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Optimising cascaded utilisation of wood resources considering economic and environmental aspects

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ABSTRACT

Cascaded wood utilisation could help to bridge the gap between the rising wood demand and fresh wood availability as well as contributing to a circular economy. However, the economic and environmental implications of cascading wood-based products are not fully known yet and are hence explored in this paper, considering both aspects simultaneously for the first time. The study focuses on the production of the following five products in an integrated system: medium-density fibre, oriented-strand board, particleboard, coated paper and wood pellets. Firstly, a multi-objective optimisation model has been developed to minimise the costs and greenhouse gas emissions of cascaded utilisation of wood. The ε-constraint method has been used to solve the model and derive Pareto optimal solutions. The latter have been used to select two cascaded-utilisation scenarios and compare their environmental performance with two other scenarios: current situation and the use of fresh wood only. The environmental impacts have been estimated using life cycle assessment. The results reveal that cascaded utilisation is more environmentally and economically sustainable than the current situation or the use of fresh wood. One of the scenario (Scenario 2) reduces the impacts by 1%-23% on the current situation; the global warming potential (GWP) is lower by 15%. However, the costs in this scenario are only 4% lower. In another (Scenario 1), the costs are lower by 24% but the reductions in impacts are more limited, ranging from 1%-8% relative to the Reference scenario with the GWP being only 1% lower. The cascaded use of wood also offers the potential to save up to 35% of fresh wood resources, thus contributing to a circular economy. Using only fresh wood (Scenario 3) is the worst option, increasing the costs by 13% while offering small or no environmental benefits in most of the impacts. These results will be of interest to the wood industry, forestry authorities and policy makers.

1. Introduction

Wood is considered one of the most versatile renewable resources for material and energy use worldwide (DFWR, 2008). In 2013, the global use of industrial round wood was 1737 million m³, a 10% increase since 2009 (FAO, 2014). In Europe, it is expected that the demand for wood will increase by 20% by 2030 on 2009 levels (FAO, 2014), exceeding the total wood supply in EU27 (Mantau, 2014). This is largely due to the increasing use of wood for energy generation (BMELV, 2012; Kharazipour and Kües, 2007; Mazzanti and Zoboli, 2013).

In Germany, wood is considered a key element for sustainable resource management as it is one of the main resources produced and processed domestically (Weimar, 2011). There is an increasing demand for wood resources due to the rising price of fossil fuels (Härtl and Knoke, 2014; Schwarzbauer and Stern, 2010). As the wood consumed for energy generation can also be utilised for the production of wood-based panel boards, pulp and paper and wood pellet, the competition for these wood resources has increased significantly (Mantau, 2014; Höglmeier et al., 2014).

Cascaded utilisation, as a method for more efficient use of raw materials, holds a potential to bridge a gap between rising wood demand and availability of fresh wood. According to Kosmol et al. (2012), cascaded utilisation is “a strategy for using raw materials or the products made from them in chronologically sequential steps as long, often and efficiently as possible for ma-

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Nomenclature

$b^t_{i,j,u}$ Binary variable denoting if wood type i (fresh wood) from forest j is transported to manufacturer of wood product u by transport type t
$b^t_{r,s,u}$ Binary variable denoting if wood type r (industrial wood residues) from sawmill s is transported to manufacturer of wood product u by transport type t
$b^t_{g,p,u}$ Binary variable denoting if waste wood type g (waste wood) from collection centre p is transported to manufacturer of wood product u by transport type t
c_i Cost of fresh wood [€/m³]
c_r Cost of industrial wood residues [€/m³]
c_g Cost of waste wood (chips) [€/t]
$c^{ch,1}_{i,u}$ Cost of chemicals for the processing of fresh wood i for the production of wood product u [€/m³]
$c^{ch,2}_{r,u}$ Cost of chemicals for the processing of industrial residue wood r for the production of wood product u [€/m³]
$c^{ch,3}_{g,u}$ Cost of chemicals for processing of waste wood g for the production of wood product u [€/t]
$c^{e,1}_{i,u}$ Cost of energy for processing of fresh wood i for the production of wood product u [€/m³]
$c^{e,2}_{r,u}$ Cost of energy for processing of industrial residue wood r for the production of wood product u [€/m³]
$c^{e,3}_{g,u}$ Cost of energy for processing waste wood g for the production of wood product u [€/t]
$CAP_{i,j}$ Fresh wood capacity (availability) in forest j [m³]
$CAP_{r,s}$ Industrial residues capacity (availability) in sawmill s [m³]
$CAP_{g,p}$ Waste wood capacity (availability) at collection centre p [t]
$co^1_{i,u}$ Coefficient proportion of input wood type i for the production of one unit of wood product u
$co^2_{r,u}$ Coefficient proportion of input wood type r for the production of one unit of wood product u
$co^3_{g,u}$ Coefficient proportion of input wood type g for the production of one unit of wood product u
D_u Wood demand for wood product u [m^3]
$d^1_{j,u}$ Distance between forest j and manufacturer producing product u [km]
$d^2_{s,u}$ Distance between sawmill s and manufacturer producing product u [km]
$d^3_{p,u}$ Distance between collection centre p and manufacturer producing product u [km]
f^{cost} The cost objective [€]
f^{GWP} The GWP objective [kg]
$Income_u$ Income from selling wood product u [€]
h^t_i CO_2 eq. emissions from transport of fresh wood by transportation type t [kg/m³]
h^t_r CO_2 eq. emissions from transport of industrial wood residues by transportation type t [kg/m³]
h^t_g CO_2 eq. emissions from transport of waste wood by transportation type t [kg/t]
k_i CO_2 eq. emissions from harvesting of fresh wood [kg/m³]
k_r CO_2 eq. emissions from the sawing processes for industrial wood residues [kg/m³]
k_g CO_2 eq. emissions from recycling of waste wood [kg/t]
l^t_i Cost of fresh wood transport by transport type t [€/t]
l^t_r Cost of industrial wood residues transport by transport type t [€/t]
l^t_g Cost of waste wood transport by transport type t [€/t]
$o_{i,\,j}$ Total output of fresh wood from forest j [m^3]
P^{cost} Total production cost [€]
P^{cost}_u Production costs of wood product u [€]
P^{GWP} Total GWP of the production process [kg]
$Price_u$ Selling price for wood product u [€/m^3]
PR^{GWP} Total GWP of procurement [kg]
PR^{cost} Total procurement cost [€]
PR^{cost}_u Procurement costs of wood product u [€]
T^{cost} Total transportation cost [€]
T^{cost}_u Transportation costs of product u [€]
T^{GWP} Total GWP of transportation [kg]
$V_{r,\,s}$ Total output of industrial wood residues from sawmill s [m^3]
$w^{ch,1}_{i,u}$ CO_2 eq. emissions associated with chemicals used for processing fresh wood i for the production of wood product u [kg/m³]
$w^{ch,2}_{r,u}$ CO_2 eq. emissions associated with chemicals used for processing industrial residue wood r for the production of wood product u [kg/m³]
$w^{ch,3}_{g,u}$ CO_2 eq. emissions associated with chemicals used for processing of waste wood g for the production of wood product u [kg/t]
$w^{e,1}_{i,u}$ CO_2 eq. emissions associated with energy use for processing fresh wood i for the production of wood product u [kg/m³]
$w^{e,2}_{r,u}$ CO_2 eq. emissions associated with energy use for processing industrial residue wood r for the production of wood product u [kg/m³]
$w^{e,3}_{g,u}$ CO_2 eq. emissions associated with energy use for processing waste wood g for the production of wood product u [kg/t]
$x^1_{i,j,u}$ Flow of fresh wood from forest j to manufacturer of wood product u [m^3]
$x^2_{r,s,u}$ Flow of industrial wood residues from sawmill s to manufacturer of wood product u [m^3]
$x^3_{g,p,u}$ Flow of waste wood from collection centre p to manufacturer of wood product u [t]
$z_{p,\,g}$ Total flow of waste wood from collection centre p [t]
ρ^1_i Density of fresh wood [kg/m³]
ρ^2_r Density of industrial wood residues [kg/m³]

terials and only to recover energy from them at the end of the product life cycle". In other words, the cascading strategy multiplies the benefit created from one unit of resource if it is used as a material as long as possible and as a fuel only when further material utilisation is not possible of feasible. In that way, cascaded wood utilisation allows the substitution and conservation of fresh wood through recovery of post-consumer waste wood and industrial wood residues. This approach is congruent with the principles of circular economy (EMF, 2014). For example, high-quality post-consumer waste wood can be utilised as an input material for producing oriented-strand board (OSB), medium-density fibreboard (MDF) and particleboard (Höglmeier et al., 2014). In Germany, waste wood is most commonly recycled for the production of the latter (Höglmeier et al., 2014; Mantau, 2012); however, the recycled-wood content is below 30% (Top, 2015; Sommerhuber et al., 2015; Kharazipour and Kües, 2007). This is due to the

Table 1
Studies of cascaded utilisation of wood.

