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LCA-based optimization of wood utilization under special consideration of a cascading use of wood

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ABSTRACT

Cascading, the use of the same unit of a resource in multiple successional applications, is considered as a viable means to improve the efficiency of resource utilization and to decrease environmental impacts. Wood, as a regrowing but nevertheless limited and increasingly in demand resource, can be used in cascades, thereby increasing the potential efficiency per unit of wood. This study aims to assess the influence of cascading wood utilization on optimizing the overall environmental impact of wood utilization. By combining a material flow model of existing wood applications – both for materials provision and energy production – with an algebraic optimization tool, the effects of the use of wood in cascades can be modelled and quantified based on life cycle impact assessment results for all production processes. To identify the most efficient wood allocation, the effects of a potential substitution of non-wood products were taken into account in a part of the model runs. The considered environmental indicators were global warming potential, particulate matter formation, land occupation and an aggregated single score indicator. We found that optimizing either the overall global warming potential or the value of the single score indicator of the system leads to a simultaneous relative decrease of all other considered environmental impacts. The relative differences between the impacts of the model run with and without the possibility of a cascading use of wood were 7% for global warming potential and the single score indicator, despite cascading only influencing a small part of the overall system, namely wood panel production. Cascading led to savings of up to 14% of the annual primary wood supply of the study area. We conclude that cascading can improve the overall performance of a wood utilization system.

1. Introduction

Wood products are often found to have lower environmental impacts when compared to functionally equivalent products from fossil or mineral resources (Sathre & O'Connor, 2010; Werner et al., 2005; Werner and Richter, 2007). Raw material acquisition and production requires less fossil based energy, which leads to overall reduced environmental impacts and therefore creates benefits if substituting conventional materials. If utilized as fuel, wood can substitute for the diminishing fossil energy carriers. Because wood materials can be utilized for energy production at their end-of-life, benefits occur two-fold. By using wood in cascades – i.e. for multiple successive applications, first as a material and finally as a fuel - the benefit created by one unit of wood could possibly be even further increased. In particular, legislative bodies have put high expectations into the concept of cascading for strengthening the efficiency of resource use (European Commission, 2011; BMU, 2012). Additionally, a cascading utilization is often regarded as a suitable strategy to bridge the gap between rising demand for wood and the projected stagnating availability of primary wood (Mantau, 2012).

Several studies analyzing wood cascading have been published so far and almost all of them, depending on the particular focus of the study, concluded that cascading creates environmental benefits. After the initial introduction of the concept by Sirkin and ten Houten (1994), Fraanje (1997) examined possible cascades of pine wood utilization in the Netherlands, finding that cascading can substantially prolong carbon sequestration to mitigate climate change. Sathre and Gustavsson (2006) calculated the primary energy and carbon balances for various wood cascades, taking into account direct cascade effects, substitution effects, and effects of

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Nomenclature

C	Model runs with the option of a utilization of waste wood in cascades
CHP	Combined heat and power plant
GWP	Global warming potential; optimized value
h	Hardwood
IC	Impact category in LCA
IRW	Industrial round wood
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LO	Agricultural land occupation (including forests); optimized value
nC	Model runs without the option of cascading of waste wood
OSB	Oriented Strand Board
PM	Formation of particulate matter (<10 μm); optimized value
PW	Primary wood from forests
s	Softwood
SC	Single Score Indicator aggregating several impact categories; optimized value
WW	Waste wood

varying land use due to cascading. They concluded that land use effects are the dominating contribution to the overall effects of cascading. A more recent study (Sikkema et al., 2013) assesses the consequences of a cascading wood use in Canada on GHG emissions, comparing different cascading scenarios to the IPCC default scenario, which assumes an immediate incineration and thereby carbon dioxide release from the wood. They found that noticeable reductions of GHG emissions can be achieved, yet they did not take into account the direct effects of cascading, such as energy savings in panel production due to lower moisture content in waste wood compared to primary wood.

Life cycle assessment (LCA) is used to evaluate impacts on the environment resulting from processes, products and related activities (ISO, 2006), thereby taking into account the whole life cycle of the product from raw material acquisition to final disposal or secondary utilization and allowing for a comparison of different product systems. LCA is frequently applied to assess environmental impacts related to the production of specific wood products such as wood based panels (Diederichs, 2014; Gonzales-Garcia et al., 2009; Wilson, 2010) and wood decking (Bergman et al., 2014). Comparative assessments of wood products, e.g. to determine possible substitution benefits as included in our study, have also been published (Sandin et al., 2014; Werner and Richter, 2007). A review by Sathre & O'Connor (2010) covers substitution effects of wood in regard to greenhouse gases. Two recent reviews of LCA studies of wood production and utilization (Klein et al., 2015; Wolf et al., subm.) further indicate that LCA is a well-established methodology to assess the environmental impacts of the whole forest-wood-chain. Yet to date, only a few studies assessing wood cascading with the method of LCA have been published (Gärtner et al., 2012; Höglmeier et al., 2014). These two studies both compared exemplary wood cascades to equivalent products from primary wood, albeit with different approaches to crediting and substitution. They conclude that cascading creates less environmental impacts when compared to the production of equivalent products from primary wood. However, when comparing exemplary cascading product chains to reference systems as displayed in the aforementioned studies, several aspects crucial for the evaluation of the environmental performance of cascading are not sufficiently considered. First and foremost, if the basis for comparison (= functional unit) is the amount of product output (materials and energy) of the system, the wood input required to provide the products is only considered in terms of resulting environmental impacts. Since the utilized amount of wood only contributes to a minor extent to the overall impacts of the provision of wood products, the fact that one system might require substantially less wood input than the other system (being therefore more resource efficient) is not sufficiently accounted for in the LCA results.

The fact that wood is a regrowing but nevertheless limited and increasingly in demand resource and the resulting competition for wood resources cannot be adequately addressed by such an approach. Furthermore, interdependencies with and consequences for wood products not assessed by the considered cascade chain, such as the use of by-products, are not taken into account when only looking at single cascades. In order to integrate these aspects into the assessment, a holistic view of the wood utilization system must be taken by integrating materials, energy production and resulting wood flows. The goal should be an optimization of the system level to which cascading might contribute in new dimensions. Therefore, this study combines an LCA-based material flow model of wood material and energy generation options based on the region of Bavaria in southeast Germany with an algebraic optimization tool to enable a systemic assessment. Cascading utilization of wood is integrated in the model.

To close this gap, the goal is to identify the relationships between various utilization options of wood in the context of a cascading use of wood and to detect and highlight decisive drivers for the environmental performance of the system. This approach will create knowledge about sensitive parts of the system in order to integrate a cascading use of resources in the most environmentally beneficial way. The model is based on the situation in southeast Germany, yet findings are in principle transferable to other areas with similar wood utilization systems, i.e. large parts of Europe and North America. In detail, the following research questions will be answered:

(1) How does cascading influence an effective wood utilization under consideration of current utilization patterns?
(2) Does cascading lead to a reduction of the overall environmental impact of wood utilization, and what magnitude of reduction can be expected?
(3) What are the determining factors in regard to the efficiency of cascading?
(4) Is the approach of combining LCA with a material flow model suitable for answering these questions?

