EMPOWERING WOODWORKING INDUSTRY STAKEHOLDERS TO REDUCE ENVIRONMENTAL IMPACTS

DISSERTATION

WITH THE AIM OF ACHIEVING A DOCTORAL DEGREE AT THE
FACULTY OF MATHEMATICS, INFORMATICS AND NATURAL SCIENCES
DEPARTMENT OF BIOLOGY OF UNIVERSITÄT HAMBURG

SUBMITTED BY

STEFAN DIEDERICHS

2015

HAMBURG

Genehmigt vom Fachbereich Biologie
der Fakultät für Mathematik, Informatik und Naturwissenschaften
an der Universität Hamburg
auf Antrag von Professor A. FRÜHWALD
Weiterer Gutachter der Dissertation:
Professor Dr. M. FINKBEINER
Tag der Disputation: 24. April 2015

Professor Dr. D. Hanelt
Vorsitzender des
Fach-Promotionsausschusses Biologie

ENGLISH REVIEW TESTIMONIAL

I certify that the English of the dissertation

Empowering Woodworking Industry Stakeholders to Reduce Environmental

Impacts written by Stefan Diederichs was reviewed and is correct.

The dissertation was reviewed by Susan J. Ortloff (US citizen), freelance translator and editor

S. J. Ortloff

Susan J. Ortloff

March 2, 2015

# ABSTRACT

Introduction The European Union is in danger of not fully meeting the energy and environmental targets for 2020. A change of course will require increased effort on the part of all relevant industry members. The woodworking industry is seen as a key contributor to achieving several of these targets. To be effective, its various stakeholders need to fully understand the relevant interrelations between their sector and others (e.g. forestry and construction), between decisions they make and their impact within context of the target paths, and how the industry in general reacts to implemented policy tools.

Aim This study aims to supply the woodworking industry's stakeholder groups with science-based methods and data that will enable them to include an understanding of the potential environmental impacts of their decision-making in their respective fields of action.

Methods The stakeholders require knowledge of the past development of environmental and energy aspects of the sector. They also require the tools to reasonably approximate the environmental implications of decisions made today and a comprehensive understanding of the current situation.
Building upon the well-established Product Environmental Life Cycle Assessment (LCA) tool, the study in hand uses different approaches. On the one hand a survey based bottom-up approach - from products to sector - is used to calculate the current environmental situation of the woodworking industry. By complementing information on the current state with historic environmental data on sector level towards a hybrid database, the monitoring approach supplies a view on the sector's historic development. On the other hand, a top-down approach - from sector to products - allows insight into the historical product-specific environmental impacts and their development over time.
For decision support, the established LCA methodology, as used in the construction sector, is analyzed in terms of its capability to include the relevant parameters for decisions on micro- meso- and macro-level. A case study addressing the significant aspects is conducted to identify any blind spots.

Results Representative information on the environmental implications of producing the core products of the woodworking industry was surveyed and expanded in the context of the bottom-up ap-

proach. With this, reliable background data to be applied in product specific LCA is available.
The monitoring approach proved to supply reliable results on greenhouse gas emissions trends within the sector and on the change in the greenhouse gas intensity of specific products over time. This allows retracing and explanation of developments of the sector. Furthermore, the approach allows to include the development of product specific environmental impacts over time within LCA.
In the context of decision support, the broadening of system boundaries identified additional aspects to be considered for micro- meso- and macro-level decision support.

Conclusion The results of this dissertation enable companies of the woodworking industry to declare the environmental impacts of their processes and products in accordance with the available product and corporate assessment schemes and labels. The study further helps them understand how technical developments influence the outcome of LCA which is applied in these assessment schemes and labels. The results can therefore be implemented into the development procedure of new products with less environmental impacts. They can also by combined with environmental or energy management systems to continuously monitor the processes.
Policy tools can be evaluated in terms of their effectiveness towards reaching the targets.
Researchers and LCA practitioners are supported in understanding problems like uncertainties and data gaps connected to the results produced with the established tools which serves them in developing methodologies. Furthermore, they gain transparently documented background data to be used in studies also apart from sustainability assessment schemes for construction. Finally, the results allow a well-reasoned choice of LCA methods for the different problems addressed in micro- meso- and macro-level decision support in the context of the woodworking industry.