Source	Wood cascading by sector				Methodology	
	Forest operations	Construction and building	Wood-based panel board manufacturing	Pulp & paper production	Optimisation	LCA
Aciu et al. (2014)				*		
Daian and Ozarska (2009)			*			
Falk and McKeever (2004)		*				
Fraanje (1997)	*					
Frühwald et al. (2000)			*			*
Frühwald and Knauf (2014)		*				*
Georgiadis (2013)				*	*	
González-García et al. (2011)			*			*
González-García et al. (2012)			*			*
González-García et al. (2014)			*			*
Gustavsson et al. (2006)		*				*
Haberl and Geissler (2000)	*					
Höglmeier et al. (2013)		*				*
Höglmeier et al. (2014)			*			*
Iritani et al. (2014)			*			*
Kara and Onut (2010)				*	*	
Kim and Song (2014)			*			*
Kishino et al. (1999)				*		
Laurijssen et al. (2010)				*		*
Merrild and Christensen (2009)			*			*
Pati et al. (2008)				*	*	
Rivela et al. (2006)			*			*
Sathre and Gustavsson (2006)		*	*			*
Sikkema et al. (2013)		*		*		*
Taskhiri et al. (2016)			*	*	*	*

current sorting methods, whereby only limited quantity of high-quality waste wood is recovered for further use (Kharazipour and Kües, 2007). However, studies show that there is a potential to improve the current sorting technology to increase the recovery rate of waste wood for recycling (Höglmeier et al., 2014; Knauf, 2015).

A number of studies have investigated the consequences of the cascading utilisation of wood in different sectors (Table 1). Some authors explored the effects of the cascaded utilisation of various forest wood resources in order to assess its environmental and economic advantages through the extended service life of wood resources (Fraanje, 1997; Dornburg and Faaij, 2005; Geldermann, 2012; Sathre and Gustavsson, 2006). Others have focused on life cycle assessment (LCA) of wood-based panel production from industrial-residue wood (Frühwald et al., 2000; González-García et al., 2011; González-García et al., 2012; González-García et al., 2014; Iritani et al., 2014; Kim and Song, 2014; Rivela et al., 2006). Höglmeier et al. (2014) considered waste wood as a potential material for the production of wood-based panels, such as particleboard and OSB. However, their study was limited to utilisation of the high-quality waste wood that can be recycled through mechanical disintegration only. It is not possible to produce other wood-based panels, such as MDF, using mechanical disintegration because the fibres are damaged in the chipping process (Kharazipour and Kües, 2007). Some studies have also assessed the environmental impacts of using waste wood for paper production, focusing on the production of low-quality graphical papers, such as newsprint (Sikkema et al., 2013; Kara and Onut, 2010; Kishino et al., 1999; Laurijssen et al., 2010). In an attempt to optimise recycling of waste wood, several studies used multi-objective optimisation and some combined it with LCA (Table 2). However, neither study considered cascaded utilisation of waste wood so its environmental and economic implications remain largely unknown.

To address this gap, this paper aims to optimise simultaneously the economic and environmental performance of a wood cascading system for the production of different wood products by combining multi-objective optimisation with LCA. The study is based in Lower Saxony, Germany, and focuses on five key products for this region: MDF, OSB, particleboard, coated paper and wood pellets. The environmental and economic implications of the cascading system are compared with the equivalent system using only fresh wood. As far as the authors are aware, this is the first study of its kind, considering simultaneously both the economic and environmental implications of the cascaded utilisation of wood for different scenarios and under different system conditions.

The next section describes the system under the study and the multi-objective optimisation model developed as part of this work. This is followed in Section 3 by the discussion of results and conclusions in Section 4.

2. Methods

2.1. System definition

The system under study, depicted in Fig. 1, includes collection of waste wood, its processing in sawmills and production of the five products considered in this work (MDF, OSB, particleboard, coated paper and wood pellets). The scope of the study is from cradle to gate as the focus is on the recovery and utilisation of waste wood to make different products. Thus, the use and end-of-life disposal are excluded. Energy recovery from wood is also excluded as the focus is on utilisation of wood as a material rather than an energy source.

The fresh wood is sourced from forests and waste wood from sawmills and post-consumer collection centres. The analysis is carried out at the level of the whole Lower Saxony so that the unit of analysis (functional unit) is based on the annual production of the five products in the region: 190,000 m^3 of MDF, 455,500 m^3 OSB, 520,000 m^3 particleboard, 17,000 tonne of coated paper and 60,000 m^3 of wood pellets. These products are produced from 1.125 million m^3/a logs, including round and industrial wood (BMELV, 2012), of which softwood and hardwood contribute 72% and 28%, respectively (Werner et al., 2007).

Post-consumer waste wood is collected in the collection centres where it is sorted and transported to a manufacturing process for recycling. Based on the level of contamination, the waste wood

Table 2
Multi-objective optimisation studies of the wood supply chain.

Source	Sector	Application	Objectives	Method(s)
Brown et al. (2009)	Energy	Biomass (wood) gasification plant of 40 MW capacity	Trade-off between total investment cost and exergy efficiency	Multi-objective optimisation
Gassner and Maréchal (2009)	Energy	Synthetic natural gas (SNG) from wood	Max. SNG production, max. electricity output and min. cost	Multi-objective optimisation
Kanzian et al. (2013)	Energy	Energy conversion from wood in 72 heating plants	Trade-off between total profit and minimum CO_2	Multi-objective optimisation (weighted sum scalarisation)
Gholamian et al. (2015); Mirzapour Al-e-hashem et al. (2011); Jaafari et al. (2015)	Material	Production of particleboard, fibre board and paper in three wood product manufacturers	Minimise total cost of the supply chain, minimise fluctuations in the rate of changes of workforce and maximise total value of purchasing	Fuzzy multi-objective multi-period mixed-integer non-linear aggregate production planning model.
Ide et al. (2015)	Material	Production of veneer in a veneer cutting industry under uncertain wood quality	Minimisation of wood offcuts, delayed or unfulfilled orders, the use of high quality pieces for lower quality orders and the number of manually cut down pieces	Robust multi-objective optimisation

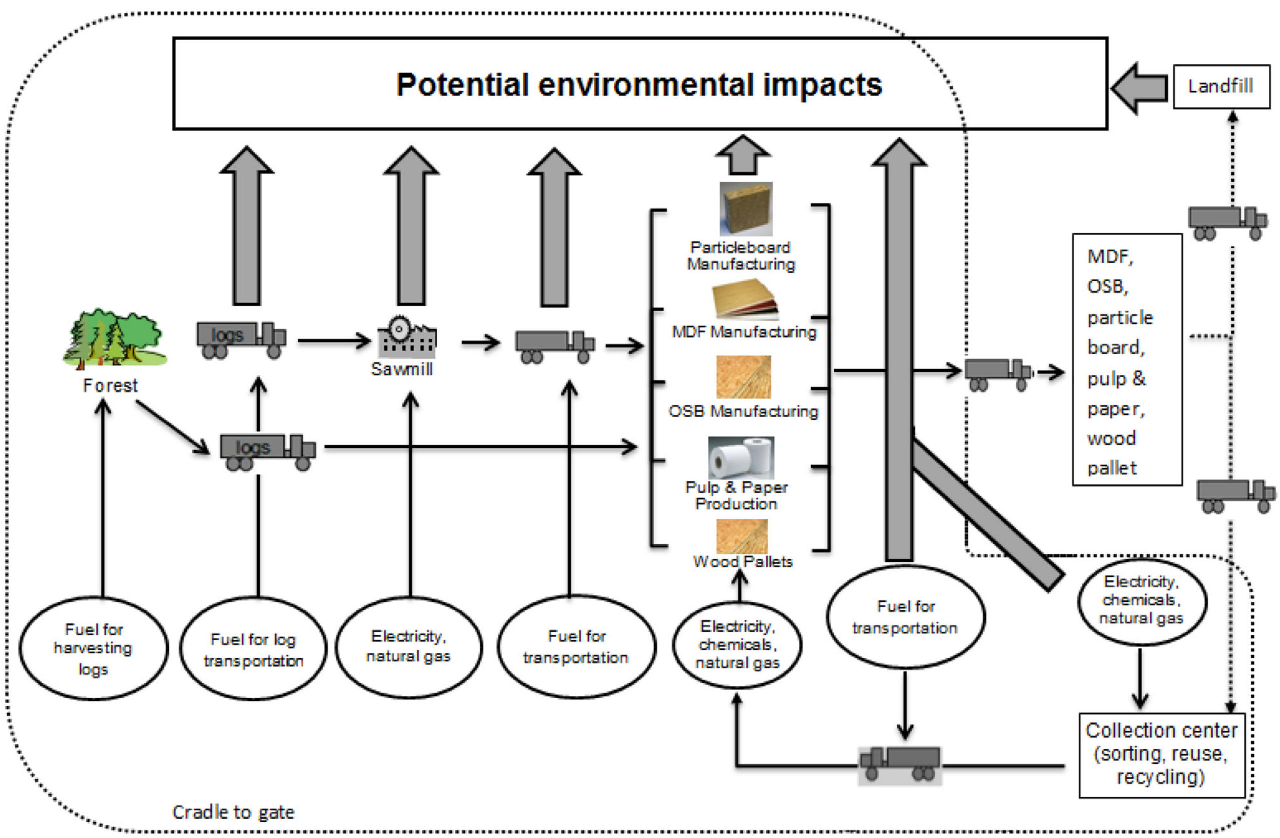

Fig. 1. Schematic representation of the life cycle of wood products considered in the study.

is classified into four categories (Frühwald, 2008). Category A-I includes natural finished wood that is not or only slightly affected by impurities. Painted, laminated waste wood, excluding organohalogen compounds, is allocated to category A-II, whereas A-III contains mature timbers with organohalogen compounds. Waste wood treated with preservatives is categorised as A-IV. Waste wood containing polychlorinated biphenyls (PCB) is classified as PCB waste wood and is disposed of as per regulatory requirements. Categories A-I and A-II make 36% and 45% of the total share in waste wood, respectively, whereas the third and fourth class contribute 6% and 13% (AltholzV, 2012). The first two categories of waste wood are suitable for material use and the last two classes for energy use.

