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LIFE CYCLE SUSTAINABILITY ASSESSMENT

Prospective sustainability assessment: the case of wood in automotive applications

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Abstract

Purpose The introduction of renewable materials into automotive applications is perceived as an innovative lightweight solution. Wood-based materials are advantageous in that they have potentially lower environmental impacts as compared with other materials such as steel. However, using wood per se does not automatically ensure more sustainability. Few prospective sustainability assessment methods or studies on the use of wood-based materials in automotive applications have been carried out, although these are needed to reduce unintended, negative sustainability effects and to support sustainable oriented research and innovation. Therefore, this study was conducted to assess the potential sustainability effects and consequences of introducing a wood-based component into an automotive application.

Methods A combination of methods was used to analyze the potential sustainability effects when introducing wood into automotive applications. This prospective life cycle sustainability analysis solely relied on secondary data. The environmental impacts were analyzed using a simplified environmental life cycle assessment on the product level. A multi-regional input-output-based assessment was conducted to model the country-specific environmental and socioeconomic consequences. The potential shift in social risks and opportunities on a national scale was analyzed by conducting a generic social life cycle assessment. Various aspects of each approach differ, with each providing a specific perspective of the system under study.

Results and discussion The results indicate that implementing wood into automotive application can have environmental, social, and economic benefits, according to most of the indicators analyzed. Mostly due to the product weight reduction due to the use of a wood-based component, the results show that environmental impacts decrease. Some possible consequences of using wood-based materials are increased value added and increasing the number of jobs in European countries. Similarly, the social risks and opportunities are shifted from countries all over the world to European countries, which perform better than developing countries according to several indicators. However, some indicators, such as migrant acceptance or local supplier quantity, perform better in the current situation.

Conclusions The presented case study is particularly notable, because the results clearly indicate the advantages of using wood-based materials in automotive applications, although the application of such relatively holistic and complex approaches often may lead to rather indifferent pictures. Policy makers, researchers, and companies can apply this combination of methods that rely solely on generic data to obtain both feasible and informative results. These methods also allow users to link the product level assessment with a regional and social perspective and screen critical topics to support sustainability research and innovation.

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Keywords Wood-based component · Automotive · Environmental life cycle assessment · Social life cycle assessment · Social hotspot · Substitution effects · Multi-regional input-output analysis · Life cycle sustainability analysis

Abbreviations

ASR	Auto shredder residue
EoL	End-of-life
E-LCA	Environmental life cycle assessment
GWP	Global warming potential
IO	Input output
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment/analysis
MRIO	Multi-regional input-output analysis
SHDB	Social Hotspot Database
SIB	Side impact beam
S-LCA	Social life cycle assessment
TRL	Technology readiness level
TLLB	Three-layered laminated board
WIOD	World Input-Output Database

1 Introduction

The transition towards a bioeconomy can be described as movement to an economy where the basic components of materials, chemicals, and energy are made out of bio-based resources (McCormick and Kautto 2013). This transition requires companies to identify new applications and markets for bio-based materials. One possible market for innovative bio-based materials is the automotive sector, which is being placed under an increasing amount of legal pressure to reduce the greenhouse gas emissions of their fleet (European Commission 2014). To meet these emission targets, the automotive sector needs to reduce the fuel consumption as well as the weights of their vehicles. Wood-based materials are lightweight alternatives to conventional materials that offer a promising solution to reduce the environmental impacts. Using wood to manufacture vehicles is not a new idea. When the first vehicles were introduced into the market, wood was used as the primary structural material for the cabs and bodies, e.g. the 1909 Ford Model T was entirely made out of wood (Brooke 2008). Today, although a typical passenger vehicle is composed of many materials, wood-based materials are not typically used in applications (Mayyas et al. 2012; Omar 2011). In recent years, the attention of researchers and manufacturers has turned to the idea of re-introducing wood into automotive applications. This re-introduction process has been the focus of several research projects (e.g., HAMMER, NIOS, or WoodC.A.R.) (Jost et al. 2018; Leitgeb et al. 2016; Müller et al. 2019a; Müller et al. 2019b). Implementing wood as a technical material in vehicles (e.g., by substituting a steel component with a wood-based multi-material system) can reduce the weight of the vehicle by about 15–20% (Kohl et al. 2016). Substituting steel with wood has the potential to reduce environmental impacts in various applications (Leskinen et al. 2018; Petersen and Solberg 2005). However, using wood per se does not automatically ensure more sustainability (Hesser et al. 2017; Osburg et al. 2016).

Researchers have carried out studies to analyze the sustainability of alternative lightweight materials (e.g., composites, high-strength steel, or aluminum) for automotive applications, mostly evaluating the environmental impacts of these materials (Alves et al. 2010; Hardwick and Outteridge 2016; Poulikidou et al. 2015; Zah et al. 2007). Virtually no studies, however, have been conducted to analyze the sustainability effects and potential consequences of using wood-based components in the automotive industry. One study by Kohl et al. (2016) was carried out to screen the environmental impacts of using 1 kg of beech veneer plywood with a urea-formaldehyde adhesive and aluminum, but the authors considered neither the whole life cycle of this component as compared with a functional equivalent nor the social or economic effects of the introduction of this component.

Unintended environmental, social, and economic substitution effects need to be assessed as early on in the product development process as possible, even though assessing the potential sustainability impacts of components at the low technology readiness level (TRL) is challenging. At this early stage in the development process, the data needed for a complete assessment are not known or not available, which inevitably results in data gaps and major uncertainties (Hesser 2015; Matthews et al. 2019). Still, if one waits until data is available, developmental opportunities to prevent or reduce possible adverse effects at an early stage will be lost (Matthews et al. 2019; Roes and Patel 2011). In such cases, prospective comparative assessments can be carried out to identify changes that can be made between alternative product systems in the future (Weidema et al. 1999). Researchers and developers need to screen for potential social, environmental, and economic effects by performing prospective assessments to identify the scope for further R&D activities and to support sustainability research and innovation (Hesser 2015; Hesser et al. 2017; Roes and Patel 2011).

Therefore, the present study was carried out to answer the question: What sustainability effects and consequences can be expected from the introduction of a wood-based component into a passenger car used in the European Union as compared to its conventional counterpart made of steel? The component analyzed in this case study is installed in the door of a passenger car and is still in the R&D phase. At this early stage in development, large-scale industrial primary data and information on production technologies or production sites are not yet available. Therefore, a prospective sustainability assessment was performed solely on the basis of secondary data.

2 Materials and methods

2.1 Methods

Various methods and tools can be used to assess the sustainability impacts of products, services, or predefined systems (Ness et al. 2007). Life cycle approaches can be applied to obtain a holistic view of product systems, considering the upstream and downstream consequences (Sala et al. 2013b). Life cycle approaches are based on a fundamental concept: All the life cycle stages of a product are considered from the resource extraction to the end-of-life (cradle to grave) phase. This prevents a temporal or geographic burden shifting from one life cycle stage to another as well as unexpected impacts (Finkbeiner et al. 2010; Matthews et al. 2019). In general, assessing the sustainability of products involves considering their environmental, social, and economic aspects (Hunkeler and Rebitzer 2005; Singh et al. 2012). Therefore, the development of life cycle sustainability assessment (LCSA) methods is an ongoing process, and different approaches are available, such as LCSA (assessment) (Kloepffer 2008) or LCSA (analysis) (Guinée et al. 2011; Zamagni et al. 2009).

LCSA (assessment) comprises a combination of different life cycle approaches, namely, environmental life cycle assessment (E-LCA), social life cycle assessment (S-LCA), and life cycle costing (LCC) (Ekener et al. 2018; Finkbeiner et al. 2010; Guinée et al. 2011; Sala et al. 2013a; Valdivia et al. 2013), and is a product-oriented approach. LCSA (analysis) serves as an integrated framework, which can be used to combine knowledge from different disciplines (Sala et al. 2013a). The LCSA (analysis) has a broader scope than the current LCA and is used to cover all three dimensions of sustainability (people, planet, and prosperity), rather than only environmental impacts, and ask questions about sectors or even entire economies, rather than predominantly products (Guinée et al. 2011). By broadening the scope bidirectionally, it is possible to assess effects and consequences on various indicator and analysis levels (Guinée et al. 2011). Various life cycle and disciplinary models have been proposed to cover different aspects of sustainability, such as E-LCA, S-LCA, LCC, IO, material flow analysis, and cost benefit analysis (Corona and San Miguel 2018; Hu et al. 2013; Zamagni et al. 2009). However, more research is needed to define the most appropriate methods for assessing the meso and economy levels (Guinée et al. 2011; Zamagni et al. 2009). LCSA (analysis) has been applied in a few case studies (Guinée 2016), including the work by Stefanova et al. (2014) on hydrogen production from biomass, that of Wang et al. (2018) on municipal solid waste management, that of Hu et al. (2013) on concrete recycling, and that of Corona and San Miguel (2018) on concentrated solar power. Quantitative and semi-quantitative methods were applied in different combinations in all these studies. Overall, LCSA (analysis) has been used more frequently as a model framework than a model itself, whereby the appropriate tools have been chosen based on the specific question being asked about sustainability and have depended on the objects of the analysis, the sustainability indicators, and the models included (Guinée et al. 2011; Wang et al. 2018).

In the present study, we aim to assess the potential sustainability effects and consequences of introducing a wood-based component which is still at a low TRL into an automotive application. To assess the environmental impacts of components with low TRLs, simplified assessments can be performed that are also referred to as ex-ante, streamlined, or prospective LCA (Hesser 2015; Niero et al. 2014; Roes and Patel 2011; Wender et al. 2014). A prospective LCA uses modeling tools that require less accurate datasets, such as generic datasets, standard modules for transportation, and energy production (Hesser 2015; Niero et al. 2014). In general, E-LCAs are used to assess the potential environmental impacts of a product system or service throughout the product life cycle from the raw material extraction to the final disposal (ISO 2006) phase. Hereby, two different approaches are proposed: attributional and consequential LCA (Curran et al. 2005; Ekvall et al. 2016; Finnveden et al. 2009). The attributional approach is taken to describe the environmentally relevant physical flows in a defined system, whereas the consequential approach is taken to provide an answer to questions like “what are the environmental consequences if a new technology is introduced into the market” (Bjørn et al. 2018; Curran et al. 2005; Finnveden et al. 2009). Attributional LCA is a descriptive approach and consequential LCA is a change-oriented approach (Finnveden et al. 2009), and according to Ekvall et al. (2005), both approaches are legitimate.

Input-output (IO) models offer one possibility to assess the consequences of a system change (Yang and Heijungs 2018). These models allow users to calculate the net effects of the introduced and displaced system. The consequences of the introduction of the new technology can then be evaluated (Corona et al. 2016). One disadvantage of using IO models to assess consequences is that linear extrapolations are used to approximate changes (Yang and Heijungs 2018). However, IO models may be sufficient for the evaluation of systems involving small changes, since using more sophisticated models might arrive roughly at the same results (West 1995; Yang and Heijungs 2018). One advantage of IO models is that they can be extended to calculate social and environmental indicators with the same inventory data and in the case of multi-regional input-output (MRIO) analysis, the impacts can be regionalized (Asada et al. 2020; Corona et al. 2016; Wiedmann et al. 2011). This means that, with just one single IO table, MRIO can be used to analyze the economic, socioeconomic, and environmental consequences of a substitution under global economic conditions by differentiating between regions or countries, including their economic structures and trading relationships (Corona et al. 2016; Corona and San Miguel 2018; Wiedmann et al. 2011).