2. Material and methods

2.1. Model description

A material flow model containing the most common wood materials as well as wood energy options for both heat and power was developed (Fig. 1). It has the annual forest wood supply of the state of Bavaria in southeast Germany as an input. The considered products (materials und energy) were chosen based on the wood use situation in the study region, however, also products, such as oriented strand board (OSB), not produced in Bavaria but in nearby areas were included in order to ensure the transferability of the results to a wider geographic scope. The utilization of waste wood and industrial residual wood originating from the production processes in the model was also included. Life cycle impact assessment (LCIA) results for all model processes, from raw wood

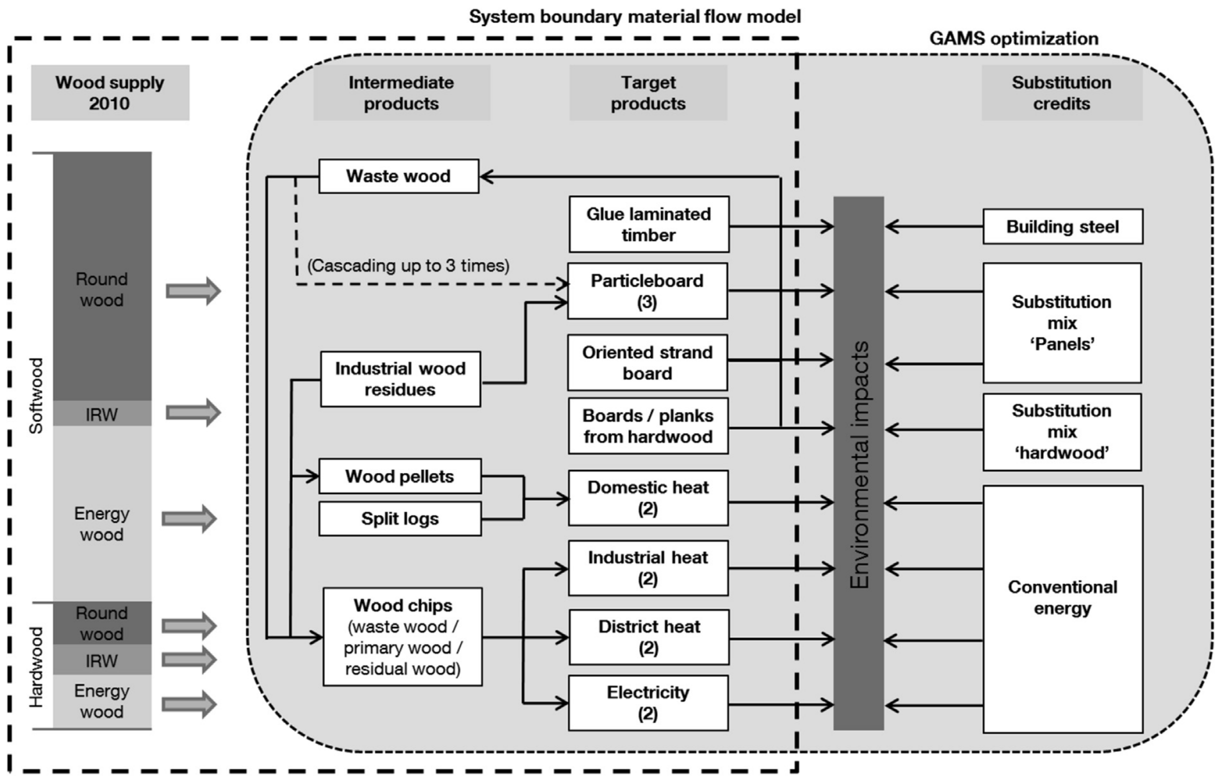

Fig. 1. Simplified overview of the model approach (only selected material flows are displayed). Numbers in brackets indicate considered amounts of variants (IRW: Industrial round wood).

Table 1
Wood products of the model and considered non-wood substitution products.

Wood product	Substitution product
Materials	
Glue-laminated timber	Building steel
Boards and planks (hardwood)	Module combining weighted LCIAs of indoor building products (windows 60%, floorings 40%)
Wood panels: a) Oriented strand board b) Particleboard with different wood input mixes (100% primary wood or 100% waste wood or 20% waste wood/ 65% Industrial residual wood/ 15% primary wood)	Module combining weighted LCIAs of fossil and mineral based panels and furniture to represent current panel utilization in Germany (Furniture 50%, gypsum boards 50%)
Energy	
Domestic heat from a) split logs b) wood pellets	Domestic heat mix (light fuel oil 80% and natural gas 20% in small scale boilers)
Industrial heat from a) forest wood chips b) industrial residual wood in a mix of different boiler sizes	Industrial heat mix (natural gas 65%, hard coal 25%, light fuel oil 10%)
District heat from a) forest wood chips or b) waste wood in heating plant or combined heat and power plant (CHP)	District heat from 100% natural gas
Electricity from a) forest wood chips b) waste wood in power plant or CHP	Conventional electricity (German grid mix)

provision to materials manufacturing and energy generation from primary and secondary wood resources, as well as transportation were included in the model. The inclusion of LCA enabled an assessment of the collective environmental impacts caused by utilizing the annual wood supply of 2010. By combining a spreadsheet-based material flow matrix, which defined types and amounts of input and output flows of all processes of the wood utilization system as well as their associated environmental impacts, with the algebraic modelling program GAMS (GAMS Development Corporation, 2013), the overall environmental impact of the system could be calculated. The aim was to determine the specific wood utilization which meets all set constraints, especially in regard to the demanded products amounts, and which causes the overall lowest environmental impact for different impact categories of LCA. Model outputs were a portfolio of different wood products produced from the annual wood supply, as well as the total environmental impact of the system – from timber production to end-of-life incineration of the wood products – for four impact categories of LCA.

In a number of the model runs, materials and energy from wood were credited with "substitution benefits", i.e. the potentially avoided environmental impacts by substituting fossil and mineral based products with wood based products (Table 1, chapter 2.3.1). The choice of the substitution product or product group reflected the common utilization of the respective wood product in the study area. E.g. in the case of wood panels, non-wood furniture as well as a variety of gypsum based panels were chosen as substitution products, since 80% of German wood panels are used for furniture production and the remaining 20% in the building sector (Mantau and Bilitewski, 2010). Detailed information regarding the substituted amounts and substitution factors is given in the Supplementary Information. For one set of scenarios, no substitution credits were given so that the optimization was carried out based solely on the environmental impacts of the provision of wood products (chapter 2.3.2).

The production of pulp and paper was not part of the model, since the paper industry has already implemented resource cascading to a high level (Peche et al., 2011). Additionally, almost all by-products of pulp and paper production are utilized internally. Consequently, after the input of fresh forest wood and industrial wood residues to the production process, no further interactions and interdependencies of pulp and paper production with other wood resources and products take place. The wood resources utilized for pulp and paper production were excluded from the total wood supply of the model.

The utilization of wood in cascades was implemented in the model by allowing wood based panels to be produced from fresh wood as well as from waste wood or a mix of both (cp. chapter 2.2.3). Alternatively to this material application of waste wood, incineration for energy production was possible in the model. The possibility to use waste wood for panels could be excluded for specific model runs, so that all waste wood had to be incinerated directly and no cascading took place. To model reality as accurately as possible, minimum values were set for each target product category. The current wood utilization in the study area was taken as a basis for determining these minimum or threshold values (see chapter 2.2.2).

2.2. Input parameters of the model

2.2.1. Annual forest wood supply

An input parameter of the model was the annually available wood supply for the state of Bavaria in southeast Germany. The amounts and quality grading ratios modeled by Härtl and Knoke (2014) for the year of 2010 were utilized. Their assessment is based on the forest optimizer model YAFO (Härtl et al., 2013) coupled with oil related timber price development scenarios. Härtl et al. (2013) modeled the expected wood supply for a time span from 2010 to 2035 with various assumptions relating to the development of the oil price and its influence on timber supply. Possible reactions of forest owners to the development of timber price with regards to felling amounts were taken into account by the model. The moderate basis scenario, which assumed a constant oil price over the coming years, was the input of the model.

Since pulp and paper production were excluded from the model, the wood amounts utilized for these products were subtracted from the overall supply (Table 2). The model distinguishes between softwood and hardwood, with the former including predominately spruce and pine and the latter beech and oak as the main tree species of the study region. For each species group, the assortments of roundwood, industrial roundwood and energy wood are distinguished.

Table 2
Annual wood supply as input values for the model.

		Total (Härtl and Knoke, 2014)	Without wood input for pulp and paper production (own calculations[a])
		[m^3 under bark]	
Softwood	Roundwood	8,875,642	8,875,642
	Industrial roundwood	1,288,655	619,055
	Energy wood	5,537,120	5,280,620
Hardwood	Roundwood	1,326,525	1,326,525
	Industrial roundwood	1,169,550	723,150
	Energy wood	1,769,988	1,684,488
Total		19,967,480	18,509,480

[a] Based on Härtl and Knoke (2014) and Friedrich et al. (2012).