Although several methods are mentioned in the literature for recycling of waste wood (Roffael and Schneider, 1978, 1979; Roffael et al., 2003; Hameed et al., 2005), many of them cannot be practised at an industrial level. This is due to the final products produced by these methods not meeting specification for certain parameters, including bending, strength and stiffness (Kharazipour and Kües, 2007). In this study, two recycling methods – mechanical treatment and thermo-hydrolytic disintegration – are considered for recycling of A-I and A-II waste wood. As mentioned above, A-III and A-IV waste wood is only used for energy recovery and is thus not considered here. For the description of these two recycling methods, see Section S1 in the Supplementary Information (SI).

2.2. Optimisation model

A multi-objective mixed integer linear programming (MILP) model has been developed and used for the purposes of this research. The model considers two objective functions, one related to the total system costs and another to the life cycle greenhouse gas emissions from the system, quantified as global warming potential (GWP). Both objectives comprise three life cycle stages: procurement of wood, its transportation and production of wood products. The decision variables are related to the flow rates of fresh wood from forests and sawmills and waste wood from collection centres.

The model considers the following four scenarios:

1) Reference scenario: current situation;
2) Scenario 1: cascaded utilisation for the minimum cost;
3) Scenario 2: cascaded utilisation for the minimum GWP; and
4) Scenario 3: use of fresh wood only.

Scenarios 1 and 2 are obtained through the optimisation and are described in the results section, together with the fresh-wood scenario (Scenario 3). These three scenarios are compared to the current situation in Lower Saxony (Reference scenario).

The optimisation model is described in more detail below.

2.2.1. Objective functions

The optimisation problem is to minimise the total costs (f^{cost}) and GWP (f^{GWP}):

$$\min \left(f^{cost},\ f^{GWP}\right) \tag{1}$$

The cost objective comprises the costs of the procurement (PR^{cost}), transportation (T^{cost}) and production (P^{cost}) of wood products:

$$f^{cost} = PR^{cost} + T^{cost} + P^{cost}\,(€) \tag{2}$$

The procurement cost of wood, which refers to the provision of fresh or waste wood, is calculated based on the price of each wood type:

$$PR^{cost} = \sum_{i\in I}\sum_{j\in J} c_i \cdot o_{i,j} + \sum_{r\in R}\sum_{s\in S} c_r \cdot v_{r,s} + \sum_{g\in G}\sum_{p\in P} c_g \cdot z_{g,p} \qquad (€) \tag{3}$$

where c_i represents the cost of fresh wood, c_r the cost of industrial wood residues and c_g the cost of waste wood; $o_{i,\,j}$, $v_{r,\,s}$ and $z_{p,\,g}$ represent respectively wood flows from forest j, sawmill s and collection centre p to the wood product manufacturer.

The total transportation costs are equal to:

$$T^{cost} = \sum_{i\in I}\sum_{j\in J}\sum_{u\in U}\left(x^1_{i,j,u}\rho^1_i \cdot \sum_{t\in T} l^t_i b^t_{i,j,u}\right) \qquad (€)$$
$$+ \sum_{r\in R}\sum_{s\in S}\sum_{u\in U}\left(x^2_{r,s,u}\rho^2_r \cdot \sum_{t\in T} l^t_r b^t_{r,s,u}\right)$$
$$+ \sum_{g\in G}\sum_{p\in P}\sum_{u\in U}\left(x^3_{g,p,u} \cdot \sum_{t\in T} l^t_g b^t_{g,p,u}\right) \tag{4}$$

where the first term in Eq. (4) corresponds to the fresh wood, the second to industrial residues and the third to waste wood. The variables x represent the flows of the respective types of wood (i, r, g), the variables d the distances they travel and ρ the density of different wood types. l^t_i, l^t_r, l^t_g are transportation costs for the three wood types for transportation type t; $b^t_{i,j,u}, b^t_{r,s,u}, b^t_{g,p,u}$ are binary variables which indicate whether the wood is transported from wood source *j, s or p* by transportation type t to the product manufacturer to make product u. The flows of fresh wood ($x^1_{i,j,u}$) and industrial wood residues ($x^2_{r,s,u}$) are multiplied by their respective densities (ρ^1_i *and* ρ^2_r) for the unit conversion from m³ to tonne since the transportation cost is calculated based on €/t.

The total production cost (P^{cost}) of the products is calculated using the production inventory data for each product (as provided in Table 5 and Table 6) and the costs of chemicals and energy inputs, which are provided in Table 7:

$$P^{cost} = \sum_{i\in I}\sum_{j\in J}\sum_{u\in U} x^1_{i,j,u}\left(c^{ch,1}_{i,u} + c^{e,1}_{i,u}\right) \qquad (€)$$
$$+ \sum_{r\in R}\sum_{s\in S}\sum_{u\in U} x^2_{r,s,u}\left(c^{ch,2}_{r,u} + c^{e,2}_{r,u}\right)$$
$$+ \sum_{g\in G}\sum_{p\in P}\sum_{u\in U} x^3_{g,p,u}\left(c^{ch,3}_{g,u} + c^{e,3}_{g,u}\right) \tag{5}$$

$c^{ch,1}_{i,u}$, $c^{e,1}_{i,u}$ and $c^{ch,2}_{r,u}$, $c^{e,2}_{r,u}$ are the costs of chemical *ch* and energy source *e*, respectively, used for the production of wood product u from fresh wood and industrial wood, respectively. When waste wood is used, the equivalent variables are $c^{ch,3}_{g,u}$ and $c^{e,3}_{g,u}$.

The second objective function, related to GWP of the system is defined as follows:

$$f^{GWP} = PR^{GWP} + T^{GWP} + P^{GWP} \qquad (kg) \tag{6}$$

where the three parameters in Eq. (6) represent the GWP of procurement, transportation and production of wood products, respectively. The GWP of the procurement processes is equal to the sum of the CO_2 eq. emissions from the preparation (harvesting, sawing and recycling) of each wood type (k_i, k_r, k_g):

$$PR^{GWP} = \sum_{i\in I}\sum_{j\in J} k_i \cdot o_{i,j} + \sum_{r\in R}\sum_{s\in S} k_r \cdot v_{r,s} + \sum_{g\in G}\sum_{p\in P} k_g \cdot z_{g,p} \quad (kg) \tag{7}$$

The total GWP of transport for the three types of wood is calculated as follows:

$$T^{GWP} = \sum_{i\in I}\sum_{j\in J}\sum_{u\in U}\left(x^1_{i,j,u} d^1_{j,u}\rho^1_i \cdot \sum_{t\in T} h^t_i b^t_{i,j,u}\right) \qquad (kg)$$
$$+ \sum_{r\in R}\sum_{s\in S}\sum_{u\in U}\left(x^2_{r,s,u} d^2_{s,u}\rho^2_r \cdot \sum_{t\in T} h^t_r b^t_{r,s,u}\right)$$
$$+ \sum_{g\in G}\sum_{p\in P}\sum_{u\in U}\left(x^3_{g,p,u} d^3_{p,u} \cdot \sum_{t\in T} h^t_g b^t_{g,p,u}\right) \tag{8}$$

with h^t_i, h^t_r, h^t_g representing CO_2 eq. emissions from transport of wood types *i, r, g* by transportation type *t*.

GWP of the production of the products is calculated based on the GWP of chemicals and energy used in the manufacturing process:

$$P^{GWP} = \sum_{i\in I}\sum_{j\in J}\sum_{u\in U} x^1_{i,j,u}\left(w^{ch,1}_{i,u} + w^{e,1}_{i,u}\right) \qquad (kg)$$
$$+ \sum_{r\in R}\sum_{s\in S}\sum_{u\in U} x^2_{r,s,u}\left(w^{ch,2}_{r,u} + w^{e,2}_{r,u}\right)$$
$$+ \sum_{g\in I}\sum_{p\in J}\sum_{u\in U} x^3_{g,p,u}\left(w^{ch,3}_{g,u} + w^{e,3}_{g,u}\right) \tag{9}$$

where $w^{ch,1}_{i,u}$ and $w^{e,1}_{i,u}$ represent CO_2 eq. emissions associated with chemical *ch* and energy *e*, respectively, used for the production of wood product u from fresh wood; $w^{ch,2}_{r,u}$ and $w^{e,2}_{r,u}$, and $w^{ch,3}_{g,u}$ and $w^{e,3}_{g,u}$ are the equivalent variables for industrial and waste wood, respectively.