Practitioners can assess the potential positive and negative social and socioeconomic impacts of products throughout their life cycle with S-LCA (Dreyer et al. 2010; Garrido 2017; UNEP/SETAC 2009). An S-LCA can be based on generic or site-specific data (Du et al. 2019). When carrying out a S-LCA, site-specific data as well as the sectoral and regional contexts play essential roles in the assessment (Dreyer et al. 2010; Jørgensen 2013). For instance, the social impacts of a sawmill as compared with a metal manufacturing company in central Europe might be completely different (Dreyer et al. 2010; Jørgensen 2013). In the present study, the early stage of the component development does not allow for the use of site-specific data; consequently, only generic and country-specific data could be used for the S-LCA. This assessment, however, allowed us to create a preliminary estimate of the risks and opportunities regarding local situations, well-being, and social themes of interest. The results based on generic data do not represent real-life circumstances, but provide an initial overview of potential social problems, risks, and opportunities associated with the substitution of steel with wood (Du et al. 2019).

By combining generic S-LCA, prospective E-LCA, and a MRIO approach, it is possible to examine the potential environmental impacts of this substitution on a product level (E-LCA); shifts in social problems, risks, or opportunities on a national scale (generic S-LCA); and potential environmental, socioeconomic, and economic consequences on a regional scale (MRIO). Each of those approaches have respective advantages and limitations. Specifically, they differ from and complement each other in terms of their (a) coverage of environmental, economic, and social indicators; (b) coverage of the product life cycle; (c) aggregation level of the data; and (d) possibility of regionalization. These differences, summarized in Table 1, provide a specific perspective of the system under study.

The LCSA (analysis) framework has already been applied in other studies with different objects of analysis and different combination of methods (Corona and San Miguel 2018; Hu et al. 2013). However, both of these studies referred to the same framework suggested by Zamagni et al. (2009) and Guinée et al. (2011), which consists of three phases: (1) goal and scope definition; (2) inventory, modeling, and assessment; and (3) interpretation of results. In the first phase, the goal, functional unit, and system boundaries are described. In the second phase, relevant subcategories and inventory indicators (S-LCA) as well as relevant impact categories and assessment methods (E-LCA) are identified. Next, the inventory data is collected (S-LCA, E-LCA, MRIO), impacts are calculated, and the uncertainties are analyzed. In the last phase, the results are prepared and interpreted.

2.2 General system description

The goal of conducting this study was to assess whether a wood-based component offer benefits over its conventional steel counterpart in terms of the environmental impacts, the economic and socioeconomic consequences, and the social risks and opportunities. The object of the case study, a side impact beam (SIB), is a component that is installed in every door of a passenger car. The functional unit chosen for this

Table 1 Main characteristics of the approaches applied in the study

Method	Life cycle assessment	MRIO-based modeling	Social life cycle assessment (generic)
Flow aggregation level	Product level (micro) — relatively specific (e.g., *three-layered laminated board*)	Sector level (meso) — relatively unspecific (e.g., *wood and products of wood and cork*)	Topic identification on sector level (meso); economy-wide data (macro) used to calculate indicators
Geographic scale of input origin	Global, regional (e.g., European average), or country-specific	Country-specific	Country-specific
Geographic scale of impact	Global	Country-specific or aggregate at regional scale	Country-specific
System boundaries	Resource and production stage, use phase, end-of-life	Resource and production stage	Resource and production stage
Sustainability dimension focus	Environmental indicators	Environmental, economic and socioeconomic indicators	Social and socioeconomic indicators
Data sources	Ecoinvent	World Input-Output Database (WIOD)	Social Hotspot Database (SHDB) and various other data sources

study was one SIB component used in the European Union that is installed in a passenger car with a petrol-driven combustion engine and an approximate maximum life span of 210,000 km. The E-LCA considered the entire life cycle from raw material extraction to the disposal phase. Figure 1 illustrates the system boundaries of the E-LCA, generic S-LCA, and MRIO analyses.

In S-LCA studies, the site-specific data as well as the sectoral and regional contexts play essential roles (Dreyer et al. 2010; Jørgensen 2013). Therefore, the affected countries for the life cycle stages of the wood-based and steel-based systems (see Fig. 1) have been identified. The aim in this study was to illustrate the potential substitution effects, but no differences or substitution effects were expected if the affected countries were identical for the conventional and the newly designed component in certain life cycle stages.

In the present study, we assumed that the component production of both variants (steel- and wood-based SIB) would be in Europe (i.e., a focus was placed purely on European car manufacturers). For all later stages, we assumed that the wood-based component would be used and disposed of in the same regions as the steel-based component. Hence, the social impacts in the use phase were assumed to be the same for both variants (e.g., a safety assurance had to be provided for both materials). The resource extraction and material production phase, on the other hand, were expected to change due to the substitution. Therefore, the system boundaries were narrowed down to the resource extraction and material production phase in the (generic) S-LCA, allowing us to screen for potential social risks and opportunities in these stages. This is feasible, since assumptions about the involved regions and sectors for those stages could be made. In the case of the MRIO-based approach, the WIOD was used to perform the analysis. This database only includes data on material flows and indicators up until the production phase; therefore, the system boundaries were again narrowed down to the resource extraction and material production phase (see Fig. 1).

2.3 Environmental life cycle assessment

For the present study, SimaPro 9.0 was used to calculate the impact assessment. Generic datasets from the Ecoinvent v3.4 database were mainly used for the calculations. Other sources of information were our company partners in the WoodC.A.R. project (http://www.woodcar.eu/) as well as academic publications (Sections 2.3.1–2.3.3). Transportation data were considered only up to the production phase, since we assumed that transportation of any kind would be similar for both cases after this phase. The average data on transportation present in the respective Ecoinvent datasets were used for the wood-based SIB (geographical scope: Europe) and the steel-based SIB (geographical scope: global). The uncertainties associated

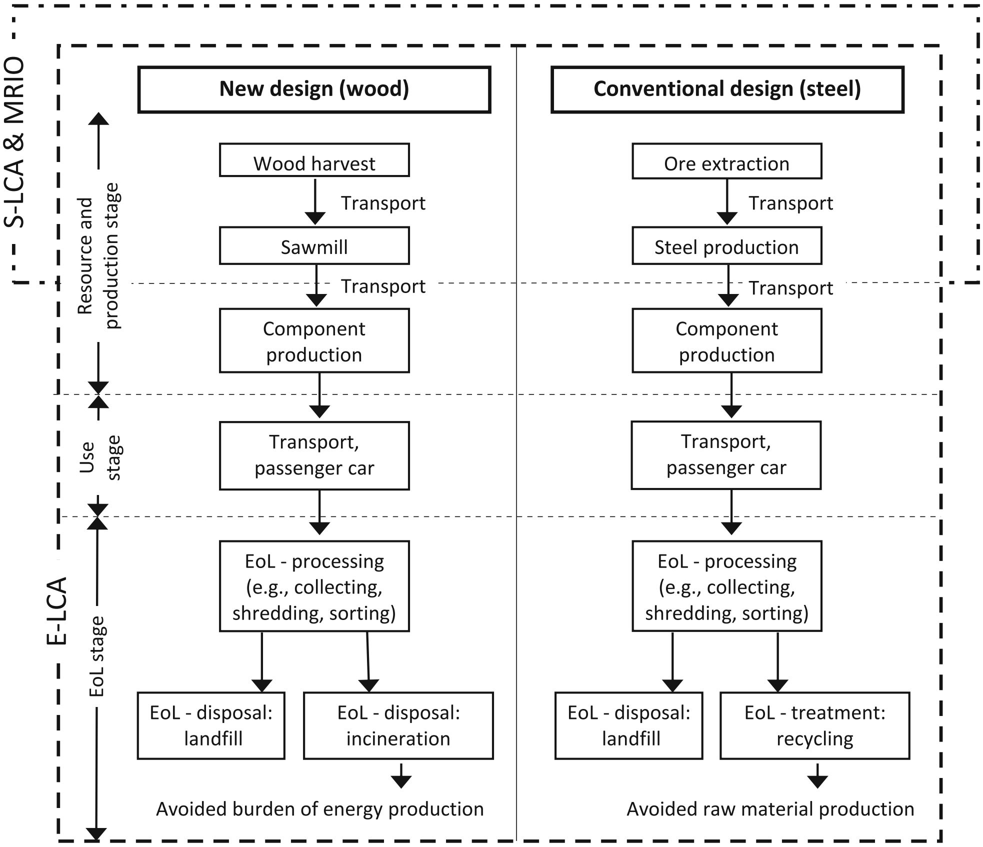


Fig. 1 Simplified illustration of the system boundaries in the present study, including the social, environmental, and socioeconomic assessment boundaries

with the use of generic datasets and the respective variations in the data were addressed using the Monte Carlo simulations implemented in SimaPro, which allowed the calculation of the data uncertainty for the LCA results (Goedkoop et al. 2016).

2.3.1 Resource extraction and production

The wood-based substitution component under study consists of a combination of different hardwoods reinforced by a viscose fabric. This component weighs 1.04 kg, including the surface finish, and has been developed to be screwed on to the passenger car door frame. The substituted steel component weighs 1.55 kg and is created by shaping a low-alloyed steel sheet using hot-rolling and welding processes. The profile created is then welded on a mounting panel made of unalloyed steel, which is used to assemble the SIB on the door. An overview of the materials and production processes considered is provided in Table 2.

Other than the materials used, no further data were available about the production processes for the wood-based SIB. However, the main processes used to produce the wood-based SIB are gluing and pressing the wood layers together. As an approximation, we assumed that the production of three-layered laminated board (TLLB) is similar to that of the wood-based SIB. Therefore, the TLLB unit process available in Ecoinvent was adapted insofar as the base material was defined as hardwood instead of softwood, taking the average transportation data for Europe from the plywood market process. Only the forming (i.e., not the cutting) processes were considered for both variants, the steel- and wood-based SIB. Another approximation was performed regarding the adhesives used (i.e., the polyurethane-based glue that joins the layers together). The amounts of materials required were taken from Messmer (2015), and the inventory data was extracted from the Ecoinvent database. For the textile used to reinforce the SIB, we assumed that the production of a textile made of cotton is analogous to the production of a textile made of viscose and adapted the "textile, cotton" process from Ecoinvent accordingly.

Table 2 Considered materials and processes in the E-LCA of the wood and steel-based SIB

Wood-based SI		Steel-based SIB	
Three-layered laminated board*	0.64 kg	Steel, unalloyed	0.3 kg
Plywood	0.03 kg	Steel, low alloyed	1.55 kg
Varnish, organic solvent-based	0.07 kg	Zinc coating	0.137 m^2
Textile, woven viscose*	0.17 kg	Sheet rolling	0.3 kg
Steel, unalloyed	0.05 kg	Hot rolling	1.25 kg
Adhesive, polyurethane*	0.15 kg	Welding, gas	0.84 m
		Deep drawing	0.3 kg

*Process adapted

2.3.2 Use phase

The environmental impacts of a vehicle in the use phase are largely caused by fuel-dependent emissions. To calculate these emissions, the driving patterns of the vehicle when in operation need to be considered (e.g., by using models like the New European Driving Cycle (NEDC) or the Worldwide Harmonized Light Duty Test Procedure (WLTP)) (Cubito et al. 2017). The reduced impacts of lightweighting can be assessed by calculating the fuel reduction value, as proposed by Koffler and Rohde-Brandenburger (2010), or by assuming a linear correlation between the vehicle weight and the fuel consumption (Koffler and Rohde-Brandenburger 2010; Poulikidou et al. 2015). Due to data availability and to simplify the analysis, the latter approach was chosen, and the Ecoinvent process "transport passenger car" was used for a full-size, petrol-engine vehicle with a weight of appr. 2000 kg and a fuel consumption > 2.0 l (Simons 2016). According to Simons (2016), the fuel consumption and emission factors for the Ecoinvent process are taken directly from the TREMOVE model, which tend to be 20% higher than those reported with NEDC.