2.2.2. Current wood utilization and resulting minimum amounts for target product categories

In order to better represent the current situation in the study area in the model and thus enable valid conclusions, minimum amounts representing the current use of wood products were set as thresholds for each of the target product groups. The demand for wood for material and especially energy production is expected to increase in the future (Mantau et al., 2010). Therefore, minimum amounts derived from current wood use can be expected to remain valid in the future, since demand will most probably not drop below these numbers. Statistical data of the most current demand for wood products are not available for the region of Bavaria. Hence, the minimum values for the different products considered in the model were derived based on the utilization of forest wood assortments in the year 2010 as assessed by Friedrich et al. (2012). By applying the wood input values (assortments and amount) for each product as utilized in the model matrix, hypothetical demands were deduced (Table 3).

2.2.3. Integration of wood cascading

The effects of a cascading wood utilization on the optimal utilization portfolios were assessed by implementing recycling possibilities into the model (cp. Fig. 1). Quality requirements of specific wood products, with regard to particle size and cleanliness of the wood, must be taken into account and limit cascading possibilities. Additionally, waste wood collection and recycling inevitably leads to losses. A technical yield of 95% following the transportation and processing (sorting and chipping/crushing) required after each service life of the wood products was assumed. This value is in accordance with process specifics derived from two German waste wood processing facilities. Additionally, a collection rate of 95% was applied. These values result in a total loss of 10% for each cascading step (Table 4).

Whether a wood product occurring in the model is suitable for material recycling or only fit for energy production was based on the relevant German legal requirements (German Government, 2003), which prohibit landfilling and require the sorting of waste wood into different classes. This classification determines the possible secondary application (material and/or energy). Data regarding the resulting shares of waste wood quality from different utilizations (e.g. building, packaging, furniture) are scarce. Höglmeier et al. (2013) assessed waste wood qualities resulting from building deconstruction. Lang (2004) provided shares of waste wood qualities resulting from different applications. In accordance with these assessments, Table 4 shows the assumed distribution into material or energy as the possible subsequent waste wood recycling steps in the model. Waste wood potentially suitable for material application can, however, be utilized further

Table 3
Required minimum amounts per product group based on actual timber utilization in 2010 without pulp and paper (based on Friedrich et al., 2012).

Target product group	Actual utilization/minimum values
Materials	
Glulam from softwoods [m^3]	3,917,455
Sawn timber from hardwoods [m^3]	478,800
Panels (Particleboard and OSB) [m^3]	1,656,000
Energy	
Domestic heat [TJ]	41,625
Industrial heat [TJ]	6,383
District heat [TJ]	22,271
Electricity [TJ]	1,237

Table 4
Quality distribution and yield of waste wood processing in the model in % of total occurring waste wood for various wood products (based on Höglmeier et al., 2013; Lang, 2004).

	Recollection rate[a]	Technical loss (transportation/processing)	Remaining waste wood suitable for	
			Materials	Energy
Glulam timber (s)	95	5	90	0
Sawn timber (h)	95	5	54	36
Panels, step 1	95	5	72	18
Panels, step 2	95	5	63	27
Panels, step 3	95	5	0	90

[a] Subject to sensitivity analysis (cp. chapter 2.4).

for energy production but not vice versa. In the case of wood based panels, three cascading steps were distinguished with varying quality shares to ensure that a certain unit of wood could only be cascaded a maximum of three times. Additional recycling steps for particleboard are technically unlikely due to the decreasing wood particle size and the increase of the adhesive resin amount in the waste wood.

2.2.4. Life cycle assessment of wood and substitution products

2.2.4.1. Life cycle impact assessment. The environmental impact categories (IC) examined in this study comprise three midpoint indicators. The global warming potential (GWP) was calculated based on the report by the IPCC (2007) and excluded biogenic carbon. The formation of particulate matter smaller than 10 µm (PM) and agricultural land occupation (LO) were assessed based on the impact assessment scheme ReCiPe 1.07 (Goedkoop et al., 2013). We focus on these ICs as they represent impacts often mentioned in public discussion in regard to wood production and utilization. Additionally to these three midpoint indicators, the ReCiPe Endpoint H/A method, which integrates weighted LCIA results of all endpoint impact categories of ReCiPe 1.07, was used as an aggregated single score indicator (SC) in order to enable the concurrent consideration of different potentially contradicting environmental impacts in the single objective optimization.

2.2.4.2. Life cycle inventory. If not specified otherwise, the basis for all LCAs was the generic datasets of the ecoinvent database in version 2.2 (Frischknecht and Jungbluth, 2007) for materials, energy and all necessary background processes. Where available, data representative for German conditions was used or the ecoinvent data was adapted accordingly. The sorting and processing of waste wood was modeled with primary industry data of three differently sized, south German waste wood recycling companies (cp. the supplementary information). The wood material models (glulam, panels, sawn timber from hardwoods) are based on the inventory data provided by Rüter and Diederichs (2012), which represents average German conditions. Particleboard from 100% waste wood is currently not produced in Germany but is part of the study system in order to assess the effects of cascading. Therefore, the average German LCI data from Rüter and Diederichs (2012), which assume a waste wood content of 20%, was adapted. The adaptions consisted mainly of increasing the wood loss by chipping and of decreasing the energy required for drying of the wood. The amount of the relative energy reduction was based on industry information from a German particleboard manufacturer. No adaptations were made for the adhesive resin fraction and other chemicals. Detailed descriptions of the adaptions can be found in the supplementary information. The process heat required for production of panels from waste wood was assumed to be produced from waste wood, whereas in the case of the panels from primary wood, only the production rejects were assumed to be incinerated for energy production and additional energy was generated from other industrial residue wood. The processes for conventional energy generation and wood energy from primary wood were taken from the ecoinvent database. For incineration of waste wood, emissions were adapted, e. g. by adding CO_2 from fossil sources originating from coatings, additives, and resins in the waste wood.

2.3. Modeled scenarios

2.3.1. Scenarios with credits for substitution of non-renewable products

In a first set of model runs, credits for the substitution of non-renewable products were given for each wood product. The model detected the optimal product portfolio by minimizing specific environmental impact categories of LCA. The total environmental impact was calculated by adding all impacts generated by utilizing the wood supply and subtracting impacts prevented by substituting conventional products with wood products. To determine optimal wood utilization and effects of cascading, all model runs were conducted with (C) and without (nC), including the possibility of a cascading utilization of waste wood consisting of the production of panels totally or partially from waste wood. This enabled for a comparison of resulting overall environmental impacts and product portfolios, thereby displaying the effect of cascading. The parameter to be optimized was the total environmental impact of the system.

2.3.2. Scenarios without substitution credits

A second set of model runs was conducted where the model considered the LCIA results for the production of the wood materials and wood energy until the end-of-life of each product, however, no effects of substituting fossil or mineral based products were assumed. The overall environmental impact of the system to be optimized was composed of the sum of the environmental impacts of wood utilization.

The intention of this additional approach was twofold: Firstly, since crediting of wood products with potential substitution benefits influences the optimal product portfolio, the approach made it possible to examine whether the conclusions to be deduced from the scenarios including credits also hold true if no, to a certain extent always subjective crediting is applied. Secondly, this approach enabled an examination of the influence of cascading on the efficiency of wood utilization. As no credits are given, the production of each unit of a wood product increases the total environmental impact of the system. Consequently, only the

Table 5
Overview of sensitivity analyses and respective examined effects.