2.2.2. Constraints

The income for each wood product u is estimated based on its selling price ($Price_u$) and demand (D_u):

$$Income_u = Price_u\ D_u \quad \forall\ u\ \in U \quad (€) \tag{10}$$

The income should also be greater or equal to the sum of the costs of procurement (PR^{cost}_u), transportation (T^{cost}_u) and production (p^{cost}_u) for each wood product *u:*

$$PR^{cost}_u + T^{cost}_u + P^{cost}_u \le Income_u \quad \forall u \in U \quad (€) \tag{11}$$

These are calculated as follows:

$$PR_u^{cost} = \sum_{i\in I}\sum_{j\in J} x_{i,j,u}^1 c_i + \sum_{r\in R}\sum_{s\in S} x_{r,s,u}^2 c_r + \sum_{g\in G}\sum_{p\in P} x_{g,p,u}^3 c_g \quad \forall u \in U \quad (€) \tag{12}$$

$$T_u^{cost} = \sum_{i\in I}\sum_{j\in J} x_{i,j,u}^1 \rho_i^1 \sum_{t\in T} l_i^t b_{i,j,u}^t + \sum_{r\in R}\sum_{s\in S} x_{r,s,u}^2 \rho_r^2 \sum_{t\in T} l_r^t b_{r,s,u}^t + \sum_{g\in G}\sum_{p\in P} x_{g,p,u}^3 \sum_{t\in T} l_g^t b_{g,p,u}^t \quad \forall u \in U \quad (€) \tag{13}$$

$$P_u^{cost} = \sum_{i\in I}\sum_{j\in J}\sum_{u\in U} x_{i,j,u}^1 \left(c_{i,u}^{ch,1} + c_{i,u}^{e,1}\right) + \sum_{r\in R}\sum_{s\in S} x_{r,s,u}^2 \left(c_{r,u}^{ch,2} + c_{r,u}^{e,2}\right) + \sum_{g\in G}\sum_{p\in P} x_{g,p,u}^3 \left(c_{g,u}^{ch,3} + c_{g,u}^{e,3}\right) \quad \forall u \in U \quad (€) \tag{14}$$

The total flow of different food types should be below or equal to the capacity (availability) of wood type i at forest j $(CAP_{i,j})$, of wood type r at sawmill s $(CAP_{r,s})$ and of waste wood type g at collection centre p $(CAP_{g,p})$:

$$o_{i,j} \le CAP_{i,j} \quad \forall i \in I, \forall j \in J \quad (m^3) \tag{15}$$

$$v_{r,s} \le CAP_{r,s} \quad \forall r \in R, \forall s \in S \quad (m^3) \tag{16}$$

$$z_{g,p} \le CAP_{g,p} \quad \forall g \in G, \forall p \in P \quad (m^3) \tag{17}$$

The wood demand for each wood product must be fulfilled as follows:

$$D_u = \sum_{i\in I}\left(co_{i,u}^1 \cdot \sum_{j\in J} x_{i,j,u}^1 \cdot \rho_i^1\right) + \quad \forall u \in U \quad (kg)$$
$$\sum_{r\in R}\left(co_{r,u}^2 \cdot \sum_{s\in S} x_{r,s,u}^2 \cdot \rho_r^2\right) + \sum_{g\in G}\left(co_{g,u}^3 \cdot \sum_{p\in P} x_{g,p,u}^3\right) \tag{18}$$

where $co_{i,u}^1$, $co_{r,u}^2$ and $co_{g,u}^3$ is the proportion of input wood type i, r and g, respectively, for the production of one unit of wood product u.

Only one mode of transportation can be used for each transportation route and each wood type at a time:

$$\sum_{t\in T} b_{i,j,u}^t = 1 \quad \forall i \in I, \forall i \in I, \forall u \in U \tag{19}$$

$$\sum_{t\in T} b_{r,s,u}^t = 1 \quad \forall r \in I, \forall s \in I, \forall u \in U \tag{20}$$

$$\sum_{t\in T} b_{g,p,u}^t = 1 \quad \forall g \in G, \forall p \in P, \forall u \in U \tag{21}$$

Finally, all flows must be nonnegative:

$$x_{i,j,u}^1 \ge 0 \quad \forall i \in I, \forall j \in J, \forall u \in U \tag{22}$$

$$x_{r,s,u}^2 \ge 0 \quad \forall r \in R, \forall s \in S, \forall u \in U \tag{23}$$

$$x_{g,p,u}^3 \ge 0 \quad \forall g \in G, \forall p \in P, \forall u \in U \tag{24}$$

2.2.3. Solving the optimisation problem

The optimisation model has in total 147 constraints and 265 variables. The ε-constraint method has been used to find Pareto optimal solutions for the two objectives considered. The MILP model has been developed and solved using the optimisation software CPLEX v12.0. In total, 20 optimisation runs have been performed, each taking 5 sec of CPU time.

2.3. Life cycle assessment

After optimisation on each objective, LCA is performed to estimate a range of environmental impacts at the Pareto optimum solutions for the minimum costs and GWP. The LCA study follows the ISO 14,040/44 methodology (ISO, 2006a; b). The LCA software UMBERTO v7 has been used for LCA modelling and the impacts have been estimated according to the CML-midpoint impact assessment method (Guinée et al., 2002). The following impacts are considered, in addition to GWP:

- abiotic depletion potential of resources (ADP);
- acidification potential (AP);
- eutrophication potential (EP);
- freshwater aquatic ecotoxicity potential (FAETP);
- human toxicity potential (HTP);
- marine aquatic ecotoxicity potential (MAETP);
- ozone depletion potential (ODP);
- photochemical ozone creation potential (POCP); and
- terrestrial ecotoxicity potential (TETP).

Furthermore, land use is also estimated due to its relevance to wood-based products. The environmental impacts are estimated for all four scenarios mentioned earlier.

2.3.1. Data and assumptions

As this work focuses on the State of Lower Saxony, four forests and four sawmills in the cities of Braunschweig, Hannover, Oldenburg and Lüneburg are considered as the sources of fresh wood. In addition, four collection centres in the cities of Twist, Hannover, Laatzen and Wardenburg are selected as the sources of waste wood (Table 3). The data for wood availability from forests, sawmills and collection centres have been sourced from BMELV (2012), Döring and Mantau (2012) and Mantau et al. (2012).

The data for the production processes of the wood-based panels (MDF, OSB and particleboard) and wood pellets are based on the inventory data provided by Werner et al. (2007). Production of the wood-based panels is carried out in two stages: i) preparation of wood chips (fibres for MDF); and ii) production of boards. In the first stage, the wood (fresh, industrial residue or post-consumer) is milled in chipping machines. For MDF, the wood chips are then converted into fibres in a defibration process. The particles (fibres for MDF) are dried in dryers before converting them into boards. The produced wood chips or fibres are glued using urea or phenol formaldehyde resins and compressed using mechanical presses. Paraffin is generally added as an additive to improve the mechanical properties and water resistance of the boards. Wood pellets are produced in a pellet mill in which dry industrial residual wood is pressed without binders or additives.

The data for paper production and paper recycling have been sourced from Hischier (2007). Cellulose fibres in softwood or hardwood and recycled paper are used as raw material for paper production. Firstly, wood logs from forests are debarked and washed with water to remove sand, stones and any other debris. The wet logs are then chipped to a length of 15–25 mm and width of 2-8 mm. The produced wood chips and the wood residue (from sawmill) are sorted, whereby the big pieces are removed for refining and the small chips are used for energy recovery. Wood pulping is the next step in the paper production process, which can

Table 3
Availability of wood resources in Lower Saxony.

Wood type	Location	Value	Unit	Moisture content (%)[a]	Density[a]	Source
Industrial softwood (spruce, pine)	Braunschweig	226,000	m^3/a	140	1080	BMELV (2012)
	Hannover	145,000				
	Oldenburg	306,000				
	Lüneburg	686,000				
Industrial hardwood (beech, oak)	Braunschweig	223,000	m^3/a	70	1105	BMELV (2012)
	Hannover	291,000				
	Oldenburg	149,000				
	Lüneburg	228,000				
Industrial residue wood, softwood	Braunschweig	158,125	m^3/a	40	630	Döring and Mantau (2012)
	Hannover	158,125				
	Oldenburg	288,750				
	Lüneburg	522,500				
Industrial residue wood, hardwood	Braunschweig	42,000	m^3/a	40	910	Döring and Mantau (2012)
	Hannover	24,000				
	Oldenburg	51,000				
	Lüneburg	6000				
Waste wood	Twist	220,000	t/a	10	556	Mantau et al. (2012)
	Hannover	27,500				
	Laatzen	27,500				
	Wardenburg	27,500				

[a] Wood moisture content and density data are from Werner et al. (2007).

Table 4
Production of wood-based products in Lower Saxony.