2.3.3 End-of-life phase

In the EoL phase, the vehicles are collected, reusable parts are dismantled and the remainder is shredded and sorted (Diener and Tillman 2016; Sun et al. 2017). After the materials are shredded, they are separated into a magnetic-metal fraction (e.g., iron and steel), a heavy-material fraction (e.g., aluminum and copper), and an automobile shredder residue (ASR) fraction (e.g., plastics, rubber, wood, and textiles) (Gradin et al. 2013; Martens and Goldmann 2016). The process of recycling metals is well-established (Gradin et al. 2013), and a recycling rate of 95% for the steel used in this study was assumed, with the remaining material being landfilled (Gradin et al. 2013; Poulikidou et al. 2015; Sun et al. 2017). The wood-based component was assumed to be sorted as an ASR fraction, which is currently either incinerated or landfilled (Martens and Goldmann 2016; Vermeulen et al. 2011). Therefore, it was assumed that most (95%) of the wood-based SIBs would be incinerated and the rest would be landfilled. The benefits of the material recovered were included as avoided burdens by broadening the system boundaries (Fig. 1) (Ekvall and Finnveden 2001; Gradin et al. 2013). It was assumed that steel replaced primary steel production and that the incineration of the wood-based SIB would prevent primary electricity and heat production (Gradin et al. 2013; Poulikidou et al. 2015; Sun et al. 2017). The electricity and heat recovered were calculated based on the calorific value of the incinerated materials, such as 16.6 MJ/kg for birch (Günther et al. 2012) and 27 MJ/kg for polyurethane (adhesive) (Font et al. 2001). As an approximation, it was further assumed that the wood-based SIB would be incinerated in a municipal incineration plant, where the thermal efficiency is about 42.5% and the electrical efficiency is about 15.3% (Murphy and McKeogh 2004). The avoided burden of the energy recovered was considered using an average European electricity and heat mix.

2.3.4 Life cycle impact assessment

In the life cycle impact assessment (LCIA) phase, the actual impacts on the environment are calculated by first selecting impact categories, category indicators and characterization models (ISO 2006). The relevant environmental issues of the system under study need to be identified to select the impact categories (EC 2010; ISO 2006; Mair-Bauernfeind et al. 2020). A primary environmental concern in connection with the automotive industry is CO_2 emissions. These contribute to climate change and are subject to legislation, such as the EU regulation on emission performance standards (European Commission 2014; Hardwick and Outteridge 2016). The potential contribution to climate change is measured with the impact category *Global Warming Potential* (GWP). The GWP is also the most commonly assessed impact category in LCA studies on automotive or wood products (Hottle et al. 2017; Klein et al. 2015; Mair-Bauernfeind et al. 2020) and, therefore, was considered in the assessment.

Mair-Bauernfeind et al. (2020) reviewed LCAs of wood and automotive components to identify relevant environmental and social topics for assessing wood in automotive applications. The results of this review show that most of the automotive LCAs assessed indicators related to the GWP and energy (Hottle et al. 2017; Mair-Bauernfeind et al. 2020). However, in systems where non-renewable resources are involved, the depletion potential of the respective resource should also be analyzed (Allwood et al. 2011; Klinglmair et al. 2014; Mair-Bauernfeind et al. 2020). Biodiversity losses, water and soil protection, and land use are of interest in systems that involve bio-based materials (dos Santos et al. 2014; Mair-Bauernfeind et al. 2020; Pawelzik et al. 2013). The main drivers of biodiversity losses include global warming, acidification, eutrophication, and ecotoxicity (dos Santos et al. 2014; Pawelzik et al. 2013). Water and soil protection can be evaluated by assessing fresh water aquatic ecotoxicity and terrestrial ecotoxicity (dos Santos et al. 2014).

For product systems involving bio-based materials, the carbon contained is either fully or partly of biogenic origin; therefore, the biogenic carbon can be accounted for in LCAs of bio-based products (Pawelzik et al. 2013). However, this is viewed critically, since the CO_2 captured in bio-based products will re-enter the atmosphere at some point, most probably after the use phase of the product (Vogtländer et al. 2014). Therefore, the biogenic CO_2 was removed from the list of emissions for calculating the GWP midpoint indicators (Vogtländer et al. 2014). In addition, Braun et al. (2016) found that the carbon storage effects are rather low compared with the potential substitution effects. Therefore, the carbon captured was not calculated in the present study. The data used and assumptions made for the life cycle stages are described in the following sections.

The impact assessment can be performed by using LCIA methods which combine various category indicators and calculate the results based on specific characterization models (Hauschild et al. 2013). For the present study, a broad range of environmental topics were covered to include all the previously mentioned environmental issues related to the use of wood and steel components in automotive applications. The baseline perspective (hierarchical) of ReCiPe was used to perform mid- and endpoint calculations, as a state-of-the-art method that is the most appropriate among all models for characterization at the endpoint level (Hauschild et al. 2013; Huijbregts et al. 2017).

2.4 Multi-regional input-output approach

A multi-regional input-output (MRIO)-based approach was used to examine the potential short-term environmental, economic and socioeconomic consequences under a replacement scenario in the European (EU27) transport equipment sector. In this scenario, conventional metal inputs were substituted by wood-based inputs. The approach is consequential in nature, as it was taken to identify the effects of choosing an alternative product system (wood-based design) (Weidema et al. 1999; Yang and Heijungs 2018). Due to the sectoral classification of World Input-Output Database (WIOD), individual technologies could not be used as the subjects of marginal changes. Instead, we assumed that the effects of changes in demand would be transmitted via relatively broad economic production sectors, such as those for basic metals and fabricated metal.

The scenario is developed by considering that an applicable substitute must be at least equal to the conventional input in terms of its function and cost; we assumed that a wood-based functional equivalent existed at the same cost. The project partners of WoodC.A.R. considered this assumption as a desired target, and this target would have to be met to make the wood component competitive. In this scenario, the transport equipment sector replaces basic metals and fabricated metal worth 4.18 USD (2009) with wood and products of wood and cork of the same monetary value (Table 3). This value roughly corresponds to the cost of the steel inputs per SIB in the conventional design. By taking this approach, linear relationships were assumed between inputs (e.g., raw materials), outputs (products) and production-induced effects (e.g., greenhouse gas emissions) along the supply chains. The geographic

Table 3 Substitution scenario; sectors are classified according to the WIOD release 2013 (Timmer et al. 2015) based on the International Standard Industrial Classification Rev. 3 (United Nations 1990)

Substituting sector	Substituted input	Value	Substituting input	Value
Transport equipment (34–35)	Basic metals and fabricated metal (27–28)	4.18 USD (2009)	Wood and products of wood and cork (20)	4.18 USD (2009)

distribution of the marginal sectors corresponds to their initial contributions as suppliers for the European transport equipment sector. The effects studied include country-specific changes in global warming potential, material use, land use, as well as capital- and labor-related indicators.

The WIOD (Timmer et al. 2015) was applied as a data source, including monetary input-output tables as well as environmental (Genty et al. 2012) and socioeconomic (Erumban et al. 2012) extension data. The 2013 release of WIOD covers 40 countries plus a rest of the world (ROW) region, differentiating 35 economic sectors and spanning the period from 1995 to 2011. Due to data gaps in the socioeconomic accounts, the most recent year with complete data is 2009, which was defined as the time reference in the model. WIOD's environmental extension data were compiled from various sources, which included the Global Material Flows Database; national accounting matrices, including environmental accounts (NAMEA); national emission inventories; the International Energy Agency; and FAOSTAT (Genty et al. 2012). Emissions to air are presented as CO_2 equivalents using the IPCC 100-year time horizon GWP factors (Myhre et al. 2014). Socioeconomic data were primarily obtained from the EU KLEMS database (Erumban et al. 2012).

The feasibility and usefulness of the approach applied have been demonstrated in a recent comparative assessment of four bioeconomic innovation cases by Asada et al. (2020), in which the authors started with the basic MRIO model (Eq. 1) (Miller and Blair 2009)

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{1}$$

where $\mathbf{x}$ is the mn-by-1 total output vector of the n sectors in m countries, $\mathbf{I}$ is an mn-by-mn identity matrix, $\mathbf{A} = \mathbf{Z}\ \mathrm{diag}(\mathbf{x})^{-1}$ is the mn-by-mn input coefficient matrix, $\mathbf{y} = \mathbf{Y}\iota$ is the mn-by-1 final consumption vector enclosing the aggregated consumption of the n sectoral outputs produced in m countries; $\mathbf{Y}$ is the mn-by-mo final consumption matrix differentiating o consumption classes, and ι is an mo-by-1 vector of ones. $\mathbf{Z}$ stands for an mn-by-mn matrix representing all flows of goods and services between the n sectors of m economies in monetary terms.

$$\mathbf{x}' = (\mathbf{I} - \mathbf{A} \odot \mathbf{S})^{-1}\mathbf{y} \tag{2}$$

Next, an mn-by-mn matrix $\mathbf{S}$ encompassing the substitution coefficients according to the scenario description was created ($\odot$ denotes the Hadamard product). With an unaffected final consumption $\mathbf{y}$ and an identity matrix $\mathbf{I}$, a new mn-by-1 vector $\mathbf{x}'$ was calculated that depicts the total outputs of the n sectors in m countries after the substitution, including direct and indirect substitution impacts (Eq. 2).

$$\mathbf{c} = \mathrm{diag}(\mathbf{x})^{-1}\mathbf{x}' \tag{3}$$

$$\Delta\mathbf{E} = \mathbf{E}\ \mathrm{diag}(\mathbf{c}) - \mathbf{E} \tag{4}$$

Subsequently, $\mathbf{x}'$ was normalized by $\mathbf{x}$, yielding the mn-by-1 output change vector $\mathbf{c}$ (Eq. 3). This vector represents the output change coefficients caused by the substitution scenario. Output changes were assumed to linearly affect the p indicators chosen; for example, a 1% increase in output production of a given sector and country is associated with a 1% increase in direct emissions into the air for that sector. As shown in Eq. 4, substitution impacts on indicators are presented in absolute terms ($\Delta\mathbf{E}$), where the p-by-mn extension matrix $\mathbf{E}$ encloses data on the p indicators that are directly associated with the production of output in the n sectors in m countries. For reasons of clarity, the results are presented in the form of four regional aggregates: EU27 (EU27 member countries), BRIC+ (Brazil, China, Indonesia, India, Russia, Taiwan), NEMO (non-European major OECD countries [Australia, Canada, Japan, South Korea, Mexico, Turkey, the USA]), and ROW (rest of the world).

The approach has some inherent limitations. First, due to the linearity assumption for input-output relations and output-impact relations, some aspects are not considered. These include potential production constraints, changes in returns to scale and prices and rebound effects. The linearity assumption is considered to allow a reasonable approximation for short-term effects of limited magnitude (Yang and Heijungs 2018). However, the larger the substitution-induced demand changes are as compared with the overall markets, the greater the role of such non-linear aspects. Second, the WIOD sectors are relatively broad depictions of economic activities, rather than precise representations of the characteristics of the specific products involved in the substitution. This may distort economic, socioeconomic and, in particular, environmental effect estimates (Steen-Olsen et al. 2014). Referring to an uncertainty assessment using Monte Carlo simulation, Asada et al. (2020) showed that some indicators react sensitively to small changes in simulated sectoral disaggregation (e.g., fossil and mineral resource use), suggesting that the results concerned need to be interpreted cautiously. Similar uncertainty calculations as in Asada et al. (2020) were performed for the present study.