ZUSAMMENFASSUNG

Einführung Für die Europäische Union besteht das Risiko, die Energie- und Umweltziele für das Jahr 2020 nicht vollständig zu erreichen. Eine Kurskorrektur setzt ein verstärktes Bestreben aller relevanten Industrieteilnehmer voraus. Die holzbearbeitende Industrie wird dabei als bedeutender Akteur zur Erreichung mehrerer dieser Ziele gesehen. Um den richtigen Kurs einzuschlagen, müssen die relevanten Akteure hierfür zunächst verstehen, welche wesentlichen Wechselbeziehungen ihres Sektors mit anderen (z.B. Forst und Bau) bestehen, welche realen Auswirkungen von Entscheidungen im Hinblick auf die Erreichung der Ziele ausgehen und wie die holzbearbeitende Industrie auf die im Kontext der Zielerreichung implementierten Politikinstrumente reagiert.

Ziel Das Ziel dieser Arbeit ist es, den Akteuren der holzbearbeitenden Industrie wissenschaftlich basierte Methoden und Daten zur Verfügung zu stellen. Diese sollen es ihnen ermöglichen, potentielle Umweltauswirkungen in die Entscheidungsfindung auf ihren jeweiligen Handlungsfeldern einzubeziehen.

Methode Die Akteure benötigen Kenntnisse über die frühere Entwicklung der Umwelt- und Energieaspekte des Sektors. Zudem muss ein umfassendes Verständnis für die heutige Situation vorliegen und Werkzeuge zur Verfügung stehen, um die potentiellen zukünftigen Umwelteffekte heutiger Entscheidung abschätzen zu können.
Aufbauend auf der etablierten Methode der Ökobilanzierung nutzt die vorliegende Arbeit hierzu verschiedene Ansätze. Zum einen dient ein auf Umfragen basierter "bottom up"-Ansatz - vom Produkt zum Sektor - dazu, den derzeitigen Zustand der Umweltwirkungen der holzbearbeitenden Industrie zu bilanzieren. Mittels einer Erweiterung der Informationen zum jetzigen Zustand um historische Daten auf Sektorebene hin zu einer hybriden Datenbasis, können im Rahmen eines Monitorings Einblicke in die bisherige Entwicklung des Sektors erfolgen. Ein "top-down"-Ansatz - vom Sektor zum Produkt - ermöglicht Einsicht in die früheren produktspezifischen Umweltwirkungen und ihre Entwicklung über die Zeit.
Zur Unterstützung von Entscheidungsprozessen wird die etablierte Ökobilanzmethodik, so wie sie derzeit für Bauprodukte Anwendung findet, hinsichtlich ihrer Eignung zur Einbeziehung aller relevanten Aspekte auf Mikro-, Meso- und Makroebene untersucht. Eine Fallstudie identifiziert in diesem Zusammenhang die außer Acht

gelassenen Bereiche.

Ergebnisse Repräsentative Informationen zu den Umweltaspekten der Produktion der Hauptprodukte der holzbearbeitenden Industrie wurden erhoben und im Sinne des "bottom-up"-Ansatzes erweitert. Damit sind umfassende Grundlagendaten zur Verwendung in Ökobilanzen auf Produktebene verfügbar.
Der Monitoring-Ansatz liefert zuverlässige Daten zur Entwicklung von Treibhausgasemissionen des Sektors und zur Veränderung der Treibhausgasintensität spezifischer Produkte über die Zeit. Damit können in Zukunft Entwicklungen des Sektor nachvollzogen und erklärt werden. Zudem bietet der Ansatz die Möglichkeit, zeitliche Veränderungen der produktspezifischen Umweltwirkungen in Ökobilanzen zu berücksichtigen.
Im Kontext der Unterstützung von Entscheidungen konnten mit Hilfe von Systemraumerweiterungen die für Entscheidungen auf Mikro-, Meso- und Makroebene wichtigen Aspekte identifiziert werden.