Wood type	Location	Value	Unit	Source
MDF production	Meppen	190,000	m^3/a	Mantau (2012)
OSB production	Nettgau	455,500	m^3/a	Mantau (2012)
Particleboard production	Nettgau	520,000	m^3/a	Mantau (2012)
Coated paper production	Alfeld	170,000	t/a	Sappi (2014)
Wood pellets production	Langelsheim	60,000	m^3/a	GD Holz (2014)

either be mechanical or chemical pulping. The former is inappropriate for production of high-quality paper, such as coated paper, as it damages the fibres (Sappi, 2014). In the chemical pulping process, initially, the lignin is removed from the fibre through cooking of the wood chips in a chemical solution. The fibres are then bleached to achieve the brightness required for white paper. The remaining lignin is removed during this process. The produced fibres from virgin material are mixed with the recovered fibres from recycled paper in a holding tank where the auxiliary chemicals and additives are added. The pulp solution is fed to the paper machine to be converted through a series of processes into the targeted paper grade for different market applications. These processes include sheet forming, pressing, drying, calendaring, coating and reeling.

For modeling the waste wood recycling, the data for mechanical treatment are from Werner et al. (2007) and the model of the thermo-hydrolytic process is based on a study by Kirchner (2000). The data for LCA have been taken from the Ecoinvent database which are based on a survey of the wood industries in Germany. The cost data have been taken from published reports and online distributors.

The annual production of wood-based products in Lower Saxony is summarised in Table 4. The inventory data for the production of the five wood products by mechanical and thermo-hydraulic treatment are provided in Table 5 and Table 6. The price of fresh and waste wood and the costs of energy and chemicals are given in Table 7.

Life cycle inventory (LCI) data are sourced from the Ecoinvent database v2.2 (Hischier, 2007; Werner et al., 2007) and summarised in Table 7. As the specific LCI data are not available for Lower Saxony, the average data for Germany have been used instead.

3. Results and discussion

3.1. Optimisation of cascaded utilisation of wood

In accordance with the ε-constraint method, the model was first optimised on the cost objective (f^{cost}) to identify the minimum cost of cascaded utilisation of wood. This represents Scenario 1 with the cost estimated at 270 million €/a and GWP equal to 633 kt CO_2 eq./a (Fig. 2). In this scenario, 82% of waste wood is used for MDF, 36% for particleboard and 62% of waste paper for coated paper. OSB and wood pellets are produced from fresh wood only (Table 8).

The model was then optimised on f^{GWP} yielding the minimum value of 542 kt CO_2 eq./a at the total costs of 337.5 million €/a (Fig. 2). These values, which define Scenario 2, differ by around 20% for the costs and 14% for the GWP relative to Scenario 1. Here, MDF is made from 100% of waste wood, OSB from 10% and both particle board and waste pellets from 35% (Table 8).

The cost objective was then converted to a constraint and the model optimised repeatedly on f^{GWP} by increasing the value of f^{cost} by 1% to obtain the Pareto solutions in Fig. 2. It can be observed that there is a linear decrease in GWP as the cost increases, up to a point where the both the cost and GWP are around 15% higher (318.6 million €/yr and 553 kt CO_2 eq.) from their respective values estimated in the optimisation of the cost objective (270 million €/a and 633 kt CO_2 eq./a). After that, the costs increase at a slightly higher rate for a smaller relative reduction in GWP.

The trade-offs between the costs and GWP are mainly due to the source of energy which is used for the production of wood products. As an example, lignin, which is extracted from wood during the chemical disintegration process, is used as a fuel in the production of coated paper from fresh wood. However, in the case of coated-paper production from waste paper, lignin is not available and, therefore, all energy needs are met using fossil fuels, such as natural gas and oil. Fossil energy sources have much higher GWP than that of lignin – the latter is of biological nature and biogenic carbon is considered to be part of the natural cycle and hence not included.

Thus, these results can help decision makers to identify compromise solutions where greater reductions in GWP can be achieved at a lower cost penalty. They can also be used to determine the implications for the other environmental impacts in comparison with the current situation and the use of fresh wood.

Table 5
Inventory data for the production of wood products from fresh wood (Hischier, 2007; Werner et al., 2007).

Materials and energy	Wood products				
	MDF	OSB	Particleboard	Paper	Wood pellets
Industrial softwood	0.389 m^3/ m^3	1.19 m^3/ m^3	0.215 m^3/ m^3	1.044 m^3/ t	–
Industrial hardwood	0.127 m^3/ m^3	0.00 m^3/ m^3	0.128 m^3/ m^3	1.245 m^3/ t	–
Industrial residue softwood	0.998 m^3/ m^3	0.104 m^3/ m^3	1.04 m^3/ m^3	0.159 m^3/ t	0.925 m^3/ m^3
Industrial residue hardwood	0.333 m^3/ m^3	0.00 m^3/ m^3	0.00 m^3/ m^3	0.00 m^3/t	1.23 m^3/ m^3
Paraffin	22.8 kg/m^3	5.03 kg/m^3	11 kg/m^3	–	–
Urea formaldehyde	49.6 kg/m^3	–	51 kg/m^3	–	–
Phenol formaldehyde	–	44.7 kg/m^3	–	–	–
Oil	–	–	86.1 MJ/m^3	125.5 MJ/t	–
Kaolin	–	–	–	170 kg/t	–
Latex	–	–	–	40 kg/t	–
Lignite briquette	–	–	–	1630 MJ/t	–
Limestone	–	–	–	170 kg/t	–
Electricity	1278 MJ/m^3	468 MJ/m^3	374 MJ/m^3	1250 MJ/t	594 MJ/m^3
Natural gas	1670 MJ/m^3	203 MJ/m^3	154 MJ/m^3	1840 MJ/t	–
Diesel	–	15 MJ/m^3	–	–	–
Transportation (lorry > 16t)	34.8 tkm/m^3	115.5 tkm/m^3	100.2 tkm/m^3	560 tkm/t	49.8 tkm/m^3
Transportation (rail)	72.6 tkm/m^3	135.3 tkm/m^3	125.8 tkm/m^3	510 tkm/t	49.8 tkm/m^3

Table 6
Inventory data for the production of wood products from waste wood and waste paper (Hischier, 2007; Werner et al., 2007; Kirchner, 2000).

Chemical material and Energy use	Wood products[a]				
	MDF	OSB	Particleboard	Paper	Wood pellets
Waste wood	0.86 t/m^3	0.73 t/m^3	0.75 t/m^3	–	0.72 t/m^3
Waste paper	–	–	–	1.17 t/t	–
Paraffin	15 kg/m^3	3.9 kg/m^3	6.8 kg/m^3	–	–
Phenol formaldehyde	–	27.5 kg/m^3	–	–	–
Oil	–	–	55.05 MJ/m^3	1320 MJ/t	–
Kaolin	–	–	–	10 kg/t	–
Rosin	–	–	–	2.42 kg/t	–
Electricity	1120 MJ/m^3	461 MJ/m^3	213.19 MJ/m^3	2840 MJ/t	617.44 MJ/m^3
Natural gas	932 MJ/m^3	56 MJ/m^3	281.2 MJ/m^3	6760 MJ/t	–
Diesel	–	14.18 MJ/m^3	24.55 MJ/m^3	–	4.85 MJ/m^3
Transportation (lorry > 16t)	18 tkm/m^3	75.7 tkm/m^3	68.2 tkm/m^3	20 tkm/t	49.8 tkm/m^3
Transportation (rail)	28 tkm/m^3	88.9 tkm/m^3	85.6 tkm/m^3	150 tkm/t	49.8 tkm/m^3

[a] MDF and particleboard are produced by the thermo-hydraulic process; OSB and wood pellets are treated mechanically.

Table 7
Cost and global warming potential (GWP) data for the procurement, production and transportation processes considered in the study.

Parameters		Cost	Reference	GWP	Reference
Procurement	Industrial softwood	80 €/m^3	BMELV (2012)	9.03 kg CO_2 eq./m^3	Werner et al. (2007)
	Industrial hardwood	90 €/m^3	~II~	6.79 kg CO_2 eq./m^3	~II~
	Industrial residue softwood	64 €/m^3	Mantau et al. (2010)	3.18 kg CO_2 eq./m^3	~II~
	Industrial residue hardwood	64 €/m^3	~II~	2.04 kg CO_2 eq./m^3	~II~
	Waste wood class A-I	30 €/t	Lauri et al. (2012)	2.10 kg CO_2 eq./t	Kirchner (2000)
	Waste wood class A-II	20 €/t	~II~	4.90 kg CO_2 eq./t	~II~
	Waste paper	60 €/t	RISI (2014)	1 10 kg CO_2 eq./t	Hischier (2007)
Production	Electricity	0.084 €/kWh	Eurostat (2014)	0 53 kg CO_2 eq./kWh	Werner et al. (2007); Hischier (2007)
	Natural gas	0.048 €/kWh	~II~	0.067 kg CO_2 eq./MJ	~II~
	Diesel	1.37 €/l	~II~	0.086 kg CO_2 eq./MJ	~II~
	Heating oil	50 €/barrel	~II~	0.094 kg CO_2 eq./MJ	~II~
	Lignite briquette	490 €/t	~II~	0.12 kg CO_2 eq./MJ	~II~
	Paraffin	1000 €/t	~II~	0.83 kg CO_2 eq./kg	~II~
	Urea/formaldehyde	1000 €/t	Alibaba (2014)	2.85 kg CO_2 eq./kg	~II~
	Phenolic resin	2600 €/t	~II~	4.16 kg CO_2 eq./kg	~II~
	Kaolin	220 €/t	~II~	0.21 kg CO_2 eq./kg	~II~
	Latex	5000 €/t	~II~	2.63 kg CO_2 eq./kg	~II~
	Limestone	120 €/t	~II~	0.01 kg CO_2 eq./kg	~II~
	Rosin	1000 €/t	~II~	1.56 kg CO_2 eq./kg	~II~
Transportation	Lorry (≤ 50 km)	7 €/t	Freightmetrics (2015); Borcherding (2007)	0.13 kg CO_2 eq./tkm	Werner et al. (2007)
	Lorry (50 km < x ≤ 150 km)	15.79 €/t	~II~	0.13 kg CO_2 eq./tkm	~II~
	Train (150 km < x ≤ 270 km)	16.3 €/t	~II~	0.04 kg CO_2 eq./tkm	~II~