2.5 Social life cycle assessment (generic)

The UNEP/SETAC (2009) guidelines have recently been cited more frequently in the S-LCA literature and referenced in S-LCA case studies (see, e.g., Benoît-Norris et al. 2011, Aparcana and Salhofer 2013, or Ekener-Petersen and Finnveden 2013). The guidelines define five stakeholder groups and 31 subcategories for assessing the social impacts of a system. These stakeholder groups and subcategories were used in the present study. As complements to the UNEP/SETAC (2009) guidelines, methodological sheets have been prepared to support data collection which provide more information on subcategories, suggestions on inventory indicators, and data sources (Benoît-Norris et al. 2011; Ekener-Petersen and Finnveden 2013).

The guidelines highlight the importance of site-specific data; however, due to the low TRL of the wood-based component included in the study, only generic data could be collected from the sources suggested in the methodological sheets and others as described below. Despite this lack of available site-specific data, the present study was carried out to illustrate possible social problems, risks, or opportunities in the affected regions. The temporal scope of the S-LCA covers the years in which the most recent data were available (i.e., 2016–2018, with the exception of the fair wage potential indicator, see supplementary material). The use of generic data is subject to some limitations; e.g., data may not relate well to the measured concept, the credibility of the data is fundamental and conducting an in-depth analysis is difficult (UNEP/SETAC 2009). However, a generic S-LCA can be seen as a screening device and "it allows the user to get a general feel for areas of social concerns in certain countries/or sectors" (Benoît-Norris et al. 2011, p. 687). The S-LCA (generic) was performed by carrying out the following steps: (1) identify affected regions; (2) identify hotspots for prioritization; (3) assign SHDB risks to subcategories; (4) data collection; (5) normalization and weighting; (6) uncertainty analysis; and (7) interpretation.

2.5.1 Prioritization of social topics

A typical product system can be highly complex, containing up to thousand unit processes, and not all of the subcategories might be important in every system (Benoit-Norris et al. 2012; Du et al. 2019). Using a database, the area of the supply chain that requires attention (Du et al. 2019) and the business activities (along a supply chain) that contribute the most in terms of topics, indicators and countries can be identified. The Social Hotspot Database (SHDB) can be used as a screening and prioritization tool to identify relevant subcategories (Benoit-Norris et al. 2012; Du et al. 2019; Ekener-Petersen and Finnveden 2013).

To proceed with the prioritization, the first step is to identify the regions affected by the use of a wood-based or steel-based system (see Fig. 1). The focus of the present study was placed on the European automotive industry. Most of the metals (82%) used by this industry are supplied by European countries (see Table 4) (World Steel Association 2016). These countries, in turn, obtain their resources (minerals) from Russia, Brazil and Sweden, among others (EUROFER 2018a, 2018b).

No factories that produce wood-based components for the automotive sector currently exist. Therefore, it is assumed that existing wood processing plants (e.g., wooden flooring production) will be converted. Austria is one of the world's largest importers of industrial roundwood, reflecting its extensive sawmilling capacities. At the same time, Austria has a significant automotive industry, especially in the area of car part manufacturing. Therefore, Austria was selected to represent a country in Central Europe. The countries that import non-coniferous wood for Austria, including Austria as a producer, are listed in Table 4.

In a second step, the hotspots were identified using the SHDB. The SHDB offers a variety of different social indicators in a Web Portal for 244 countries, split into 26 subcategories and then further into five categories, namely, labor rights and decent work, health and safety, human rights, governance and community infrastructure (Du et al. 2019; Norris and Benoît-Norris 2015). Although the SHDB is similar to the UNEP/SETAC guidelines (Norris and Benoît-Norris 2015), not all relevant social issues are included in the SHDB. Four risk levels are defined (from low to very high) in the SHDB (Norris and Benoît-Norris 2015), and all indicators which showed a very high risk level within the involved regions were initially highlighted for the wood- and steel-based systems. As mentioned by Norris and Benoît-Norris (2015), especially very high risk issues are important for countries that are acting or planning to act in specific countries. Next, the indicators that had been identified as having a very high risk level were assigned to the subcategories and the stakeholder groups of the UNEP/SETAC (2009) (see the summary in Fig. 2 and a more detailed version in the supplementary material).

As illustrated in Fig. 2, 12 subcategories were identified as relevant in the present study (very high-risk topics of the SHDB). For three indicators of the SHDB, no assignment was possible (see under *no assignment* in the supplementary material). Several social topics and indicators that are relevant for bio-based materials were identified in a review of Mair-Bauernfeind et al. (2020). Based on the results in this review, relevant subcategories were added (food security and quality of life). Other relevant subcategories identified by Mair-Bauernfeind et al. (2020) are energy security and land access, but these were not included in the present study, as no suitable

Table 4 Affected regions and considered sectors of the product system under study. Total in brackets describes the coverage of supplying countries, e.g., about 80% of the non-coniferous wood is supplied to Austria by the countries listed

	Sector	Countries	Source
Wood-based	Forestry	Germany, Slovakia, Hungary, Slovenia, Czech Rep., Croatia, Austria (total: 80%)	(FAOSTAT 2016)
	Wood products	Germany, Slovakia, Hungary, Slovenia, Czech Rep., Croatia, Austria (total: 80%)	(FAOSTAT 2016)
Steel-based	Minerals nec.	Sweden (91% in EU from Sweden), Germany, Austria, Kazakhstan, Russia (65% CIS from Russia), Ukraine, Brazil (92% other America from Brazil), Chile, Peru, Venezuela (total: 77%)	(World Steel Association 2016)
	Ferrous metals	Germany, Italy, France, Spain, Poland, Austria, Belgium, the UK, and the Netherlands (total: 82%)	(EUROFER 2018a, 2018b)

data were available. The final list of included subcategories is provided in Table 5.

2.5.2 Data gathering, normalization, and weighting

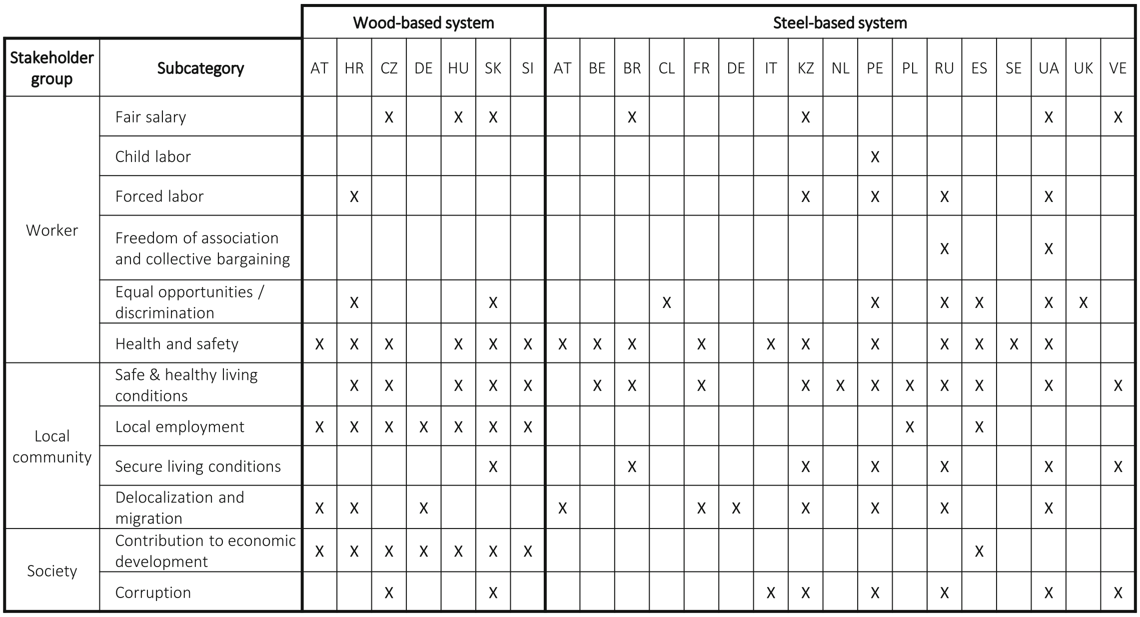
In order to make a comparison between the potential shifts in social risks and opportunities for the two product systems under study, an online search for the indicators and generic data for the prioritized subcategories was conducted, following recommendations given in the methodological sheets of the UNEP/SETAC (2009) or in selected publications (e.g., Ekener-Petersen and Finnveden (2013), Neugebauer et al. (2017), Du et al. (2019), or Siebert et al. (2018)). The main data sources were obtained from various, publicly available databases, e.g., from the World Bank, ILO, and OECD (details see in supplementary material).

Generic data on a national scale for the indicators in the 13 subcategories were inventoried (see Table 5). Some of the collected data are provided in form of an index, as is the case for the *government response rating* or *occupational safety and health* indicators. For other indicators (i.e., *DALY* or *life expectancy at birth*), the data had to be normalized with respect to "min-max linear normalization method," which is used to standardize the results on a scale of 0 to 1, where 0 is considered the best and 1, the worst value (Eq. 5) (Ibáñez-Forés et al. 2014; Yıldız-Geyhan et al. 2019)

$$\text{Country Index}\ (x_k) = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \quad (5)$$

where x_i is the inventory indicator value of country i, $x_{\min}$ is the minimum value of indicator x, and $x_{\max}$ is the maximum value of indicator x.

To compare the potential social risks and opportunities of the wood-based and steel-based systems, the normalized values for all indicators were weighted according to the production volumes or trade volumes of the countries involved. This was done to keep countries with small production capacities from being treated as equal to countries with high



		Wood-based system							Steel-based system																
Stakeholder group	Subcategory	AT	HR	CZ	DE	HU	SK	SI	AT	BE	BR	CL	FR	DE	IT	KZ	NL	PE	PL	RU	ES	SE	UA	UK	VE
Worker	Fair salary			X		X	X				X					X							X		X
	Child labor																	X							
	Forced labor		X													X		X		X			X		
	Freedom of association and collective bargaining																			X			X		
	Equal opportunities / discrimination		X				X					X						X		X	X		X	X	
	Health and safety	X	X	X		X	X	X	X	X	X		X		X	X		X		X	X	X	X		
Local community	Safe & healthy living conditions		X	X		X	X	X		X	X		X			X	X	X	X	X	X		X		X
	Local employment	X	X	X	X	X	X	X											X		X				
	Secure living conditions						X				X					X		X		X			X		X
	Delocalization and migration	X	X		X				X				X	X		X		X		X			X		
Society	Contribution to economic development	X	X	X	X	X	X	X													X				
	Corruption			X			X								X	X		X		X			X		X

Fig. 2 Summary of the identified very high risk topics of the SHDB, assigned to the subcategories and stakeholder groups of the UNEP/SETAC (2009) guidelines. A more detailed overview can be found in the supplementary material

Table 5 Identified inventory indicators and the respective normalized value range. An extended table including data sources as well as indicator description are provided in the supplementary material

Subcategory	Indicator/index	Normalized value range
Stakeholder group: worker		
Forced labor	Government response rating	0: good response to 1: bad government response
	Vulnerability to modern slavery	0: low vulnerability to 1: high vulnerability to modern slavery
Equal opportunities/discrimination	Economic participation and opportunity (gender equality)	0: parity to 1: gender imparity
	Vulnerable employment	0: low risk to 1: higher risk to vulnerable employment
Fair salary	Fair wage potential	0: better to 1: worse
Health and safety	Occupational safety and health	0: high level to 1: low level of safety
	All-cause DALY rate attributable to occupational risks	0: better to 1: worse
Freedom of association and collective bargaining	Global rights index	0: best to 1: worst
Stakeholder group: local community		
Safe and healthy living conditions	Age-standardized DALY rates	0: better to 1: worse
	Domestic general government health expenditures	0: better to 1: worse
	Coverage of essential health services	0: good to 1: bad
Food security	Prevalence of severe food insecurity	0: better to 1: worse
	Consumer expenditure spent on food	0: less to 1: more
Quality of life	Human development index	0: better to 1: worse
	Self-reported life satisfaction	0: best to 1: worst
	Political empowerment (gender equality)	0: parity to 1: imparity
Local employment	Local supplier quantity	0: extremely numerous to 1: largely nonexistent
Secure living conditions	Political stability and absence of violence	0: good to 1: bad
	Proportion of population covered by at least one social protection benefit	0: more to 1: less people covered by social protection
Delocalization and migration	Number of ratifications of human rights instruments relevant to migration	0: better to 1: worse
	Migrant acceptance	0: better to 1: worse
	Migration stock	0: more to 1: less welcome
Stakeholder group: society		
Contribution to economic development	Unemployment	0: better to 1: worse
Corruption	Corruption perception index	0: very clean to 1: high corrupt

capacities in the comparison. Finally, the sum of the weighted normalized data for all indicators is calculated, the results were compared, and the uncertainties were analyzed by performing analytical calculations.