Fazit Die Ergebnisse dieser Arbeit versetzen Unternehmen der holzbearbeitenden Industrie in die Lage, die Umweltwirkung ihrer Prozesse und Produkte in Übereinstimmung mit den verfügbaren Nachhaltigkeitsbewertungssystemen und Labeln auf Produkt- und Unternehmensebene zu deklarieren. Darüber hinaus machen sie deutlich, welchen Einfluss technische Entwicklungen auf die Ergebnisse von Ökobilanzen haben, die im Rahmen dieser Bewertungssysteme und Label angewandt werden. Die Ergebnisse können daher genutzt werden um Produkte mit geringeren Umweltwirkungen zu entwickeln bzw. fortlaufend die Produktion zu überwachen indem Ökobilanzen mit Umwelt- oder Energiemanagementsystemen kombiniert werden.
Politikinstrumenten können auf ihre Effektivität im Hinblick auf eine Erreichung der Ziele bewertet werden
Wissenschaftler und Ökobilanzexperten werden beim Umgang mit Datenlücken und Unsicherheiten bei den Ergebnissen unterstützt so dass sie die entsprechenden Methoden weiterentwickeln können. Darüber hinaus erhalten sie transparent dokumentierte Hintergrunddaten zur Nutzung in Ökobilanzen auch jenseits der Nachhaltigkeitsbewertung von Gebäuden.
Schließlich kann auf Basis der Ergebnisse eine begründete Wahl von Ökobilanzmethoden erfolgen, die eine sinnvolle Unterstützung von Entscheidungen auf Mikro-, Meso- und Makroebene mit Relevanz für die holzbearbeitende Industrie erlaubt.

ESSENTIAL PUBLICATIONS

ORIGINAL SCIENTIFIC PAPERS

2010 Status quo for life-cycle inventory and environmental impact assessment of the core sawmill products in Germany. Diederichs, S. (2014). Wood And Fiber Science, 46(1), pp.65-84. *Original Scientific Paper I*

2010 Status quo for life cycle inventory and environmental impact assessment of wood-based panel products in Germany. Diederichs, S. (2014). Wood And Fiber Science, 46(3), pp.1-16. *Original Scientific Paper II*

Life cycle assessment of wooden interior doors in Germany - A sector representative approach for a complex wooden product according to EN 15804 methodology. Wenker, J., Achenbach, H. & Diederichs, S. (2015). Journal of Industrial Ecology. DOI: 10.1111/jiec.12296 *Original Scientific Paper III*

Monitoring Energy efficiency and environmental impact of the Woodworking industry in Germany. Diederichs, S. (2015). European Journal of Wood and Wood Products. DOI: 10.1007/s00107-015-0934-9. *Original Scientific Paper IV*

Potential environmental benefits of ultralight particleboards with bio-based foam cores. Ganne-Chédeville, C. & Diederichs, S. (2015). International Journal of Polymer Science. DOI: 10.1155/2015/383279 *Original Scientific Paper V*

The papers OSP I and II as well as IV and V are reprinted in Part II of this dissertation.

conference proceedings

Conference Proceeding I

Deviation of LCI results from primary industry data and application of derived LCA in the framework of sustainable construction certification schemes using the example of glue laminated timber. Diederichs, S., & Rüter, S. (2011). In F. Caldeira, J. V. Ferreira, M. Petric, & R. M. Rowell (Eds.), Minimizing the environmental impact of the forest product industries (pp. 17-24). Porto. ECOWOOD 2010. Conference Proceedings

Conference Proceeding II

Ökobilanzierung zur Ermittlung von Umweltkennwerten von Holzprodukten und Ableitung der Rahmenbedingungen für eine Bewertung von TMT. Diederichs, S. Rüter, S. (2012). In 7. Europäischer TMT-Workshop (pp. 91-100). Dresden: IHD. Conference Proceedings

reports

LCA Report

Ökobilanz-Basisdaten für Bauprodukte aus Holz. Rüter, S. & Diederichs, S., 2012. Arbeitsbericht aus dem Institut für Holztechnologie und Biologie des Johann Heinrich von Thünen Instituts. Hamburg: 316 p.