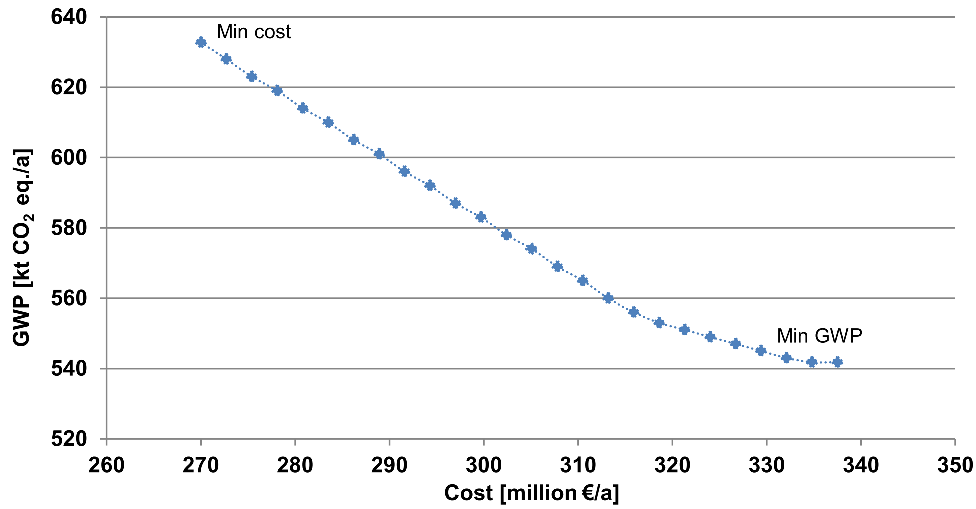

Fig. 2. The Pareto curve obtained using the ε-constraint method, showing the trade-offs between costs and global warming potential (GWP) for cascaded utilisation of waste wood.

This is discussed in section 0. Prior to that, the next section provides more detail on the scenarios selected for consideration in the study, followed by an analysis of their costs.

3.2. Overview of scenarios

Table 8 gives an overview of the three scenarios selected for consideration in this work and the current situation in Lower Saxony. For the latter, representing a Reference scenario (RS), only fresh wood is used for the production of MDF and OSB (Mantau, 2012). Wood pellets are also produced only from fresh wood, utilising industrial residue generated during its processing. Particleboard can contain at most one-third of waste wood (0.095 million t/a) because the waste wood has a cubic shape and an increase in its proportion would affect the mechanical-technical properties of particleboard (Kharazipour and Kües, 2007). For the production of coated paper, 70% of the feedstock (310 kt/a) is provided from forests and sawmills and the rest is from waste paper which is recycled through chemical pulping. It is not possible to utilise waste wood for paper production since the fibres gets damaged during the mechanical treatment of post-consumer wood products (Sappi, 2014).

The cascaded-utilisation Scenarios 1 (minimised cost) and 2 (minimised GWP) are based on the result of the optimisation discussed in the previous section. In both scenarios, wood products can be produced from either fresh or waste wood. It is also assumed that it is possible to produce all wood products except coated paper from 100% waste wood. This assumption is based on the studies by Höglmeier et al. (2014); Loth and Hanheide (2004) and Kirchner (2000) which reported that there is a potential to utilise waste wood from categories A-I and A-II for the production of MDF, OSB and particleboard. Furthermore, it is assumed that category A-I waste wood could be treated mechanically for the production of particleboard and OSB and wood pellets (since it is a mixture of particles). Regarding MDF, since there are no studies that discuss the possibility of the production of MDF from A-I waste wood, it is assumed that there is enough A-II wood which could be recycled by the thermo-hydraulic method (Kirchner, 2000) for MDF production. Furthermore, particleboard can be produced from A-I or A-II waste wood. Concerning paper production, in all of the scenarios, either fresh wood or waste paper is considered as a feedstock.

Finally, for comparative purposes, Scenario 3 considers a case whereby all five products are produced from fresh wood obtained from forests and sawmills (Table 8). This scenario is based on the assumption that all post-consumer waste wood will be used for energy recovery (Mantau, 2012).

In all the scenarios, the transportation distances for fresh and waste wood are based on the actual locations of forests, sawmills, collection centres and wood product manufactures in Lower Saxony.

3.3. Cost analysis

The total cost for the production of each wood product in all scenarios is calculated based on the data for consumption of materials, chemicals and energy as well as the transportation cost (Table 8). The results are summarised in Fig. 3; for further details, see Table S1 in the SI. As can be inferred from Fig. 3, the total cost in the Reference Scenario (RS) is estimated at 352 million €/a. The production contributes 41% to the total, while the procurement and transportation account for 51% and 8%, respectively. In this scenario, wood pellets have the lowest cost with 6.5 million €/a and OSB have the highest cost with 131 million €/a. The total cost for the other products are 69.6 million €/a for particleboard, 47 million €/a for MDF and 98 million €/a for coated paper.

As discussed in the previous section, the total cost of Scenario 1 (optimised on total costs), is 270 million €/a, which is 24% lower than in the RS. This reduction is mostly because of the reduction in procurement costs, which are reduced by 47% from 143 million €/a to 97 million €/a. This is due to more post-consumer waste wood being utilised in this scenario for the production of wood products. However, in the RS, most of the wood products, including MDF and OSB, are produced from fresh wood only, which has higher costs (including harvesting and debarking) in comparison with waste wood. In Scenario 1, the production costs are reduced by 18% to 152 million €/a and the transportation costs by 39% to 20.6 million €/a.

In Scenario 2 where the GWP is minimised, more waste wood is utilised for the production of wood board and less for paper. This reduces the GWP by 15% and other impacts by 1%–23% relative to the RS. However, the total costs in this scenario are only 4% lower than in the Reference scenario. For the specific products, the cost of MDF and particleboard is reduced by 47% and 26%, respectively, but increased slightly for OSB by 4%. The cost for coated paper, however, is increased by 17% as it is produced from fresh wood only.

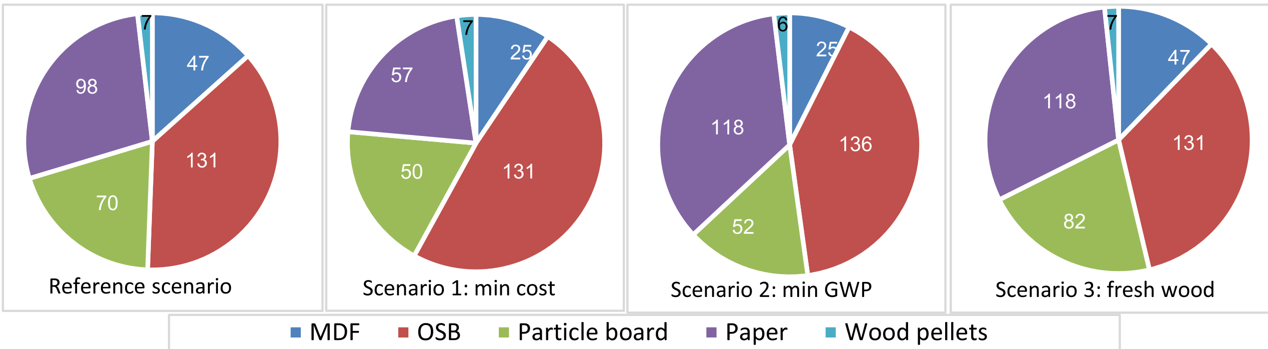

Fig. 3. Summary of costs for different scenarios (million €).

In the fresh wood scenario (Scenario 3), the total cost increases by around 9% to 385 million €/a in comparison with the RS. This increase is due to the higher cost for the production of particleboard and coated paper from fresh wood compared to waste wood or waste paper. In the RS, 30% of the particleboard and coated paper are produced from waste wood or waste paper, respectively (Table 8). The total costs for OSB and wood pellets remain unchanged because, as mentioned earlier, these are also produced only from fresh wood in the RS.