3 Results and discussion

3.1 Environmental effects

The potential environmental impacts of the SIB were calculated by performing attributional LCA using ReCiPe for the LCIA. The results are presented at the endpoint level (Fig. 3), illustrating the impacts in terms of damage to ecosystem, human health, and on resources and at the midpoint level with 18 impact categories (Fig. 4) for the resource and production (R&P) and the End-of-Life (EoL) phase.

In total, the impacts over the whole life cycle of the wood-based SIB component are lower than the steel-based SIB component in almost all impact categories except for land use (increase of 30%) and marine eutrophication (almost no changes) and all damage categories. In general, these results suggest that a positive substitution effect can be expected when introducing a wood-based component into an automotive application. However, as can be seen in Fig. 3, the observed reductions in environmental impacts are mostly due to reductions in the use phase. For simplification purposes, a linear relation between weight reduction and fuel

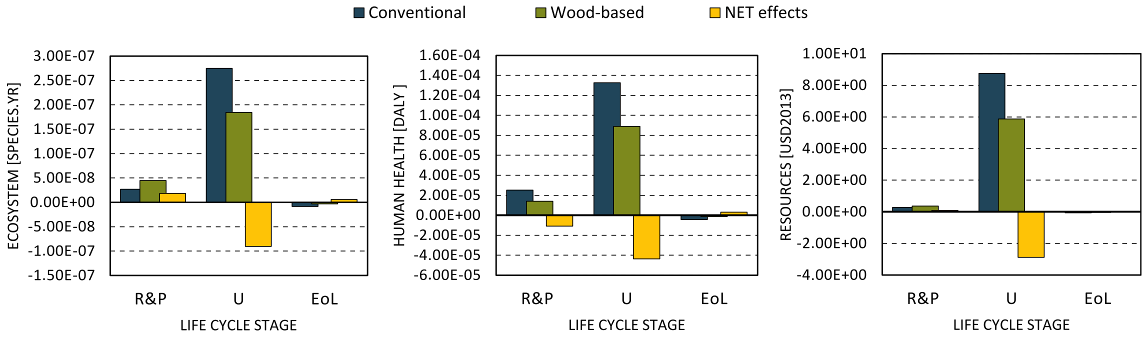


Fig. 3 E-LCA results for the wood-based and the conventional steel SIB as well as the net effects for the damage categories ecosystem, human health, and resources (ReCiPe)

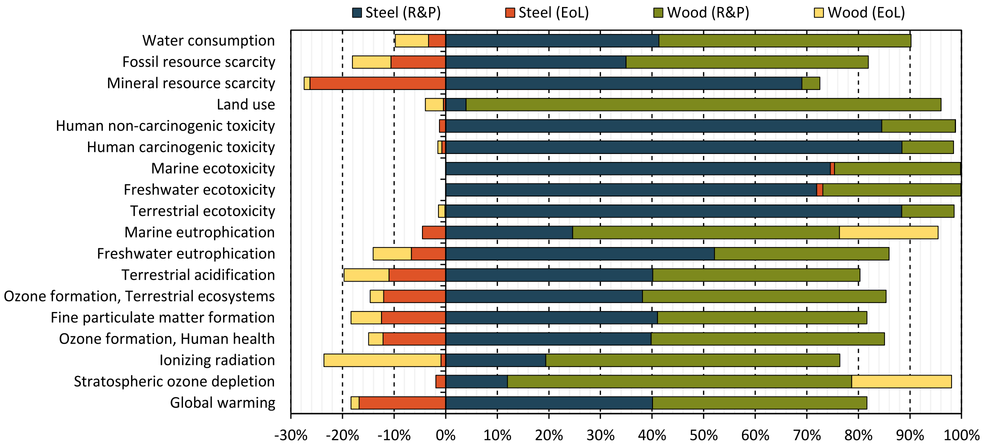
consumption was assumed (see Section 2.3.2), and the impacts are shown to decrease by 20% across all impact categories. In automotive LCAs, the use phase impacts are the highest as compared with the impacts of other life cycle stages, in terms of the life cycle emissions and energy demand (Hottle et al. 2017). In this context, lightweighting has already been recognized as an important measure to reduce fuel consumption and, hence, the use-phase impacts (Delogu et al. 2017; Koffler and Rohde-Brandenburger 2010). Due to the dominance of the use-phase impacts, a reduction of emission and energy demand can be achieved by using various materials like high-strength steels, aluminum, or composite materials (Hottle et al. 2017; Poulikidou et al. 2015). This means that weight reduction can be achieved by using different materials, regardless of whether the material is bio-based or not. However, every material substitution might result in tradeoffs between the life cycle stages or between different impact categories (Delogu et al. 2017).

In the present study, the use of a lightweight design decreased the damage observed in the use phase but increased the damage observed for ecosystems and resources in the R&P stage (Fig. 3). This is in part due to the fact that the increased use of bio-based materials results in an increase in land use, which directly affects ecosystem damage. In Fig. 4, we clearly see that substituting the wood-based component in the R&P phase increases the impact in several categories (e.g., increase in *land use* by 88%, *marine eutrophication* by 26%, *ionizing radiation* by 38%, and *stratospheric ozone depletion* by 55%). The impacts in the R&P and EoL phases for both variants are also illustrated in Fig. 4. The avoided burdens obtained by recovering energy through incineration or recycling are illustrated as negative impacts. The avoided burdens are much higher for the steel SIB (red bars) than for the wood-based SIB (yellow bars), except for the impact category *ionizing radiation*.

The reasons for the increased impacts in the R&P phase of the wood-based component are illustrated in Fig. 5, where the process textile viscose, used for reinforcing the SIB, forms a hotspot in most of the 18 impact categories. The fact that global average data were used for all inventories of the Ecoinvent textile process might explain this finding. The energy used in this process is mostly provided by fossil-based energy sources.

Other hotspots in the R&P phase of the wood-based SIB are the adhesive used in the impact categories *water consumption* (30%) and *fossil resource scarcity* (15%), the varnish used in the category *ozone formation* (human health [20%] and *terrestrial ecosystems* [30%]) and the TLLB in the category *land use* (83%). Hotspots in the R&P phase of the steel component are the zinc coating process and the low-alloyed steel in most impact categories.

Fig. 4 E-LCA results for the wood-based and the conventional, steel-based SIB on the midpoint level for the resource extraction and production phase (R&P) and the end-of-life phase (EoL) (ReCiPe)



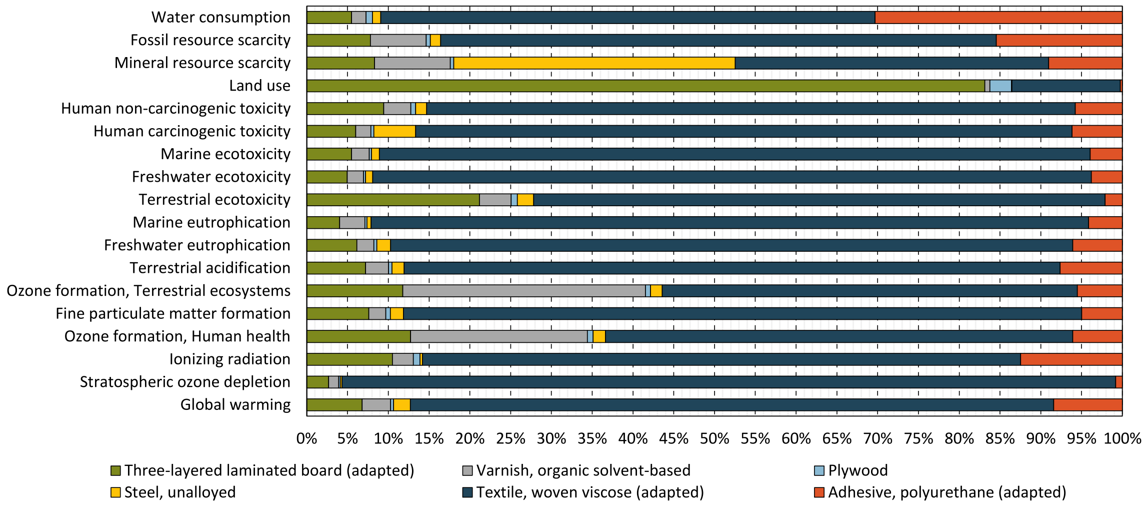


Fig. 5 E-LCA results for the wood-based component on the midpoint level for the resource extraction and production phase (R&P) (ReCiPe)

The results of the prospective E-LCA indicate that implementing wood-based components in automotive applications has the potential to be environmental beneficial in most of the impact categories considered. Nevertheless, because most of the calculations were performed on data from generic datasets (Ecoinvent), these are subject to uncertainties. Therefore, Monte Carlo simulations were performed to address the effects of data uncertainties on the LCA results. The results of analyzing the uncertainties involved in the resource and production stage of wood show that the uncertainties are extremely high for the impact categories *water consumption*, *ionizing radiation*, and *land use*, as well as the toxicity categories (see Fig. 10 in the Appendix). The uncertainties are especially extreme for water consumption. Several challenges must be faced when calculating the water consumption for the production of wood, as various factors must be taken into account, such as plantation type, irrigation methods and groundwater uptake (Sutterlüty et al. 2017). Nevertheless, the analysis of whether wood performs better than steel in the R&P and U phases clearly indicated that the wood-based system was superior in all impact categories except *land use*. If the uncertainties of the R&P phase of wood versus steel are compared, the results are no longer so clear, especially in the impact categories *water consumption*, *terrestrial acidification*, and *fine particulate matter formation* (see Fig. 11 in the Appendix). More accurate data on the foreground processes are needed to draw clear conclusions for these stages. Nevertheless, since carbon storage was not considered in the calculations, and no appropriate process was available for the textile reinforcement, the current assumptions made for the wood-based component are believed to represent a worst-case scenario. For this reason, the real impact of the wood-based components is believed to be lower than the impact shown by the results presented.