PUBLICATIONS WITH RELATED CONTENT

CONFERENCE PROCEEDINGS, REPORTS AND OTHERS

LCA of an in-development ultralight particleboard. Ganne-Chedeville, C. & Diederichs, S.K., 2014. In A. Kutnar et al., eds. Proceedings of COST FP1303-meeting in Kranjska Gora (23-24.10.2014), Performance and maintenance of bio-based building materials influencing the life cycle and LCA. Ljubljana: University of Ljubljana, pp. 61-62.

Energiemanagement und Ökosteuer Anforderungen und monetäre Bedeutung am Beispiel der deutschen Sägeindustrie. Mertens, O., Diederichs, S. & Meyer, M., 2014. Thünen Working Paper 18. Braunschweig. 36 p.

Ökobilanzen für Holz-Bauprodukte: Voraussetzung für die Nachhaltigkeitsbewertung von Gebäuden. Diederichs, S., & Rüter, S. 2012. Holzbau, (2), 17-19.

Verwendungspotentiale heben durch Kaskadennutzung am Beispiel Holz. Frühwald, A., Diederichs, S. & Morgan, R., 2010. In Erneuerbare Energie, Band 4. TK Verlag - Fachverlag für Kreislaufwirtschaft, pp. 37-50.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Figures and tables published in Part II are not listed here.

ACRONYMS

ALCA	Attributional Life Cycle Assessment
BNB	Bewertungssystem Nachhaltiges Bauen für Bundesgebäude
CHP	combined heat and power
CLCA	Consequential Life Cycle Assessment
DGNB	Deutsche Gesellschaft Nachhaltiges Bauen e.V.
EEG	Erneuerbare Energien Gesetz
EoL	end of life
EPD	Environmental Product Declarations
EPF	European Panel Federation
EPS	expandable polystyrene
ETS	Emissions Trading System
FAO	Food and Agricultural Organization of the United Nations
FB	fiberboard
FEC	final energy consumption
GHG	greenhouse gas
GLT	glue laminated timber
GWP	Global Warming Potential
HiRel	inventory flows with high relevance
IES	Joint Research Center, Institute for Environment and Sustainability
ILCD	International Reference Life Cycle Data System
IOLCA	Input Output Life Cycle Assessment
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LULUCF	Land Use, Land Use Change and Forestry
LoRel	inventory flows with low relevance
MC	moisture content
NACE	Nomenclature Generale des Activites Economiques dans l'Union Europeene
NIR	National Inventory Submission
NMVOC	non methane volatile organic compounds
OSB	Oriented Strand Board
OSP	Original Scientific Paper
PB	particleboard
PCR	Product Category Rules
PEF	Product Environmental Footprint
PEC	primary energy consumption
PLA	polylactic acid
PMMA	polymethyl methacrylate
PRODCOM	Production Communautaire
PW	plywood
SMI	sawmill industry
TMT	thermally modified timber
ULPB	ultra-lightweight particleboard
VOC	volatile organic compounds
WBCSD	World Business Council for Sustainable Development
WBPI	wood based panels industry
WRI	World Resource Institute

Acronyms used in Part II may not be listed here.

Part I

SUMMARY OF THE CUMULATIVE DISSERTATION

1 CONTEXT

1.1 Introduction

The aim of this dissertation is to supply the woodworking industry's various stakeholder groups with science-based methods and data that will enable them to include an understanding of the potential environmental impacts of their decision-making in their respective fields of action. These groups are companies and associations of the woodworking industry, policy makers, users of sustainability assessment schemes and researchers.