Sensitivity analysis name	Varied parameter	Default setting	Variation	Examined effects
Yield 95	Yield of waste wood collection & processing	90%	95%	Product portfolio/ Environmental impacts
Yield 86	Yield of waste wood collection & processing	90%	86%	
Yield panel	Yield of waste wood collection & processing	90%	30 … 100% recollection of waste wood	Total produced amount of panels
Subst gas	Substitution electricity	German grid mix	Natural gas 100%	Product portfolio/ Environmental impacts
Subst panel	Substitution module for wood panels	Furniture 50%, Gypsum boards 50%	Gypsum boards 100%	

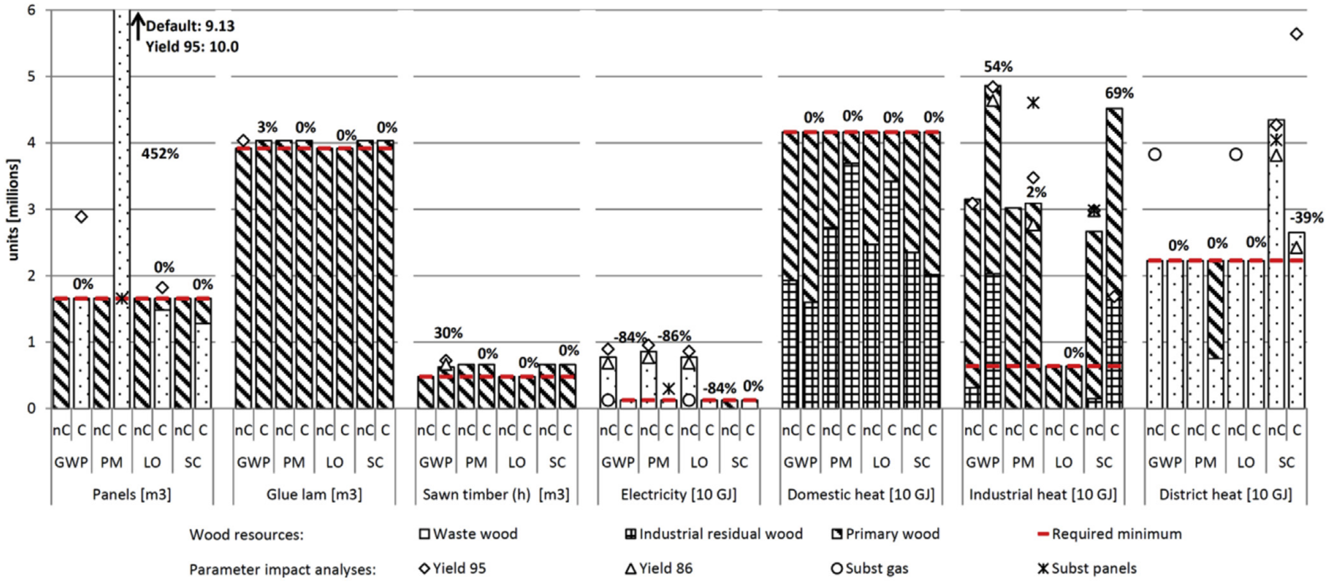

Fig. 2. Optimal product portfolio for the optimization parameters GWP, PM, LO and SC with and without the possibility of cascading. Numbers on the cascading columns indicate the difference of produced amounts between the respective cascading and non-cascading scenarios. Minimum amounts are indicated by the bold line. Markers indicate portfolio changes by parameter analyses (no changes if no markers are displayed).

minimum values set for each of the target product categories are produced, contrary to the crediting-scenario where as many products as possible are produced.

2.4. Sensitivity analyses

To assess the robustness of the results, scenarios with variations of a number of parameters of the model with crediting for substitution were conducted (Table 5). Since it directly influences the efficiency of the use of secondary wood, the recollection rate of waste wood was the first parameter to be analyzed. No reliable assessment of the actual share of wood products recollected after their service life is available for Germany. Yet, due to a strict legislation and effective collection system, rather high shares can be assumed. Since panels are the only material application of waste wood considered in the model and also the only one with actual real importance, an additional examination was also carried out of the effects of the efficiency of waste wood collection and sorting on the amount of panels produced with different optimization parameters.

The second examined parameter was substitution credits for electricity and wood panels. Credits for electricity was chosen because its substitution benefits are generally higher than those of heat and thereby more strongly influence the optimal product portfolio composition. Panels are an important and variable product group that was credited by a module containing a mix of several products, and the composition of this module was the other substitution credit examined in the sensitivity analysis.

3. Results

3.1. Scenarios with substitution credits

3.1.1. Product portfolios with different optimization parameters

The option of cascading waste wood influences the composition of product portfolios, both in terms of produced amounts and in the wood assortments used (Fig. 2). Changes occur mainly in the product groups that allow waste wood as a raw material. Apart from panel production, where cascading leads to a substantial share of panels produced from waste wood even though the overall amount varies only for optimizing PM, mainly electricity and to a certain extent district heat are influenced. The results suggest that panels are not an optimal wood allocation, since in most scenarios only the required minimum amount was produced by the model. The reason is the relatively high environmental impacts of panel production due to the required wood processing, adhesives and additives. Therefore, the benefits achievable by substituting non-wood products are lower for panels when compared to other wood products, since the difference in environmental impacts between wood and non-wood products is smaller. However, engineered wood products, such as panels, are flexible products with a multitude of applications and with a stable demand. Production from waste wood through cascading is the preferable way to meet this demand, as shown by the change in utilized raw materials for panels in the model runs allowing cascading.

With cascading, electricity production drops to the minimum value in all cascading scenarios, since the provision of panels in multiple cascading cycles decreases the available waste wood amount due to consumption of waste wood for process heat production and some losses. Yet waste wood is found as the preferred raw material for electricity and district heat in nearly all scenarios. Industrial heat as well as domestic heat could only be produced from waste wood in our model. Cascading also influences these product groups because primary wood and industrial residual wood is available in higher amounts when waste wood can be cascaded. When optimizing PM, even district heat is produced from primary wood to a certain extent. Specifically, cascading leads to a shift from industrial roundwood from panel manufacturing to split log production and therefore to a decrease in the second source of domestic heat (pellets). This, in turn, increases the availability of industrial residual wood for the production of industrial heat (Fig. 3).

However, as can be seen in Fig. 3, in order to optimize the impact category global warming potential, no substantial increase of production is possible in the case of glulam and sawn timber. The suitable raw wood assortments for these products (roundwood from softwoods and hardwoods) are limiting factors, since a major