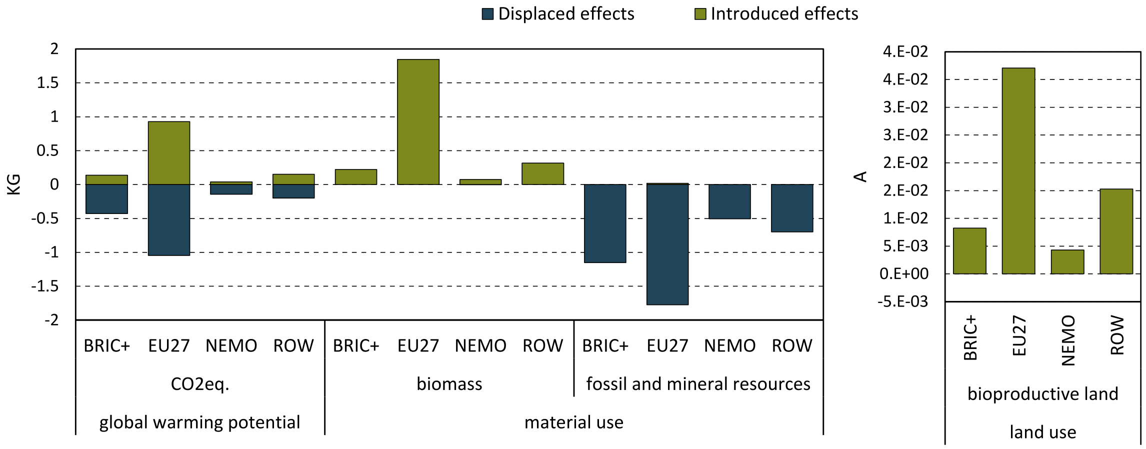


Fig. 6 Substitution effects in terms of GWP, material use, and land use for one SIB out of wood instead of steel. Regional aggregates: EU27 (EU27 member countries), BRIC+ (Brazil, China, Indonesia, India, Russia, Taiwan), NEMO (non-European major OECD countries [Australia, Canada, Japan, South Korea, Mexico, Turkey, the USA], ROW (rest of the world)

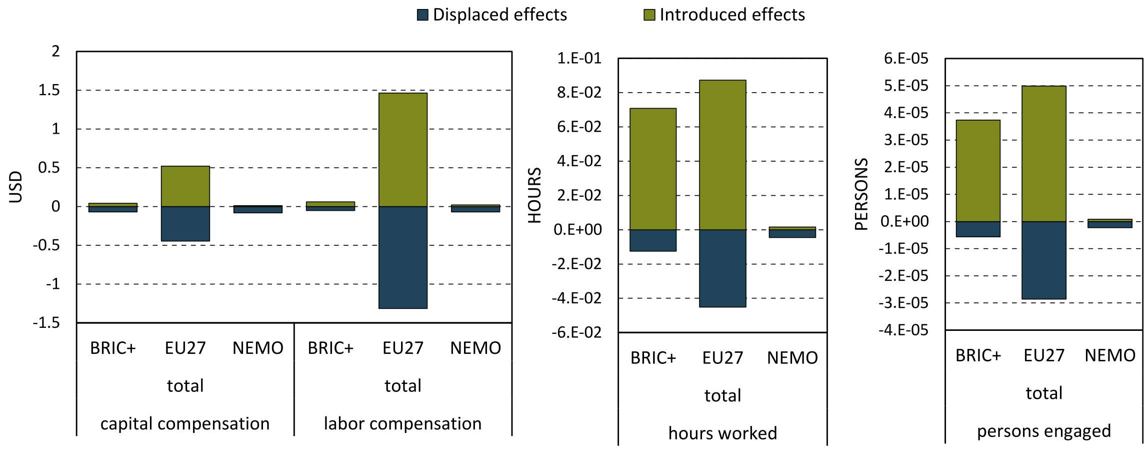


Fig. 7 Substitution effects in terms of capital and labor compensation, hours worked and person engaged. Regional aggregates: EU27 (EU27-member countries), BRIC+ (Brazil, China, Indonesia, India, Russia, Taiwan), NEMO (non-European major OECD countries [Australia, Canada, Japan, South Korea, Mexico, Turkey, the USA], ROW (rest of the world)

3.2 Regionalized environmental, economic, and socioeconomic consequences

The results of the MRIO approach are illustrated in Fig. 6 (GWP, material use and land use) and in Fig. 7 (labor and capital compensation, hours worked and person engaged). In general, the results of Fig. 6 are not surprising; the substitution is shown to increase the use of biomass (2.46 kg year^{-1}) and decrease the use of fossil and mineral resources ($-$ 4.11 kg year^{-1}). However, less material is used overall in the current linear model ($-$ 1.65 kg year^{-1}), and most of the bio-based materials are expected to come from EU27 countries, whereas the displaced materials mostly originate from BRIC+, NEMO, and ROW. Naturally, the use of bioproductive land is highly correlated with the use of biomass (0.06 year^{-1}). The results show that a substitution has the potential to mitigate GWP ($-$ 0.56 kg year^{-1}) with the largest net reduction found in BRIC+ countries ($-$ 0.29 kg year^{-1}).

As Fig. 7 shows, mostly EU27 countries were affected by the capital and labor compensation changes involved in shifting from the “basic metals and fabricated metal” sector to the “wood and products of wood and cork” sector. The

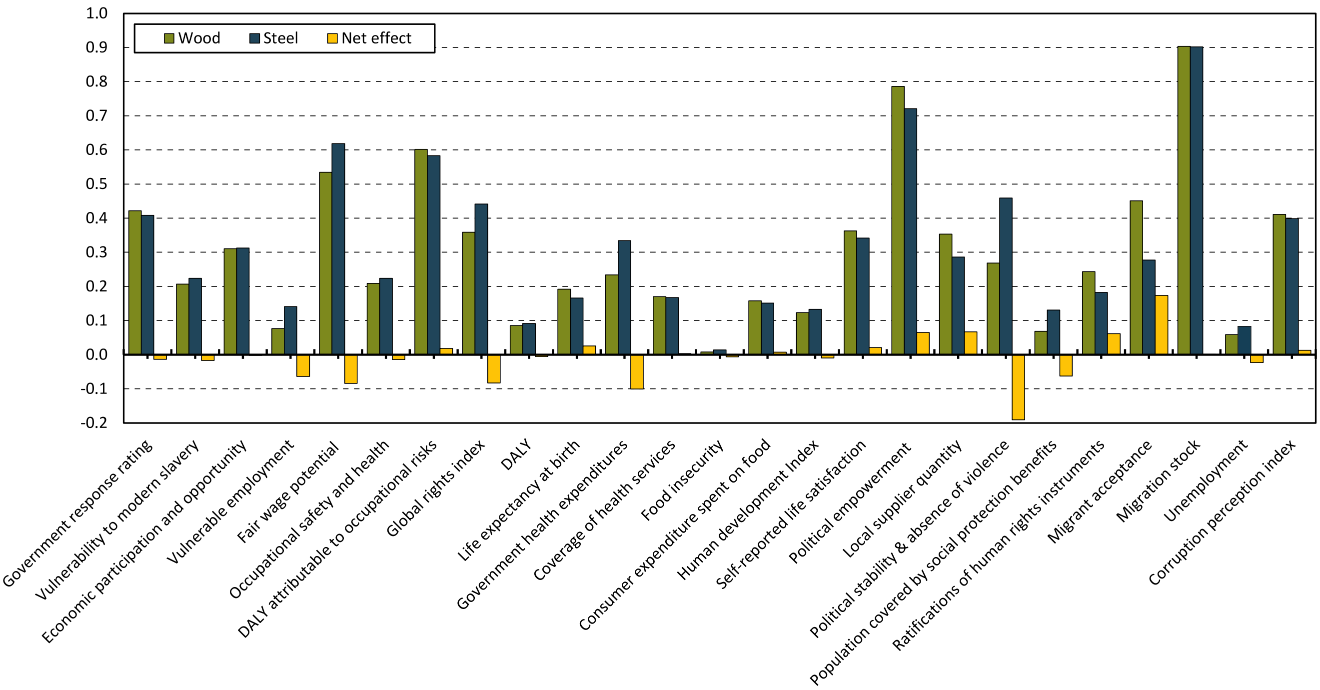


Fig. 8 Comparison of the wood- and steel-based systems for all indicators showing the risks or opportunities and net effects. Normalized values from 0: better to 1: worse performance. Negative net effects mean that the wood-based system performs better than the steel-based system. Explanation of the indicators and sources can be found in the supplementary material

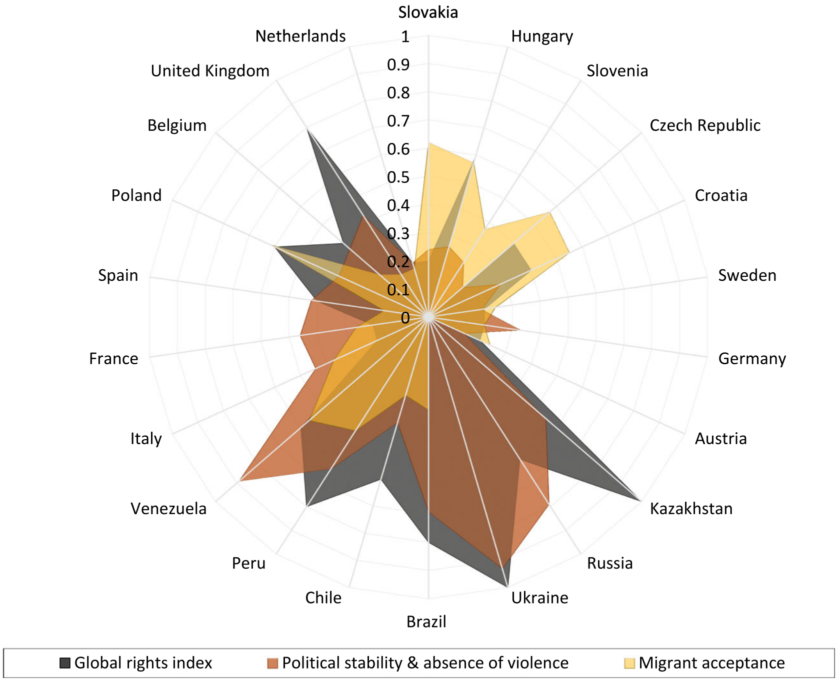


Fig. 9 Social risks or opportunities of three selected indicators, highlighting the biggest differences between the analyzed countries. Normalized values from 0: better to 1: worse performance

capital compensation was slightly impaired by the substitution in BRIC+ and NEMO, leading to a minor reduction in the indicator across all regions (− 0.03 USD year^{-1}). However, if EU27 countries alone are examined, capital compensation indicates a (small) positive change (0.14 USD year^{-1}). The change in value added, which is defined as capital compensation plus labor compensation, is positive. In this scenario, the present innovation case provokes a sectoral shift within Europe, which potentially exerts pressure on capital and labor compensation and increases the risk of local job losses in the metalworking industries.

However, this shift is also expected to cause an increase in the number of hours worked and persons engaged in EU27 (0.04 h year^{-1}/2.14E−05 persons year^{-1}) and BRIC+ (0.06 h year^{-1}/3.17E−05 persons year^{-1}) countries, which may be explained by the high labor intensity in the forest and wood sector.

In contrast to the E-LCA method, MRIO is a top-down approach, which — at least in principle — covers economy-wide production and consumption. Due to the nature of this method, sectoral inputs and outputs are subject to a higher aggregation level than the product systems investigated using a bottom-up approach such as E-LCA. To explore the uncertainty associated with the level of aggregation, a Monte Carlo simulation was performed in which sectors are repeatedly disaggregated at random (see also Asada et al. 2020). In most cases, the simulation results support the net change direction (positive/negative) of the initially estimated impact within the EU27. However, one major uncertainty is the GWP, where the uncertainty interval clearly extends into both the negative and positive range. The results of the Monte Carlo simulations are provided in Fig. 12 in the Appendix.

Comparing the results of the environmental indicators obtained by applying both the E-LCA and MRIO, we see that the total net impact change of the GWP in the R&P phase is positive for E-LCA and negative for MRIO, with the Monte Carlo simulation confirming the uncertainty regarding the direction of change (positive/negative) in the MRIO results. The direction of change is similar in MRIO and E-LCA for the indicator *land use*, but the differences between the methods with respect to the indicator definitions do not allow comparisons to be made in the case of *fossil and mineral use*. The numerical results differ, which can again be explained by the methodological differences described in Table 1.