As the fields of action can vary for each stakeholder group, the dissertation addresses each of them individually and supplies methods and data to disseminate impacts, to understand and interpret them and to justify decisions by showing their potential impact and relevance.

In Chapter 1 of Part I, the dissertation initially outlines the essential policy background on international and national level and describes the related issues which are specific to the woodworking industry. Secondly, life cycle thinking is presented as the essential tool used in this dissertation and the field of required research is identified before the objectives of the dissertation are derived.

In the second chapter, the document includes short summaries of the publications with essential content for the dissertation. The methods are described in Chapter 3 before the conclusions and recommendations are given in the fourth chapter.

Part II of the dissertation includes reprints of the publications.

1.2 Stakeholders - policy, industry and society

1.2.1 *International framework*

The following description of the international framework explicitly comprises facts which are relevant for the woodworking industry. It is not exhaustive.

20-20-20 targets

The EU climate and energy package was enacted in 2009, setting binding energy and environmental targets to be reached in the year 2020. These so called 20-20-20 targets set objectives in terms of a 20 % energy efficiency improvement, a 20 % reduction of greenhouse gas (GHG) emissions and a share of 20 % renewable energy of the total energy consumption. The targets are expected to be achieved by

several different measures.
For the reduction of GHG emissions, a major tool is represented by the Emissions Trading System (ETS), which operates in the EU-28 Member States, Norway, Iceland and Liechtenstein. It "caps" the total emission allowances for many power plants, heavy industry and air transport while enabling "trade" of allowances between those emission sources.
However, about 60 % of the EU wide GHG emissions are outside the ETS. For those, national targets have been set for the EU Member States under the "Effort Sharing Decision" (Decision No. 406/2009/EC). Each Member State has limits for GHG emissions from non ETS sources in 2020, resulting in -10 % reduction for EU-28 compared to 2005. The combination of the ETS and the "Effort Sharing Decision" are intended to accomplish the 2020 reduction target, cutting emissions 20 % below 1990 levels.
The major increase of the share of renewable energy up to 20 % is supposed to be achieved by the "Renewable Energy Directive" (Directive 2009/28/EC). It sets a framework to promote the use of renewable energy and sets mandatory national targets for the share within the energy mix.
The tools to reach energy efficiency targets are not directly included within the EU climate and energy package. Instead, the European Commission adopted the "Energy Efficiency Plan 2011" (COM/2011/0109) to increase energy efficiency. The communication paper proposes to foster low energy consumption in the construction sector, develop a competitive European industry, intensify energy taxation and carbon tax, help consumers save energy, and to widen the scope of national primary energy reduction targets to cover all stages of the energy chain. The legislative result of the communication paper is the Energy Efficiency Directive (2012/27/EU) which obligates each Member State to set indicative energy efficiency targets for 2020.
For 2030, more ambitious targets were set. On 23 October 2014, EU leaders agreed upon a 40 % reduction target for GHG emission and an increase of renewable energies up to 27 % until 2030 (Press release IP/14/54).

Kyoto targets

Besides the 20-20-20 EU targets, GHG emission commitments have to be fulfilled due to the responsibility under the Kyoto Protocol's compliance mechanism. For EU-15, legally binding national targets for 2012 have been agreed on in the "burden sharing" agreement. In accordance with article 4 of the Kyoto Protocol, Member States and the European Community (EU-15) quantified emission reduction commitments expressed as percentages of emissions in their chosen

base years (in most countries 1990 for CO_2, CH_4 and N_2O, and 1995 for fluorinated gases). For the second period from 2013 - 2020, the EU intents to fulfill its commitments as EU-28 jointly (-20 % compared to 1990 emissions).
During the 1st period of the Kyoto Protocol Land Use, Land Use Change and Forestry (LULUCF) activities have been taken into account. With decision (2/CMP. 7) (UNFCCC, 2011) of the Kyoto Protocol, annex I parties to the convention now shall also account for anthropogenic greenhouse gas emissions resulting from forest management (UNFCCC, 2011, Article 3.4, paragraph 7) and the change in carbon pools of harvested wood products (UNFCCC, 2011, General, paragraph 26).