3.4. Environmental impacts

Fig. 4 and Table S2 in the SI compare the environmental impacts of the three scenarios relative to the current situation, showing the contribution of different products. As can be seen, Scenario 2 is the best option for seven impacts and Scenario 1 for three; for one impact (human toxicity), they have the same value, which is lower than for the other two scenarios. The fresh-wood scenario has the highest values for six impacts and Scenario 3 for the remaining four. The greatest contribution of the products to the impacts is generally from paper, particleboard and OSB. These results are discussed in more detail in the following sections.

3.4.1. Global warming potential

As can be seen in Fig. 4, Scenario 2 is the best option for this impacts, with the GWP 15% lower than for the RS, which represents the worst option. This is not surprising as the system is optimised on GWP in Scenario 2. Scenario 3 is the next best option, with a 4% lower impact, followed by Scenario 1 which is only 1% better than the current situation. The contribution of different products and life cycle stages in the scenarios is discussed below.

In Scenario 1, the GWP of MDF is 37% lower than in the RS, mainly owing to the lower energy consumption during fibre recycling in comparison to fibre production from fresh wood and the avoidance of formaldehyde for the production of MDF in the recycling process. However, since the contribution of MDF to the total impacts is relatively small, this reduction does not translate into a larger overall reduction of the GWP. Also, the impact from particleboard and paper is higher (2%−12%). This is due to the higher utilisation of fresh wood in the case of particleboard and higher fossil fuel consumption in the waste paper recycling process. The reason for the latter is that black liquor and lignin (by-products of paper production process) are used as the main energy sources in the paper production process, while the paper recycling process relies on fossil fuels (Sappi, 2014). The GWP remains unchanged for OSB and wood pellets in both scenarios since both products are produced from fresh wood (Table 8).

In terms of different life cycle stages (see Fig. S1 in the SI), the greatest contributors in all the scenarios are energy and chemicals (~40% each), followed by processing (~10-15%) and procurement (~5%); the contribution of transport is negligible. In Scenario 1, energy has a 15% higher contribution to the total impact relative to the RS, although the energy consumption for all the wood products (except paper) is lower. This is due to the fact that the chipping or stranding of the industrial round wood takes place at the wood manufacturing site, whereas the waste wood is already delivered in chipped form (which occurs in the procurement stage). Additionally, less energy is required for particleboard and wood pellets in cascaded utilisation as waste wood has a considerably lower moisture content and hence lower drying needs compared to the production from fresh wood. However, in Scenario 1, 42% more fossil fuel is used in the production of recycled paper compared to the RS as mentioned above.

Compared to the RS, the contribution of chemicals to the GWP in Scenario 1 is 10% lower (244 vs. 270 kt CO_2 eq./a) as less chemicals are used in the production of MDF, particleboard and coated paper from waste feedstocks. The procurement stage has a 23% lower GWP than in the RS. This is because sorting and recovering the wood particles and fibres to produce particleboard, wood pallets and paper is less resource intensive than using fresh wood. There is also a small reduction in transport-related impacts because of relatively shorter distances for waste wood compared to fresh wood. Moreover, waste wood has a lower moisture content, hence less mass is transported in Scenario 1.

In Scenario 2, the 15% reduction in GWP on the RS is due to more waste wood being used for the production of MDF, OSB, particleboard and wood pellets. In this scenario, MDF is produced only from waste wood, which results in a 43% reduction of the GWP of this product relative to the RS. For OSB, only a slight reduction is achieved (1%) as only 10% of waste wood is used. The impact of particleboard and paper is reduced by 5% and 13%, respectively. For wood pellets, although the utilisation of waste wood is increased to 35%, the GWP decreases just by 2%.

Looking at the contribution of different stages in Scenario 2 (Fig. S1), it can be seen that the reduction in GWP is due to lower usage of fossil energy and chemicals. In comparison to the RS, the contribution of energy to GWP is 26% lower, while the contribution of chemicals is 10% smaller. However, the impact of the production stage is 24% higher compared to the RS.

In Scenario 3, which assumes that only fresh wood is used, the total GWP is 4% lower relative to the RS. This reduction occurs because of the lower impact of paper production from fresh wood compared to waste paper recycling (practised in the RS). The GWP is the same for MDF, OSB and wood pellets as in the RS since there is no change in inputs. However, it is slightly higher for particleboard (by 5%).

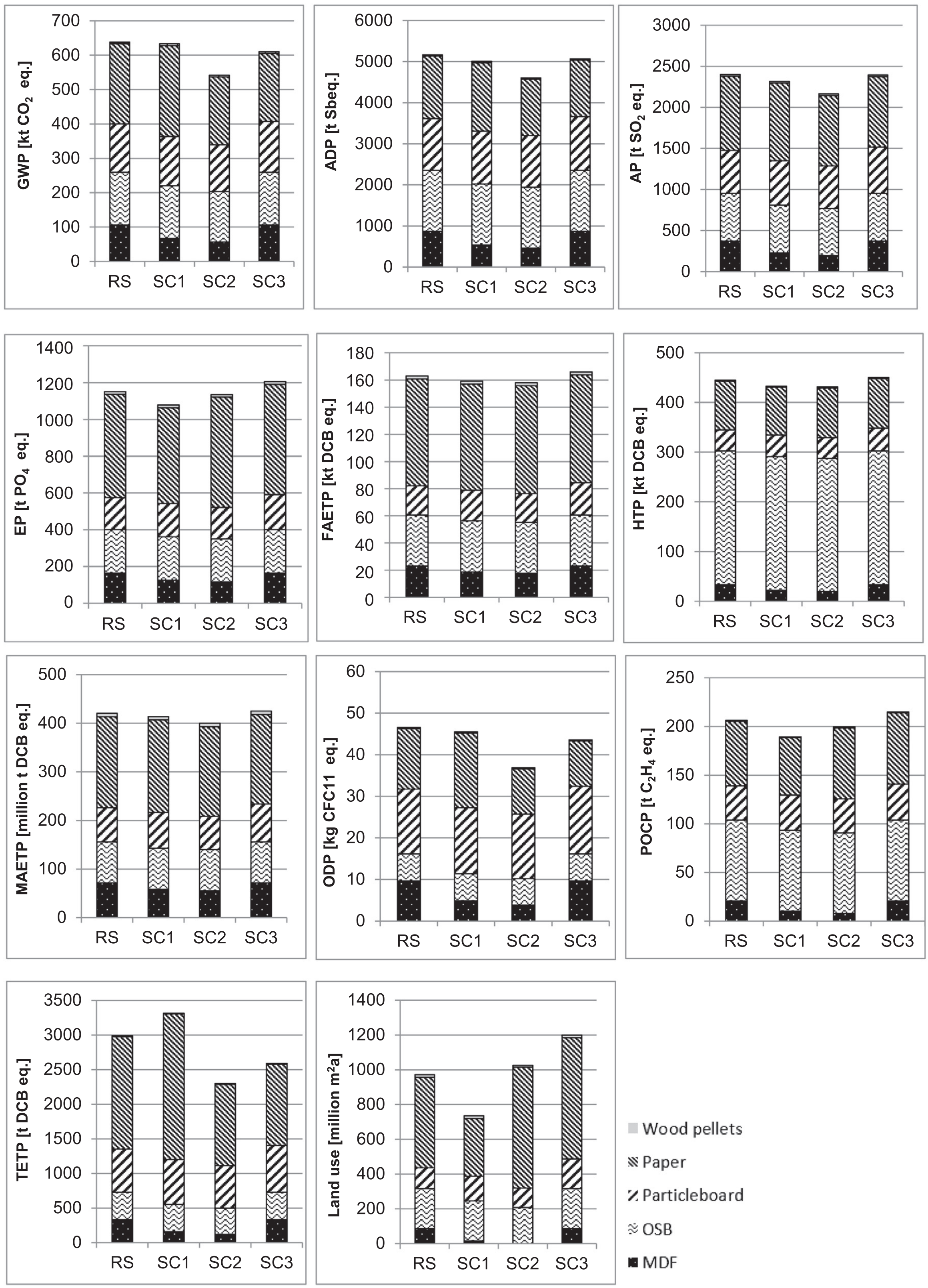

Fig. 4. Environmental impacts of different scenarios showing the contribution of individual products.
[*All impacts expressed per functional unit* (*annual production of different products*: 190,000 m^3 *MDF*, 455,500 m^3 *OSB*, 520,000 m^3 *particleboard*, 17,000 *tonne coated paper and* 60,000 m^3 *of wood pellets*). *System boundary: cradle to gate. Scenarios: RS - Reference scenario* (*current situation*); *SC1 - Scenario 1*; *SC2 - Scenario 2*; *SC3 - fresh wood scenario. Impacts: GWP - global warming potential; ADP - abiotic depletion potential of resources; AP - acidification potential; EP - eutrophication potential; FAETP - freshwater aquatic ecotoxicity potential. HTP - human toxicity potential; MAETP - marine aquatic ecotoxicity potential; ODP - ozone layer depletion potential; POCP - photochemical oxidants creation potential; TETP - terrestrial ecotoxicity potential.*]

Table 8
Scenarios considered for the production of MDF, OSB, particleboard, paper and wood pellets in Lower Saxony.