3.3 Regionalized social risks and opportunities

The sum of the weighted normalized data for each indicator was calculated to compare the social risks and opportunities of the wood-based and steel-based systems. The results for all subcategories and indicators are illustrated in Fig. 8. In Fig. 8, the performance of the wood-based (green) and steel-based (blue) systems is shown as well as the net effects (yellow) between those systems. The observed negative net effect indicates that the wood-based system performs better than the steel-based system. In general, the results shown in Fig. 8 indicate that a substitution would lead to positive or no changes in most social indicators. No change would signify that the situation for the indicator concerned is similar in the countries considered. The substitution would result in a shift in social risks and opportunities from production sites in countries all over the world to sites in mostly European countries, where the situation for several indicators might be better compared with, e.g., developing countries (see Table 4). This is the case for the indicators *political stability* and *absence of violence*, *government health expenditures*, *global rights index*, *vulnerable employment*, and the *fair wage potential*, where the countries affected by the wood-based system perform better than those affected by the steel-based system (Fig. 8). However, four indicators perform more poorly in the new product system. These are *political empowerment*, *migrant acceptance*, *local supplier quantity*, and *ratification of human rights instruments*. Political empowerment refers to gender equality, which is below average in some countries that play a stronger role as suppliers in the new product system (e.g., Hungary, Czech Republic). The same is the case for migrant acceptance, where people were asked if their hometown is a good place to live for immigrants from other countries. The considered substitution, therefore, may lead to an increased risk of discrimination in the supply chain, in terms of migrant acceptance and gender equality. It should be noted that this analysis refers to data for entire countries, and intra-country variation may exist (e.g., urban/rural differences). In addition, the results could look completely different on the company and sector levels, since the site-specific and sectoral contexts are essential in S-LCAs (Dreyer et al. 2010; Jørgensen 2013). This implies that more research on the company as well as sector levels is needed to draw firm conclusions about the social substitution effects of introducing wood-based components in automotive applications.

To gain a better understanding of the influence of country involvement on certain indicators, a radar chart was used to plot results for selected countries (Fig. 9). Figure 9 illustrates these results for three indicators, highlighting where the differences between the two systems are the biggest (Fig. 8). This illustration identifies country hotspots (i.e., which countries perform worst or best in a certain indicator). For instance, Kazakhstan and Ukraine perform worst for the *global rights index* indicator but the situation is also worse in the UK as compared with the other countries. For the indicator *migrant acceptance*, data were not available for all countries, but European countries (Poland, Czech Republic, Slovakia, and Croatia) most frequently perform worse. The *perceived corruption* indicator is highest in countries like Venezuela, Brazil, Ukraine, Russia, and Kazakhstan. The same countries perform worst with regard to *political stability* and *absence of violence* as well as to *coverage of health services*, which might be partly responsible for the lower *life expectancy* observed. *Government health expenditures* are lowest in Brazil and Venezuela. Russia and Venezuela perform worst in the subcategory *forced labor* as well as for the indicator *occupational safety and health*. The *fair wage potential* is worst in Brazil, Russia, Croatia, and Poland, but this indicator was not calculated for all countries due to a lack of data.

As is the case for streamlined E-LCAs, which rely on generic data, generic S-LCAs are also subject to uncertainties with regard to data gathering, index calculations, or missing data for certain countries. To gain some insight into the validity and robustness of our results, we performed an uncertainty analysis of the data used in the generic S-LCA. For the ELCA, a Monte Carlo sampling was used to obtain probability distributions for the various impact categories. For the generic S-LCA, analytical calculations were done to perform exactly the same analysis (details on the calculation procedure can be found in the Appendix). The results of the uncertainty analysis show that, for indicators with small net effects (see Fig. 8), it is unlikely that the wood-based system performs better than the steel-based system. For indicators with bigger net effects, the direction of the results could be confirmed by performing an uncertainty analysis (see Fig. 13 in the Appendix).

In summary, the generic S-LCA shows that some indicators (e.g., political stability and absence of violence, vulnerable employment) indicate that the social performance will be better with the wood-based system than with the steel-based product system; this increase in social performance, however, might come at the cost of people losing work when production sites are shifted from one country to another. Other indicators, such as migrant acceptance or local supplier quantity, indicate that the current situation performs better.

4 Conclusion and outlook

In the present study, a prospective sustainability assessment was performed in which the environmental impacts were analyzed using a simplified environmental LCA method on the product level. A multi-regional input-output-based assessment method was applied to model country-specific environmental and socioeconomic substitution effects. The potential social problems, risks, and opportunities were analyzed with a generic social LCA. Taken together, the results of these methods reveal a sustainability profile of potential environmental, social, and economic substitution effects. They also show that these methods can be used in combination to screen for potential negative and positive sustainability effects of components in an early development stage. The prospective assessment results indicate that implementing wood-based components into automotive applications has the potential to be environmentally, socially, and economically beneficial in most indicators analyzed. Regarding environmental indicators, only one (*land use*) from among 18 midpoint categories is clearly in favor of using the conventional component; hence, the weighting of this category in the analyzed system is most relevant for the total assessment. Still, these results are mostly due to the strong influence of the use phase on the life cycle emissions. If the resource and production stage alone is assessed, the advantages become unclear, and the wood-based component performs more poorly in several impact categories. Both the E-LCA and MRIO approaches show an increase in land use with the use of a wood-based component. This result was repeatedly obtained, despite the differences among the approaches regarding the flow aggregation level, the geographic scale of input origin, system boundaries, and data sources. The consideration of regionalized impacts broadened the understanding of total impacts caused, and particularly those caused by indirect effects. Reduced transportation, as a matter of more local raw material sourcing, is a major issue. However, this effect is dependent on the structure of the current economic system. Other researchers may investigate whether this is a reasonable assumption and determine how much additional biomass will be demanded, as well as the cause effects that may occur thereafter. Another important outcome is the relative or absolute shift of impacts from one region to another. For instance, the results of the MRIO show that the substitution might lead to job creation in European countries, which will probably result in job losses in other regions.

Countries may be affected very differently by the substitution scenario, which emphasizes the significance of regionalization approaches, if policy recommendation is intended. At the same time, global figures remain important in order to identify possible leakage effects. In this case study, the economic and environmental impacts were not perfectly synchronized, although they were partly correlated. In particular, it seems possible to create regional jobs without compromising environmental impacts, serving as a good example of green job creation. However, the results of the generic S-LCA indicate that the countries affected by the wood-based system perform worse in indicators like *migrant acceptance*, *local supplier quantity*, and *political empowerment*. These indicators perform below average in some countries that are affected by the new product system (e.g., Hungary, Czech Republic). For other social indicators, the case study revealed the clear advantages of the wood-based system, e.g., for the indicators *political stability* and *absence of violence* or *government health expenditures*. However, this observation is a consequence of shifting production activity from one region to another and, hence, neither really changes social systems per se nor takes into account social risks and opportunities in the use or EoL phases (assumed to remain constant). An improvement in the social system can be achieved by taking measures that increase migrant acceptance, gender equality, or local supplier quantity as well as foster a fair wage.

In general, the results are subject to several uncertainties regarding data gathering, unit process assumptions and aggregation levels. These uncertainties were addressed by performing Monte Carlo simulations and analythical calculations. The direction of the results is mostly consistent with the results of the uncertainty analyses, which provide insight into the potential sustainability substitution effects. However, the meaningfulness of the indicator values must be treated with caution. To obtain a more accurate picture of the sustainability effects, site-specific and sectoral information should be added to the S-LCA and primary data should be added to the E-LCA in future assessments. Further methodological development is also needed to assess the socio-economic and social impacts in the use and EoL life cycle phases. The use of primary data for both S-LCA as well as E-LCA calculations would allow researchers to gain deeper insights into the hotspots and potential risks and opportunities of the substitution case, which is a necessary step that must be taken to support sustainable product design. However, the choice of material influences the environmental and social impacts. In the present study, results show that the textile used to reinforce the SIB forms a hotspot in all impact categories and that the social risks are connected with the geographical origin of the material. By considering these and other factors, the sustainability performance of product can be influenced.

In general, the presented case study is particular notable, because its results clearly indicate the advantage of the wood-based solution, even though a relatively holistic and complex approach was applied. In other studies, this approach has yielded rather unclear results. Policy makers, researchers, and companies can use this approach to link the product level assessment with a regional and social perspective to obtain feasible and informative results. The R&D activities required to get comparable eco-innovations into markets are seldom carried out by single companies. Different forms of public-private partnerships that involve significant amounts of public funding are, hence, being established with increasing frequency. Therefore, the expansion of the product perspective towards regional economic, environmental, and social impacts is both necessary and useful. This is particularly because the linkages between environmental, economic, and social impacts are not linear, especially when considering different regional effects. However, the nature of the inter-linkages between economic, environmental, and social impacts in different regions requires us to develop a deeper understanding of these cases, as in the example of a case of potential impacts that clearly reach beyond historical developments.

The LCSA (analysis) framework is still being developed, and further research is needed regarding how to perform assessments on various case studies, integrate temporal and geographical perspectives, and define appropriate methods to cover the different levels of assessment (Costa et al. 2019; Guinée 2016). The present study provides the results of an LCSA (analysis) case study of a wood-based component in an early development stage, where data availability is an issue. The combination of methods applied in the present study (E-LCA, S-LCA, MRIO) offers a prospective approach that can be taken to assess the sustainability of a component that is still in a low TRL. Although this prospective sustainability assessment was conducted solely on the basis of generic data, a first impression was obtained of the potential sustainability effects and consequences of introducing a wood-based component into an automotive application.

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Appendix

The uncertainties associated with the use of generic datasets and the respective variations in the data of the E-LCA were addressed by using the Monte Carlo simulations implemented in SimaPRo (Goedkoop et al. 2016). The uncertainties involved in the resource and production stage of the wood-based component are illustrated in Fig. 10 and, for a comparison of the same stage with steel, is shown in Fig. 11. The latter shows the probability that wood is more beneficial than steel or vice versa.

Fig. 10 Uncertainty range per impact category for the resource and production stage of wood for ReCiPe midpoint (H) V1.02 with a confidence interval of 95%. Note that the change in water consumption by far dominates all other values and has, hence, been rescaled for visibility

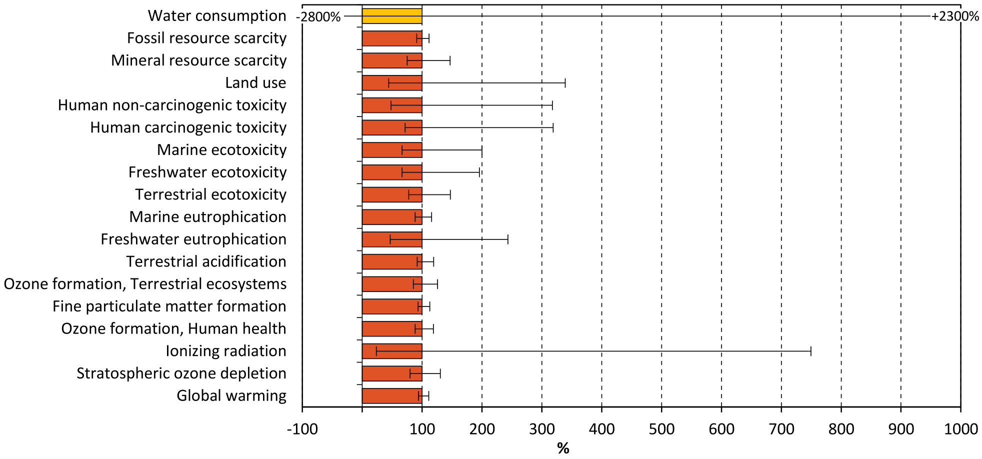
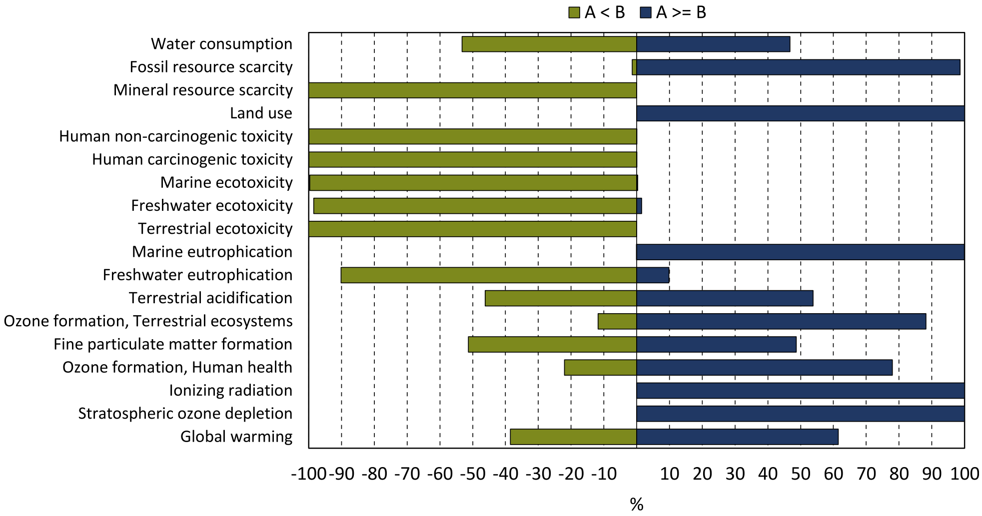