Progress towards the targets

The EU progress towards reaching the agreed targets varies between the targets. It is on track to reach the Europe 2020 target and the Kyoto target for the period 2013-2020 in terms of reduction of GHG emissions (European Commission, 2013b). Essential reductions (48 % on EU level) were achieved during the industrial recession in 2009 (ADEME, 2013).
Underpinned by a revision of the Emissions Trading Directive (Directive 2009/29/EC), in phase 3 of the ETS a single EU-wide cap for ETS emissions and a reduction of free allocation of emission allowances towards more auctioning has been agreed upon. This will ensure the reduction of EU wide ETS emissions to be 21 % below 2005 levels in 2020 (European Commission, 2013b).
In contrast, however, the growth of renewable energy in the EU reveals a less optimistic outlook for 2020 (European Commission, 2013c). To achieve the agreed goals here, Member States need to implement further measures. One reason for the forecast gap, although not being the most evident failure in terms of compliance with EU targets, is the negative trend for biomass energy utilization, which means that it is increasingly diverging from its target path (European Commission, 2013c). The cited progress report assumes that "this deviation could be linked to the production cycles of the wood, pulp and paper industries, whose wastes and residues constitute a significant part of biomass feedstock" (European Commission, 2013c, p.5).
The energy efficiency (energy consumption compared to macroeconomic variables) increased by 12 % from 2000 to 2010. After 2007, the efficiency progress slowed down drastically. The EU industry (25 % of the total final energy consumption) even reversed the trend towards a decrease in energy efficiency in 2009 and 2010. Moreover, 60 % of the efficiency gains made before 2008 can be explained by a shift towards less energy intensive industry branches only.
But the industry was not the only sector of concern. The even larger

building sector (41 % of total final energy consumption in Europe in 2010) increased its final energy consumption by 1 % per year (ADEME, 2013) since 1990.
In total, final energy consumption in the EU did not decrease as is should have but instead increased by 23 Mtoe from 2000 to 2010.

1.2.2 *German framework*

In terms of GHG emission reductions, the ETS is implemented in Germany and the country agreed upon emission reductions in the context of the "Effort Sharing Decision" as specified on EU level. Starting in 2015, the LULUCF activities in terms of aspects in relation to afforestation, deforestation and reforestation which were reported already on a voluntary basis in the previous National Inventory Submissions (NIRs) (after the voluntary option had been chosen, the reporting was obligatory from that year onwards) and carbon storage in wood products will be reported in the NIRs.
The fundamental national implementation to reach the renewable energy targets is the "German Renewable Energy Act" (Erneuerbare Energien Gesetz (EEG)), guaranteeing feed-in tariffs for electricity produced from renewable sources. With its revision in July 2014, feed-in tariffs for new installation were capped (or the build-up of new installations respectively) and the EGG surcharge has to be paid as well by producers of renewable energy which use their own energy. The larger power plants will be capped in production (remote controlled) if too much energy is available temporarily in the market.
An increase in energy efficiency in the industry was agreed upon between the German industry association and the government (BDI et al., 2012) and with the implementation of the Energy Efficiency Directive, tax reductions which had been granted to industry members without obligations before, are tied to the implementation of energy auditing schemes.
In the building sector, assessment schemes for sustainability in construction have been introduced broadly on EU level and within several Member States, including Germany. The German DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen e.V.) started its voluntary scheme in 2007 and the BNB (Bewertungssystem Nachhaltiges Bauen für Bundesgebäude) started its scheme, mandatory for public buildings, in 2011. Besides social and economic aspects, both schemes include the assessment of environmental and energy related issues connected to the life cycle of the construction materials. The share of renewable energy, the consumption of primary energy as well as the emission of GHG are substantial pieces of information disseminated by those schemes.