Wood products	Unit of analysis	Reference: Current situation			Scenario 1: Minimum cost			Scenario 2: Minimum GWP			Scenario 3: Fresh Wood		
		Input materials			Input materials			Input materials			Input materials		
		Wood [million t/a]		Chemicals [million t/a]	Wood [million t/a]		Chemicals [million t/a]	Wood [million t/a]		Chemicals [million t/a]	Wood [million t/a]		Chemicals [million t/a]
		Fresh wood[a]	WW & WP[b]	Paraffin, urea formaldehyde, latex, etc.	Fresh wood[a]	WW & WP[b]	Paraffin, urea formaldehyde, latex and etc.	Fresh wood[a]	WW & WP[b]	Paraffin, urea formaldehyde, latex and etc.	Fresh wood[a]	WW & WP[b]	Paraffin, urea formaldehyde, latex, etc.
Medium density fibreboard (MDF)	190,000 [m³/a]	0.283 (100%)	0.00 (0%)	0.013	0.051 (18%)	0.095 (82%)	0.004	0.00 (0%)	0.116 (100%)	0.002	0.283 (100%)	0.00 (0%)	0.013
Oriented strand board (OSB)	455,500 [m³/a]	0.615 (100%)	0.00 (0%)	0.022	0.615 (100%)	0.00 (0%)	0.022	0.553 (90%)	0.027 (10%)	0.021	0.615 (100%)	0.00 (0%)	0.022
Particle-board	520,000 [m³/a]	0.374 (70%)	0.118 (30%)	0.023	0.342 (64%)	0.142 (36%)	0.022	0.348 (65%)	0.137 (35%)	0.022	0.535 (100%)	0.00 (0%)	0.032
Coated paper	170,000 [t/a]	0.310 (70%)	0.06 (30%)	0.045	0.168 (38%)	0.123 (62%)	0.025	0.443 (100%)	0.00 (0%)	0.064	0.443 (100%)	0.00 (0%)	0.064
Wood pellets	60,000 [m³/a]	0.11 (100%)	0.00 (0%)	–	0.11 (100%)	0.00 (0%)	–	0.072 (65%)	0.038 (35%)	–	0.11 (100%)	0.00 (0%)	–

[a] Weight of wood at forest, after harvesting.
[b] WP (waste paper) is used for coated paper only and WW (waste wood) is used for other products.

3.4.2. Other environmental impacts

The other impacts are all lower (except for TETP) for Scenario 1 than for the RS (Fig. 4). The greatest reduction is observed for land use (24%) and POCP (8%), both of which are due to MDF. Its land requirement is 81% lower because less fresh wood is utilised and POCP is reduced by 62% due to the smaller amount of chemicals used in comparison to the RS. The other impacts from MDF are also lower, from 25% (EP) to 52% (TETP). However, for particleboard, there is an increase in the impacts due to a greater utilisation of fresh wood. In the case of paper, ADP, ODP and TETP are higher respectively by 10%, 24% and 30% than in the RS because paper recycling is increased in Scenario 1 from 30% to 62% (Table 8). This increases the TETP due to higher emission for chemicals (such as rosin) used for paper recycling in comparison to paper production from fresh wood. There are no changes for wood pellets and OSB for any of the impacts compared to the RS because in both scenarios these are produced from fresh wood.

The impacts for Scenario 2 are also lower than for the RS, with the greatest reduction found for TETP (22%). This is related to the lower rate for paper recycling in Scenario 2 in comparison to the RSs. Regarding the specific products in Scenario 2, the need for land is completely eliminated for MDF and some of its other impacts, such as TETP, POCP, ODP are reduced significantly (60%). For particleboard, land use is reduced by 7% due to a slightly higher utilisation of waste wood; the reductions for the other impact categories are below 5%. For wood pellets, land use is reduced by 35% due to a higher use of waste wood; the reduction in the other impact categories is not significant. For paper, however, the land use increases by 34% due to higher utilisation of fresh wood for paper production. On the other hand, ADP, ODP and TETP are reduced by 9%, 25% and 28%, respectively, mainly due to the lower use of fossil energy.

In comparison to Scenario 1, Scenario 2 has lower impacts for all the categories, except for EP, land use and POCP. The main reason for this is that, in Scenario 2, paper production is solely from fresh wood, which has higher impacts for these categories compared to the production of recycled paper. Although the use of chemicals in Scenario 2 has lower HTP than in Scenario 1, this effect is balanced out by the higher HTP from energy use in Scenario 2 (see Fig. S1 in the SI). As a result, there is no difference between these scenarios for HTP.

The contribution of energy to the impacts in Scenarios 1 and 2 follows the same trend as for the GWP (see the previous section and Fig. S1). In other words, compared to the RS, most of the impacts from energy use are higher in Scenario 1 and lower in Scenario 2. A similar trend is also observed for the chemicals, which have lower impacts in Scenarios 1 and 2 than in the RS.

These results suggest that cascaded utilisation of wood has some environmental benefits over the current situation. These benefits are even greater when compared to the use of fresh wood in Scenario 3 (Fig. 4), ranging from 11% for GWP to 39% for land use. In addition, there is a potential to contribute to a circular economy by increasing resource efficiency through a reduction in fresh wood consumption by up to 35%, from 1.986 million tonnes in the fresh wood scenario to 1.286 million tonnes in Scenario 1 (Table 8). Furthermore, using fresh wood leads to the highest EP, FAETP, HTP, POCP and land use in all the scenarios considered. For the other impacts, it is largely comparable to the current situation. On the other hand, it has a slightly better ODP and TETP values than Scenario 1.

3.5. Further discussion and future work

Although a number of studies have highlighted the environmental and economic benefits of cascade utilisation of wood products (Table 1), it is important that such systems be optimised to ensure the highest benefits for both environmental and economic aspects. This study attempted to do so by employing a multi-objective optimisation model for a wood cascading system for the Lower Saxony region in Germany. The results indicate the potential for both environmental and economic enhancements of the supply chain compared to the current situation. However, as expected, there are some trade-offs between the environmental and economic benefits, with the former more pronounced when GWP is minimised (Scenario 2) and the latter when costs are minimised (Scenario 1).

Considering that climate change is very high on the policy agenda in Europe, GWP has been chosen as the most important environmental objective in the optimisation model. To ensure that the other LCA impacts are not worsened at the expense of GWP, a detailed LCA has been conducted at each Pareto-optimal solution. It is likely that the optimum solutions could be different if any other LCA impact is chosen as an objective function. This could be considered in future studies.

Future studies could also consider the end-of-life disposal of the products which was beyond the scope of this work. This would require consideration of the lifespan of different wood product from less than a year for paper products to 30 years for MDF and OSB. Furthermore, end-of-life disposal routes also differ between different products and should be modelled accordingly. Moreover, some products can be recycled several times which should also be taken into account. All these considerations would make the optimisation model much more comprehensive but also much more complex.

All studies involving the use of big datasets present some uncertainty associated with those data and ideally this should be tested through an uncertainty analysis. In this study, large datasets have been required related to the production quantities, transport logistics and production processes as well as the background data on economic and environmental impacts for process inputs. To ensure high quality of the data and minimise the uncertainty, every effort has been made to source the data from trustworthy and reliable sources. These include data obtained from industry, government reports and peer reviewed papers reliable LCA databases, such as Ecoinvent. However, it has not been possible to carry out a quantitative uncertainty analysis due to a lack of data required for generating the probability distribution functions.

4. Conclusions

Waste wood and wood by-products are becoming attractive alternative sources of raw materials for different applications. Their efficient use is important due to the rising demand and limited wood supply from forests in many world regions. Cascaded utilisation is gaining interest as a strategy to bridge this gap. However, the economic and environmental impacts of different cascading systems for wood-based products are underexplored in the literature.

In an attempt to address this knowledge gap, this work has determined the potential economic and environmental consequences of cascaded utilisation of wood. Using Lower Saxony as an example, five wood products have been considered: medium density fibre (MDF), oriented strand board (OSB), particleboard, coated paper and wood pellets. Multi-objective optimisation and life cycle assessment (LCA) have been combined to explore environmental and cost implications of four different scenarios.

Two scenarios with the cascaded utilisation of wood have been selected from the Pareto curve generated through multi-objective optimisation, one for the minimised costs (Scenario 1) and another for the minimum global warming potential, GWP (Scenario 2). Their environmental performance has been compared through LCA with the Reference scenario (current situation) and Scenario 3 in which only fresh wood is assumed to be used, without any cascaded use of wood. The results suggest that the cascaded utilisation of wood reduces environmental impacts in comparison to the Reference scenario. The best option is Scenario 2 for most impacts, which reduce by 1% - 23%; the GWP is lower by 15%. However, the total costs in this scenario are only 4% lower than in the Reference scenario. The impacts reductions in Scenario 1 are more limited, ranging from 1%–8% relative to the Reference scenario; the GWP is only 1% lower. However, its costs are 24% lower than in the Reference. The cascaded use of wood also offers the potential to save up to 35% of fresh wood resources, thus contribution to a circular economy. Using only fresh wood (Scenario 3) is the worst option, increasing the costs by 13% while offering small or no environmental benefits in most of the impacts. It is expected that these results will be of interest to the wood products industry, forestry authorities and policy makers.

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Supplementary materials

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