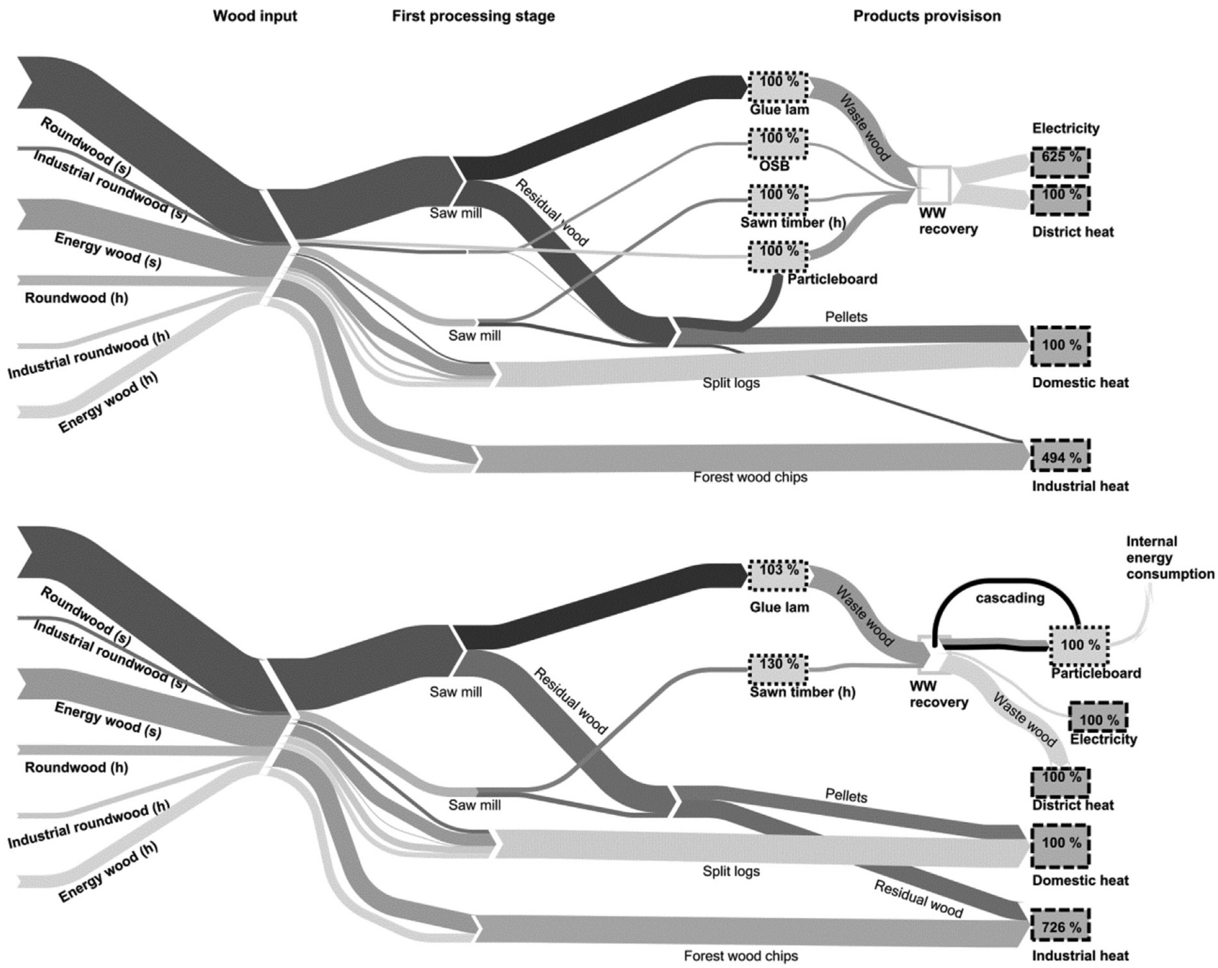

Fig. 3. Sankey diagrams displaying the material flow for optimizing GWP, without (top) and with (bottom) the possibility of cascading. Percentages show the degree of fulfillment of the required minimum amounts per product category. The arrow width is determined by dry matter content of the wood flow.

share is already required to produce the defined minimum amounts indicated by the bold line in Fig. 2. The increases of 3% of glulam and 30% of sawn timber from hardwoods, which occur in the cascading scenario of GWP, are the maximum possible increases. In all cascading scenarios, regardless of the optimized environmental impact, the total roundwood supply is used for sawn products.

Overall, the changes in the wood flows by cascading are noticable. Yet the general allocation of the primary wood input assortments is not influenced, with the exception of rather small amounts of industrial roundwood. Cascading mainly influences the wood flows after the first processing stage.

3.1.2. *Resulting environmental impacts of wood utilization*

A focus was placed on the difference between non-cascading and cascading variants rather than on absolute amounts. A first trend that can concluded from the environmental impacts of wood utilization (Table 6) is that if cascading is a possibility in the system, the overall environmental impacts of the system generally decrease. Exceptions are global warming potential when optimizing land occupation and the single score indicator when optimizing particulate matter formation and land occupation. With regard to relative differences between cascading and non-cascading scenarios, the biggest improvements occur for the formation of particulate matter, where reductions of 571% and 519% are possible for optimizing PM and LO.

Minimizing the single score indicator leads to rather similar outcomes as those from the optimization of GWP. In particular, the reduction of greenhouse gases is in the same magnitude.

The overall environmental impact including substitution credits is negative in most scenarios, meaning that possible credits exceed the impacts caused by the provision of wood products. An exception is the impact category land occupation, where impacts exceed credits in all scenarios. Conventional products often have an advantage when compared to wood products, since they lead to less land occuption.

The overall impacts are lowest when optimizing land occuption for all categories. However, this is due to the fact that in the LO-scenarios only a certain share of the total primary wood supply was used by the model, namely the amount required to provide the minimum needed per target product group. This is as no net credits result from the provision of wood products for this category (chapter 3.1.3). In the category of particulate matter formation, credits are lower than impacts in wood production processes for some scenarios. However, as already mentioned, cascading can lead to substantial reductions in this category. This is mainly caused by the shift of domestic heat production from the incineration of split logs in small furnaces to the use of pellets, as more industrial residual wood is available for pellets when particleboards are produced from waste wood. The effect of substantially increasing particulate matter formation by small scale domestic furnaces is widely being discussed in Germany, since rising fossil fuel prices

Table 6
Total environmental impacts of wood utilization for different impact categories and optimizations for nC and C variants with consideration of substitution credits. Relative difference (Δ) of the C in relation to the nC variant.

	Optimization parameter											
	GWP			PM			LO			SC		
	nC	C	Δ	nC	C	Δ	nC	C	Δ	nC	C	Δ
	[10^6 kg CO_2 eq.]		[%]	[10^6 kg PM10 eq.]		[%]	[10^6 m^{2}*a]		[%]	[10^6 ReCiPe points]		[%]
GWP	*−9,100*	*−9,714*	*−6.7*	−9,055	−9,059	0.0	−7,021	−5,983	14.8	−9,001	−9,609	−6.8
PM	0.61	0.53	−12.7	*−0.22*	*−1.45*	*−571*	0.19	−0.79	−519	0.49	0.25	−49.9
LO	20,351	20,339	−0.1	20,353	19,922	−2.1	*17,043*	*15,371*	*−9.8*	20,370	20,357	−0.1
SC	−1.84	−1.96	−6.3	−1.84	−1.73	5.8	−1.48	−1.31	11.5	*−1.93*	*−1.96*	*−2.0*

have led to an especially strong increase of using split logs for heating.

3.1.3. Changes in wood utilization parameters by cascading

To get a better understanding of the effects of cascading on the material flow system, several parameters characterizing wood utilization in the system were assessed additionally to the portfolio composition and environmental impacts (Table 7). Lines 1 to 3 of Table 7 show the share of the total produced energy that has been provided by incineration of waste wood. The highest total shares (heat and power, line 3) of 38% are obtained in non-cascading scenarios, which is due to the fact that particleboard production from waste wood in the cascading scenarios decreases the available waste wood for energy production at the end-of-life. This trend can be detected for most of the cascading scenarios as well as when looking separately at the different energy types (lines 1 and 2).

Another characterizing aspect is the share of the total primary wood supply utilized in a material application in the first step, thus enabling a later potential use in cascades. Noticeably, these numbers are higher for the non-cascading model runs, since panels have to be produced from primary wood in these cases. Yet this finding does not automatically allow for the conclusion that cascading of waste wood leads to a higher share of incineration of primary wood. The reason is rather the specific setup of the model, which credits wood products for substituting conventional products. Hence, if less primary wood is needed for providing the required materials due to cascading, the remaining primary wood is incinerated, which leads to the displayed higher shares of primary wood for energy production (line 4). Reviewing the scenarios that optimize the land occupation impact category confirms this. In this case, the provision of wood products does not lead to positive credits, and, therefore, only the required minimum amount of wood products is produced in each category. As can be seen in line 6, the cascading scenario requires only 66% of the primary wood, whereas the non-cascading scenario utilizes 80% of the available resources. Additionally, the share of the wood used for material production (line 4) is higher in the cascading scenario in this case. To have a closer look at the effects of cascading on wood utilization, scenarios without substitution credits were modeled (chapter 3.2).

Finally, lines 5a and 5b display the amount of waste wood used for a material application instead of incineration in relation to the total primary wood supply (5a) and in relation to the part of primary wood that could potentially be used for material application (5b), namely the assortments of saw timber and industrial roundwood. With the exception of the PM-scenario, where a rather high amount of particleboard is produced (more than five times the minimum amount), all scenarios result in similar shares of cascaded wood, both in relation to the total wood supply as well as in relation to the assortments potentially suitable for cascading (roundwood and industrial roundwood).

Table 7
Characterization of wood utilization with and without the possibility of cascading for modelling with substitution credits (WW: waste wood).

