of the customers and an apprehension to possibly exceed maximum permissible values of contaminants on the part of the manufacturers.

Even as recovered wood from building deconstruction only contributes a minor share to the overall amount of recovered wood, it is nevertheless important for a cascading utilization of wood. Due to the partly larger size compared to recovered wood parts from other sources such as furniture, applications with a higher quality such as OSB, floorings or re-use are possible. This requires a planned and thoroughly executed deconstruction in order to salvage those parts which are suitable for these purposes. Kibert (2003) describes the opportunities and constraints associated with deconstruction. Among the constraints are especially the uniqueness of most buildings and the use of aggregated and hardly separable materials.

As deconstruction rates cannot be expected to increase, the focus should be on improving and simplifying deconstruction, thereby maximizing the originating potential amounts of secondary resources.

In order to facilitate a disassembly of buildings and allow a re-use and recycling of the incorporated materials, some steps should be taken already in the design phase and during the construction process. Of major importance is a profound knowledge regarding the incorporated materials, accessibility to all parts of the buildings and the possibility to remove and replace individual building parts without demolishing the whole complex (Crowther, 1999; Kibert, 2003). In the case of wood as a building material, efforts have been made over the last years to implement these principles of design for disassembly: Buildings constructed with pre-assembled wood frame wall elements can easily be disassembled after their service life and the reduction of chemicals in wood preservation also facilitates a re-use as secondary material. However, it is additionally necessary to further develop and implement robust and efficient analytical sensor technologies to secure a reliable identification of impurities and contaminants.

4. Conclusion

Our study revealed a considerable amount of recovered wood from the building sector available in conditions which allow a high-quality material cascading and thus a secondary utilization.

Forty-four percent of the recovered wood from building deconstruction is potentially suitable for use as raw material for particle- or fiberboard production, and 25% would even be applicable in a re-use scenario, thereby adding an additional step to a possible cascading of recovered wood and thus increasing the time span of carbon storage in the wood products in order to delay its contribution to the greenhouse effect. Twenty-one percent of the recovered wood could be utilized for high-quality secondary applications.

Yet, to be able to use this resource potential of the building stock to its fullest extent, the deconstruction of existing buildings has to be conducted in such a way that a recovery of the incorporated valuable secondary resources is possible. Currently, the awareness of the importance of resources stored in the building stock is rather unpronounced, resulting in a destruction of valuable resources during the process of demolishing. With rising prices for resources, a change in awareness can be expected in the future.

Additionally, legal regulations currently hinder certain aspects of an effective cascading use of recovered wood, such as the reuse of structurally used wood components. To facilitate cascading in the future, adaptions in the legal guidelines should be considered. Especially the reuse of structural components should be permitted for those suitable in regard to strength properties und contamination.

Detailed information regarding the stock and its contents – as provided by this study for the wood fraction – is crucial and will become even more important with increasingly scarce primary resources. To apply the concept of cascading of recovered wood in the most beneficial way, further research regarding the ecological and economic benefits, the necessary logistics and the technical processing is necessary.

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