Fig. 11 Uncertainty analysis of the resource and production stage of the wood (A) and the steel (B) alternative for ReCiPe midpoint (H) V1.02 with a confidence interval of 95%



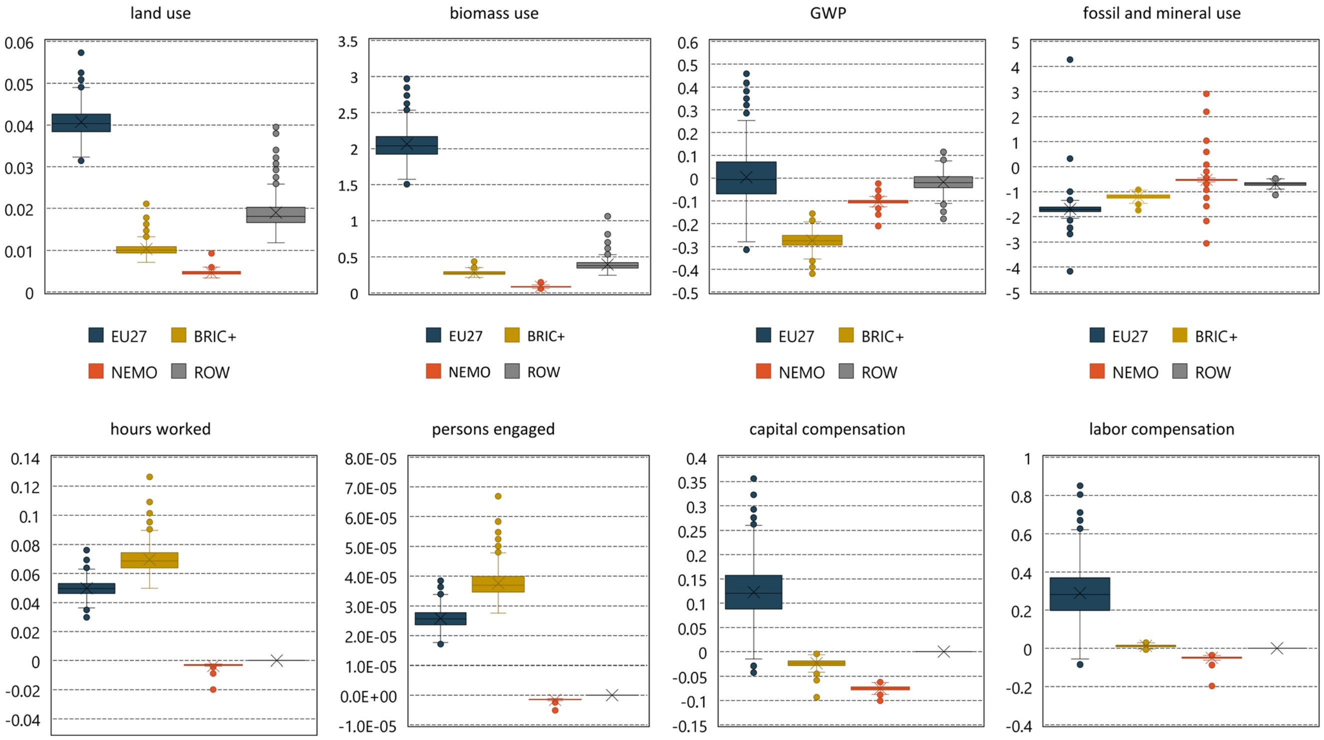


Fig. 12 Uncertainties of the regional net effects for the MRIO indicators. In order to more clearly illustrate the range of uncertainties, outliers were cut off: 14 kg fossil and mineral use EU27, − 0.55 h worked in NEMO and − 0.0002 persons engaged in NEMO

Unlike the E-LCA method, MRIO is a top-down approach that covers economy-wide production and consumption. This means that sectoral inputs and outputs are subject to a higher aggregation level. To explore the uncertainty associated with the level of aggregation, a Monte Carlo simulation was performed in which sectors were repeatedly disaggregated at random (see also Asada et al. 2020). The results of this analysis are illustrated in Fig. 12.

Uncertainties for the various social indicators of the S-LCA can be obtained in the following way. Probability distributions for the various social indicators are calculated using analytical calculations instead of the Monte Carlo sampling. For this step, two assumptions need to be made: first, since the various indicators are obtained from different sources and concern very different aspects of social sustainability, the uncertainties of the values are uncorrelated from each other to a very good level of approximation; second, the uncertainties of the individual indicators are modeled using Gaussian probability distributions. This is a good approximation, since the indicators used in this study are often aggregates (e.g., global rights index or human development index) of many other indicators and are, therefore, normally distributed according to the central limit theorem (von der Linden et al. 2014). Note that these or similar assumptions also need to be made prior to the Monte Carlo sampling.

With those two plausible assumptions made, the analysis of the uncertainties of the indicators can be performed analytically. The only remaining question is how to obtain the actual values of the indicators and their uncertainties. In several cases, the sources did not provide values for the uncertainties; therefore, they were estimated (see Supplementary Material). In addition, not every indicator was available for all countries. In these cases, the value of the missing entry was estimated by taking the average of the countries for which the data was present and a large uncertainty was added to reflect the uncertainty of this estimate (see Supplementary Material). The results of the uncertainty analysis are illustrated in Fig. 13, showing the probability distributions of each indicator for steel (blue) and wood (green). This figure also shows the probability that wood outperforms steel for each indicator based on the assumptions made above. This probability should not be overinterpreted (since it strongly depends on the assumptions), but it serves to condense the information in each plot into a single number.

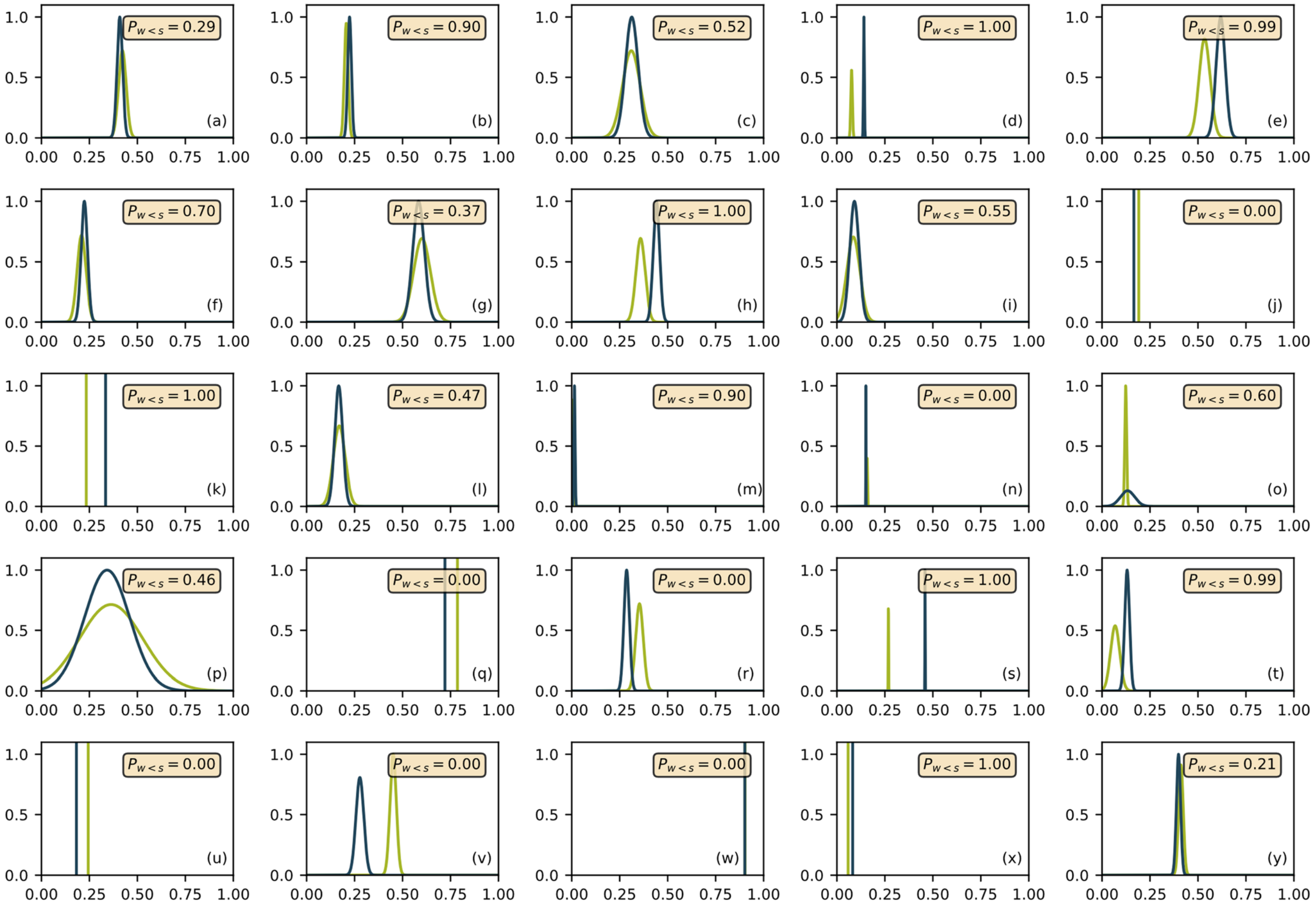


Fig. 13 Probability distributions of each indicator for the wood-based (green) and steel-based (blue) systems. Normalization for each indicator is chosen such that the maximum value is 1. $P_{w<s}$ provides the probability that wood performs better than steel in the respective indicator based on the assumptions made in the uncertainty analysis. Indicators without uncertainty are drawn as a vertical line at their value. The indicators are **a** government response rating, **b** vulnerability to modern slavery, **c** economic participation and opportunity, **d** vulnerable employment, **e** fair wage potential, **f** occupational safety and health, **g** DALY attributable to occupational risks, **h** global rights index, **i** DALY, **j** life expectancy at birth, **k** government health expenditures, **l** coverage of health services, **m** food insecurity, **n** consumer expenditure spent on food, **o** human development index, **p** self-reported life satisfaction, **q** political empowerment, **r** local supplier quantity, **s** political stability and absence of violence, **t** population covered by social protection benefits, **u** ratifications of human rights instruments, **v** migrant acceptance, **w** migration stock, **x** unemployment, and **y** corruption perception index

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