	[% of total produced or used]	Optimization parameter							
		GWP		PM		LO		SC	
		nC	C	nC	C	nC	C	nC	C
1	Heat from WW	23	20	24	8	32	32	39	23
2	Electricity from WW	100	100	100	100	100	100	0	100
3	Total energy from WW[a]	29	21	30	9	38	33	38	24
4	Primary wood for material application	56	54	62	57	74	81	60	57
5	Cascaded wood…								
5a	…in relation to total PW supply		11		59		15		9
5b	…in relation to roundwood + industrial roundwood		18		95		18		14
6	Primary wood supply utilized	100	100	100	100	80	66	100	100

[a] Heat and power generated from waste wood relative to the overall energy production of the system (in MJ at plants).

3.2. Scenarios without substitution credits

When modelling without credits for substitution, the resulting environmental impacts of wood utilization (Table 8) show similar trends to those from the model runs with credits. For nearly all optimization parameters, the environmental impacts can be reduced when allowing a cascading use of waste wood in the model. Possible savings with regard to greenhouse gases are slightly over 10% when optimizing the category GWP and increase to 11% when optimizing the single score indicator, but with higher absolute amounts. Again, in accordance with the results from modelling with crediting, the highest relative reductions by cascading can be detected for particulate matter formation when optimizing the categories PM and LO. The fact that both approaches – the modelling with and without credits – results in similar trends of the environmental impacts is a strong indicator that the crediting did not lead to distortion of the results.

As already briefly discussed in the previous chapter, the total utilization of the wood supply as a consequence of crediting for substitution influences the performance of the system. In order to gain an additional perspective, scenarios without substitution crediting were run. They have in common that only a part of the available quantity of primary wood is utilized, since no credits counteract the environmental impacts of the provision of wood products. Thus, the minimization of environmental impacts of the model leads to a limitation of the produced amounts to the defined minimum per category. Nevertheless, the energy provided by the various scenarios varies, since all wood products must be handled until their end-of-life, which, in our model, is incineration for energy production (Table 9). All cascading scenarios show a lower utilization share of primary wood when compared to the non-cascading scenarios. The highest input of primary wood is required by the two model runs with optimization of the single

Table 8
Total environmental impacts of wood utilization for different impact categories and optimization parameters for nC and C variants without consideration of substitution credits. Relative difference (Δ) of the C in relation to the nC variant.

	Optimization parameter											
	GWP			PM			LO			SC		
	nC	C	Δ	nC	C	Δ	nC	C	Δ	nC	C	Δ
	[10^6 kg CO_2 eq.]		[%]	[10^6 kg PM10 eq.]		[%]	[10^6 m^{2}*a]		[%]	[10^6 ReCiPe points]		[%]
GWP	*2,279*	*2,045*	*−10.3*	2,384	2,270	−4.8	2,389	2,280	−4.6	2,626	2,335	−11.1
PM	9.69	10.50	8.4	*8.87*	*7.36*	*−17.0*	8.88	7.39	−16.8	10.08	10.08	−0.1
LO	18,678	18,164	−2.7	17,661	16,064	−9.0	*17,192*	*15,514*	*−9.8*	20,388	19,400	−4.8
SC	0.36	0.34	−4.1	0.37	0.38	1.7	0.37	0.38	2.0	*0.39*	*0.36*	*−6.7*

score indicator. Since all the resulting wood products have to be incinerated at their end-of-life, these two scenarios also lead to the highest amount of additional energy (line 7; sum of electricity and heat, converted to lower heating value). Generally, the cascading scenarios display a lower amount of surplus energy, since a part of the wood material is not incinerated directly but utilized for another material application, during which the amount decreases due to provision of process energy and losses.

Contrary to the modelling with substitution credits, the cascading scenarios display a higher share of primary wood used for a material application, a desirable effect when aiming to prolong the average time of carbon storage in the wood products. The numbers in lines 4 and 6 can also be seen as indicators for an assessment of the influence of cascading on the efficiency of wood utilization. Since the different model runs lead to differing produced amounts of energy, these numbers are not totally comparable. However, they strongly indicate that implementing the possibility of cascading in a wood utilization system increases the efficiency by allowing more flexibility of possible assortments for specific products and, consequently, requiring less primary wood for providing a specific product portfolio.

3.3. Sensitivity analyses

3.3.1. Product portfolio composition

To determine the influence of the assumptions regarding substitution and the yield of waste wood collection and sorting, impact analyses for four different parameters were conducted. The resulting changes in the composition of the products portfolio are displayed in Fig. 2 together with the portfolio of the default scenarios. Markers indicate changes of the produced amounts. If no marker is displayed for a scenario-column, the specific amount remained unaffected by the respective impact analysis.

Increasing the efficiency of waste wood processing by improving the overall share of waste wood recovery from 90 to 95 % as carried out in the first impact analysis (*Yield 95*) favors panel production from waste wood. With all optimization parameters except the single score indicator, the produced amount of panels increases with a rising collection rate, but only when cascading is possible. Because losses during recovery of waste wood can be expected to be particularly of influence with cascading of wood, since it can require several recollection cycles until the final incineration and losses add up, an additional examination of the correlation of recovery rate and produced amount of panels was carried out (*Yield panels*; Fig. 4). The produced amount of the solid wood products glulam and sawn timber from hardwoods are rather unaffected by a change in the waste wood recollection rate, as can be expected. The amount of electricity from incineration of waste wood increases with a rising recollection rate and decreases if the recollection becomes less efficient, as assumed in the variation *Yield 86*. This effect can only be detected for non-cascading scenarios, since with cascading, the default recollection rate also only allows for providing the minimum electricity required as waste wood is mainly used for particleboard production. A decreasing efficiency of waste wood collection, as done in variation *Yield 86*, also results in lower amounts of the energy categories providing heat.

As a default, the German grid mix was assumed to be substituted by electricity from wood. To determine the influence of this assumption on the results, a variation with electricity from natural gas as the basis for substitution was conducted. It did not influence wood materials production, but it made electricity production less favourable when optimizing GWP and LO. The respective waste wood was shifted to the provision of district heat.

Another parameter variation was set for the product mix which wood panels are assumed to substitute for. This change led to a reduction of the produced particleboard amount to the minimum value. The waste wood no longer needed for panels production could then be used for increasing the produced amounts of

Table 9
Characterization of wood utilization with and without the possibility of cascading for modelling without substitution credits (WW: waste wood).

	[% of total produced or used]	Optimization parameter							
		GWP		PM		LO		SC	
		nC	C	nC	C	nC	C	nC	C
1	Heat from WW	32	27	43	32	44	32	0	11
2	Electricity from WW	100	100	100	100	100	100	100	100
3	Total energy from WW[a]	38	28	44	33	45	33	19	22
4	Primary wood for material application	68	66	74	81	74	81	57	60
5	Cascaded wood…								
5a	…in relation to total PW supply	0	13	0	16	0	15	0	5
5b	…in relation to roundwood + industrial roundwood	0	16	0	17	0	18	0	7
6	Primary wood supply utilized	80	77	78	63	80	66	98	86
7	Energy surplus over required minimum [PJ][b]	20.4	17.1	20.3	0.0	20.3	0.0	48.6	31.7

[a] Heat and power generated from waste wood relative to the overall energy production of the system (in MJ at plants).
[b] From end-of-life of wood products; displayed as lower heating value of wood for better comparability.

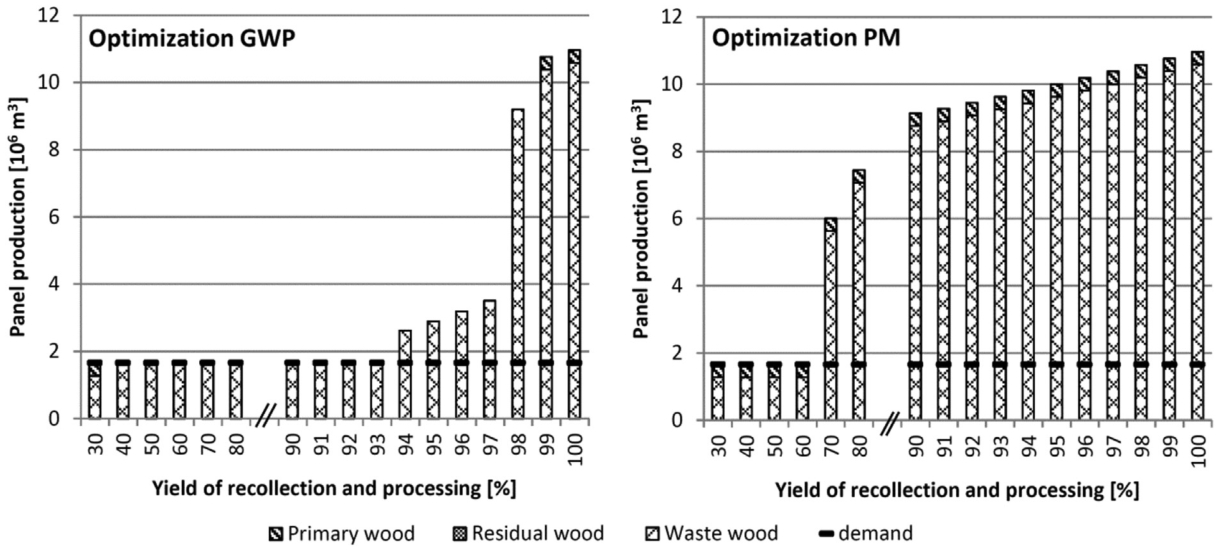

Fig. 4. Development of panel production with varying efficiencies of waste wood collection and sorting (cascading variants). The bold line indicates the required minimum amount of panels set as a constraint in the model.

electricity, district and industrial heat. This outcome indicates that a general conclusion towards the environmental preference of panel production from waste wood in regard to particulate matter formation can not be drawn from the results of our study. The LCIA of non-wood furniture production, which is included in the substitution product mix in the default setting but was omitted in the variation, seems to influence the preference of panels when optimizing particulate matter formation, yet it can not be seen as totally representative for the whole furniture sector in Germany.

The final analysis was the examination of the effects of the efficiency of waste wood recollection on the produced panel amount when cascading is possible in the model (*Yield panels;* Fig. 4). The efficiency of waste wood collection and sorting, as assumed for the default model runs, is based on rather rough assessments due to a lack of reliable data for Germany. However, the parameter analyses *Yield 95* and *Yield 86* have shown that the recollection rate of waste wood strongly influences the amount of particleboard produced. Therefore, more in depth examinations were carried out to examine the effects of the recollection rate on panel production. Fig. 4 shows that when optimizing GWP with the possibility of cascading, panel production drops to the required minimum already with the rather high recollection yield of 93%. If the yield drops to 30%, the amount of waste wood in the system is no longer sufficient to produce the required panels; primary wood has to be used additionally. In contrast, when optimizing particulate matter formation, a surplus of panels is produced until the yields drops below 70%. This indicates that the efficiency of waste wood handling is essential when considering a cascading use of wood, as the losses multiply with each additional processing step and are simply lost for energy generation at the end of life. Only rather high yields of waste wood processing support cascading.

3.3.2. Environmental impacts

The environmental impacts resulting from the model runs during the variation analysis were compared to the results of the default scenarios (Table 10). Overall, the conducted variations only selectively influence the environmental impact of the system. Particulate matter formation shows the most pronounced differences. An increase of the yield of waste wood recollection and processing in most scenarios has a positive impact on particulate matter formation, whereas the variations of the substitution products for wood panels and electricity lead to an impairment for all scenarios, since the substitution credits for the impact category PM decrease with both variations.

The single score indicator, which integrates a variety of different impact categories, is relatively unaffected by the examined variations. This shows a robustness of the model towards assumptions and choices in the model setup, thereby indicating a good reliability of the results.

4. Discussion

4.1. Modelling approach

The aim of our study was to analyze and quantify effects of a cascading use of wood resources by taking the whole system of wood utilization on a regional level into account. The advantage of such a comprehensive, supply based approach over the assessment of cascading with conventional LCA is the possibility of integrating effects on the environmental impact of the system which are less

Table 10
Difference of environmental impacts between parameter analyses and the default scenarios. Differences to the default scenario greater than 5% are highlighted in bold.

[Δ % of environmental impacts]		Optimization parameter							
		GWP		PM		LO		SC	
		nC	C	nC	C	nC	C	nC	C
Yield 95	GWP	−1.4	−1.7	−1.5	−4.8	−1.9	−0.6	−2.3	**5.1**
	PM	**−37.5**	**−21.8**	−4.4	**−5.6**	−4.8	−0.4	**−8.5**	**272.1**
	LO	0.0	−0.4	0.0	−0.3	0.0	−0.8	0.0	0.1
	SC	−1.4	−0.5	−1.2	−3.7	−1.4	−0.1	−1.8	−1.1
Yield 86	GWP	−1.4	1.9	−1.5	4.2	−1.9	0.2	−2.3	1.4
	PM	1.5	**−6.6**	4.4	**5.0**	4.8	−0.7	**−20.3**	**−11.8**
	LO	0.0	0.0	0.0	0.3	0.0	0.9	0.0	0.0
	SC	1.2	1.7	1.2	3.2	1.4	0.0	1.6	1.7
Subst gas	GWP	0.4	0.3	2.1	0.3	0.5	0.4	0.3	0.3
	PM	**51.1**	**7.5**	**127.1**	2.7	**164.0**	5.0	**8.0**	**15.9**
	LO	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0
	SC	−4.5	−0.5	−3.9	−0.6	**−5.6**	−0.8	−0.5	−0.5
Subst panels	GWP	1.4	1.7	1.4	−2.3	1.8	2.4	0.6	1.3
	PM	**43.3**	**64.2**	**121.9**	**31.2**	**139.0**	**38.4**	**38.8**	**106.1**
	LO	0.2	0.3	0.2	2.4	0.2	0.3	0.2	0.2
	SC	0.7	0.8	0.7	**−9.4**	0.9	1.1	0.6	0.6

directly associated with the use of wood in cascades but should still be taken into consideration. Some examples are the reduction of available waste wood in each cascade step through losses or shifts of wood assortments other than waste wood as input for materials and energy. Additionally, the model based approach enabled the integration of current wood utilization and demand of derived wood products into the study area as a constraint to ensure that the system including cascading also fulfills the wood products demand.

The combination of LCA with optimization is a common approach (Pieragostini et al., 2011) and has been recently applied to detect the optimal utilization of biomass potentials (Čuček et al., 2012; Saner et al., 2014; Steubing et al., 2012; You et al., 2012) from an environmental perspective. However, the integration of cascading wood utilization paths in order to assess their influence on the wood utilization system as a whole has, to the best of our knowledge, not been conducted previously.

The study compares optimum states of the system. In reality, both the cascading as well as the reference system will hardly ever be in this state. Nevertheless, to assess effects of changes in the system, such as cascading, comparing optima is a viable approach if information regarding the actual status quo – in this case the environmental impacts of the utilization of the annual wood supply – are not available. The calculated savings by cascading of wood resources should be seen as best-case assessments of possible effects by cascading. Decisive factors detected in this study, e.g. that the benefits of cascading highly depend on the efficiency of recovery of waste wood, can be expected to hold true also in reality.

A result indicating the robustness of the model approach is the similar trend that the considered impact categories display in most scenarios. They were chosen with the goal of displaying the extensive effects of wood utilization, and the category of particulate matter formation especially aims at accommodating current criticisms towards wood utilization and the integration of the important aspect of human health. Land occupation was considered, since one of the fundamental aspects of cascading is the provision of a resource virtually without the environmental impacts associated with the provision of primary resources. However, the choice of indicators is always subjective to a certain extent and further investigation of the effects of cascading on other environmental impacts is called for.

The products, both materials and energy, accounted for in our study were chosen to achieve a realistic abstraction of the current utilization of the wood supply. Although not all utilization options were integrated into the model, the applications with the main relevance in regard to amount and economic value for the various wood assortments were considered. This allows the results to be seen as representative not also for the study areas, but also for beyond. As the considered wood products are rather common and the applied LCA data is mostly representative for middle European conditions, the detected effects of a cascading use of wood are not limited to the study area but can be expected to occur in a similar way in other countries with an equivalent wood utilization system.

The study focused on the difference between a system enabling a cascading of wood and a system without this option. Therefore, the use of generic LCA datasets from the ecoinvent database for all conventional and most wood based energy generation options can be seen as suitable, despite the fact that potentially the environmental impacts of energy generation in the study area do not perfectly match reality because of differing incineration and flue gas cleaning technologies and plant capacities. This is a weakness our study shares with most LCA studies where generic data are used for energy generation processes.

We chose the application of substitution credits in order to quantify optimal wood utilization and assess the influence of cascading on four environmental indicators. One of the underlying assumptions of this approach is that each unit of manufactured wood product in fact displaces fossil or mineral based products. This may not always be the case in reality, as wood products may as well substitute other wood or biomass based products. Especially with particleboard that is used for furniture production, substitution is more unlikely due to a differing perception of particleboard-based and e.g. glass- or steel based furniture. We took this into account by carrying out an impact analysis without furniture as part of the substitution mix. The choice of substitution products and their associated environmental impacts can be decisive for the results. By considering “substitution modules” consisting of a mix of different products for panels, sawn hardwood and all energy substitutes, we integrated a variety of products and production technologies, thereby striving to ensure that the uncertainty of actual substitution is considered in the model to an adequate extent. By carrying out a second set of scenarios without the integration of substitution, it was verified that the displayed effects of cascading are not overly influenced by the substitution approach.

The optimization of ecological parameters, as done in our study, can indicate the direction in which a system should be developed. However, in reality, factors beyond those considered here are equally or even more influential for such a development. This holds especially true for economic factors not considered here. Additionally, decisions influencing wood utilization by private households, both for energy production and as a material, are probably only to a small part influenced by rational considerations regarding eco-friendliness and far more by practical considerations in regard to availability or personal preferences. Further research is needed in order to quantify the influence of economic and social factors on the effects of a cascading use of wood.

4.2. Limitations of the model

Time is not considered in the model. Products and by-products of processes are assumed to be available for further utilization instantaneously. This is especially noticeable when comparing a cascading utilization of wood with a scenario not enabling cascading. With cascading, the materials are available at different points in time, whereas without, all materials would be available at the same time. The same holds true for assuming energy from waste wood incineration is equivalent to energy from incineration of primary wood, as is done in our model. However, when assuming a steady-state system over a longer time span, the model may nevertheless be an adequate description of reality, since waste wood and by-products of production processes would occur in the same quantities every year and could be used for the applications as assumed by the model.

How to integrate biogenic carbon and its associated implications for global warming potential in LCA is currently under discussion in the scientific community, and several approaches have been presented up to now (Cherubini et al., 2011; Levasseur et al., 2012). As no consensus regarding the preferred approach has been reached (Brandão et al., 2013; Helin et al., 2013; Pawelzic et al., 2013) and since our model has no consideration of time, the timing of carbon emissions and uptake including carbon storage in wood products has not been accounted for in this study.

4.3. Results discussion

The results indicate that exploiting the possibility of a utilization of wood in cascades leads to a decrease of the overall environmental impacts of wood utilization when taking the whole system into account. Additional benefits of cascading as found for the indicator global warming potential in the single digit percentage range might seem low, but the reference for these relative assessments has to be taken into account. Although cascading, as examined in our study, only influences a rather small part of the system, namely the production of particleboard, the additional benefits are referenced to the respective environmental impacts of the total system, which, with the exception of pulp and paper production, represent the annual wood utilization of the 12-million-inhabitant area of Bavaria. In this context, the fact that the "non-cascading" reference system already contains the possibility of a cascading utilization must be considered. Since the reference system represents the status quo of wood utilization, a basic cascade – namely the incineration with energy recovery of all primary wood products at their end-of-life – is already integrated. Landfilling of waste wood is prohibited by German legislation. Consequently, already today, virtually all accruing waste wood is incinerated, either in specific facilities or together with other municipal waste. In countries where existing wood utilization structures include substantial shares of landfilling, which is the case in most countries throughout the world, implementing a cascading utilization would increase possible environmental benefits even further, since the then implemented incineration at the end-of-life of wood products creates less environmental impacts compared to landfilling if the resulting energy is utilized (Cherubini et al., 2009; Lippke et al., 2011). If the additional steps of a material application were added, the benefits detected in our study would occur additionally.

The relative benefits of cascading over equivalent primary wood products found in our study show a similar trend as findings of previous case studies (Gärtner et al., 2012; Höglmeier et al., 2014). Höglmeier et al. (2014) reported a 10% GWP reduction for the cascading system compared to equivalent products from primary wood. The same relative reduction was found in this study when substitution effects are not taken into account. However, since the system boundaries differ greatly (comprehensive wood utilization system vs. specific waste wood cascade), the values are not directly comparable. Gärtner et al. (2012) reported absolute values in person-years based on substitution effects achievable by cascading of a specific amount of wood. Hence, a direct comparison to this study is not possible.

The absolute potential reductions of environmental impacts by cascading can be referenced to the emissions occurring in the study area. The current greenhouse gas inventory for Germany (Federal Environmental Agency, 2013) reports a total annual average emission of 11.52 tons of CO_2 eq. per capita in the year 2010. The difference between the cascading and non-cascading scenarios when optimizing the indicator GWP therefore accounts for the annual per-capita emissions of over 50,000 persons if substitution credits are included and of still over 20,000 if only the environmental impacts of the wood utilization are accounted for. No data on the total greenhouse gas emissions of the study area is available. However, assuming the German per-capita value is correct for the state of Bavaria, the possible reduction (without credits) would account for 0.2% of the annual emissions. Considering that wood utilization is only a minor contributor to the overall greenhouse gas emissions, this can be seen as substantial. For the second considered environmental impact, the formation of particulate matter, the cascading scenario leads to reductions equivalent to the emissions of over 550,000 inhabitants based on German emission data (Federal Environmental Agency, 2014).

5. Conclusion

To conclude, we can answer our research questions as follows:

(1) Despite the fact that cascading in our model only directly influenced the production of particleboard, since it enabled the use of waste wood as a raw material, it impacted the whole wood utilization system. The amount of energy from waste wood decreased, since the material use of waste wood over several cascading steps considerably decreased the available waste wood at the end-of-life. Regarding the efficiency of resource use, in most scenarios cascading led to a substantial decrease in the amount of primary wood required to provide a defined product portfolio. The possible savings ranged from 3 to 14 % of the total primary wood supply. The characteristic that the cascading scenarios frequently displayed of having a higher share of primary wood utilized for energy generation might be seen as critical regarding attempts to increase the carbon storage in the wood products pool and increase resource efficiency. To increase the overall efficiency of wood utilization, the primary wood amounts additionally available by cascading should also be used in an efficient way, preferably also in cascades.

(2) The overall environmental impacts of the wood utilization system in our model could be considerably decreased if cascading of waste wood was an option, both for the scenarios including effects of substitution as well as if only the environmental impacts of the manufacturing system were taken into account.

(3) The efficiency of a cascading use of wood strongly depends on the magnitude of losses during each cascading step. If losses, especially because of ineffective recovery, are high, the consequently lost possibility of generating wood energy and its associated benefits outweighs the possible benefits created by preceding additional material applications of the wood by cascading. For cascading to be able to compete with a direct incineration of the waste wood for energy production, collection and processing yields of at least 70% are required in regard to the indicator PM and 92% respectively for GWP. This strongly indicates that an effective cascading wood utilization requires a minimization of losses over the cycles in order to conserve the wood amount as efficiently as possible during the cascade steps. This can be achieved both by improving the yield of waste wood collection and processing steps as well as by improving process efficiency in the wood industry by minimizing the amount of wood that is ultimately removed from the cycle.

(4) The chosen approach of comparing the overall environmental impacts of different variations of the wood utilization system has proven to be a viable method to assess direct effects of the use of waste wood for products and of substitution. This has also been done in previous studies, albeit not on the level of entire systems. Additionally, indirect effects of cascading such as shifts of the use of wood assortments for specific products and substitution effects on the level of input materials could be incorporated by the presented study. The integration of wood products demand as a constraint contributed to the goal of completing a comprehensive assessment on the system level rather than looking at single utilization options.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.01.018.

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