1.2.3 *The woodworking industry*

The woodworking industry - a stakeholder in various contexts

The German woodworking industry is a relevant stakeholder in the national implementation of climate, environment and energy related regulations.
Forests and wood products are deeply embedded within the LULUCF mechanism of the Kyoto protocol. As forests are the main primary resource of wood, and wood products are the primary output of the woodworking industry, changes, for example, to the production volumes, the total mass of wood within the products (for wood based panels this can vary) and the recycling intensity have a potential influence on the reported quantities in the NIRs.
From a fuel flow perspective, almost 56 % of all renewable energy (as final energy) consumed in the German industry in 2012 was consumed by the woodworking industry (Destatis, 2014b, NACE 2.2 Code 16). Furthermore, the woodworking industry ranks at position 9 among the largest energy consumers of all German industry sectors with a total share of 2.5 % of energy consumed in the industry (Destatis, 2014b).
Since the ETS assigns an emission factor of zero to biomass (EU ETS Directive, Annex IV) (sustainability emission factors in case of liquid biomass and biofuels exist, but not for solid biomass European Commission DG A.3 (2012)), the ETS it is relevant for the fossil parts of the fuels used in combustion plants exceeding 20 MW of thermal input (Parliament and Council of the EU, 2009) only.
Consequently, the woodworking industry has not shown much interest in actively taking part in the trading system (Stassen et al., 2012).
In total, the woodworking industry was responsible for the emissions of approximately 5 million tonnes of CO_2-eq. (non - biomass) (see Section 3.2), which equals about 0.6 % of the total German CO_2-eq. emissions in 2012 UBA (2014). In addition, 7 - 8 million tonnes of CO_2-eq. emissions are emitted on site from the combustion of biomass (see Section 3.2).
The extensive use of wood fuel in the woodworking industry is also well embedded within the national electricity mix. Since drying procedures (especially in sawmills) operate with low temperatures, combined heat and power (CHP) plants have been proven to be feasible additions on production sites: with a production of about 2 TWh of electricity in 2012 (Destatis, 2012a), they produced approximately 6 % of the gross electricity production from biomass in Germany (BDEW, 2013). Therefore, the prosperity of the sawmill industry (SMI) and the wood based panels industry (WBPI) depends not only on the availability and price of the resource wood, but also the feasibility of benefiting from selling "green" energy in terms of remote heat or electricity from CHP plants. Any policy action with influence on this has a po-

tential impact on the economic circumstances of the woodworking industry.
With regard to the policy tools installed to reach the 2020 targets and those to come to reach the 2030 targets, the woodworking industry is a relevant stakeholder. Thus, any policy framework in context with energy efficiency increases, a reduction of energy consumption, the share of renewable energy and the reduction of GHG emissions has a potential relevant impact.

The woodworking industry - Understanding its role from a life cycle perspective

As a stakeholder in the presented policy framework, the woodworking industry needs to understand its role within that framework and its development towards the targets. To understand the impact of decisions made at company level, all gains or losses which result from those decisions need to be visible and clearly distinguished from gains and losses triggered by other stakeholders. The companies of the woodworking industry need to understand the relationship between choices they can make in terms of process and product design and the resulting impact of those choices. Changing supply chains, the mix and composition of materials, the weight and size of products, the reduction of energy consumption, changing fuel types and others need to be understood in context of the implemented assessment schemes their products are ranked with.
For the latter, the development of the environmental impacts triggered by the woodworking industry thus have to be embeddable into the context of the complete forest wood chain. If the environmental impact of the woodworking industry is to be included within long term evaluations of current political decision making, being aware of the environmental aspects of the complete forest wood chain, the life cycle of its products and services, monitoring their development and understanding their reaction to policy changes is indispensable. Product consumers need to understand the potential impact of their choices. Industry associations which like to discuss policy implications in terms of their effectiveness to reach political targets need to be able to holistically explain the development of their branch and possible interrelations with policy tools.
To put it in a nutshell, firstly the assessment of the development of environmental impacts of the woodworking industry has to be delimited to reflect decisions made at the company level in particular, while the interfaces to the rest of the forest wood chain have to be defined unambiguously. In terms of defining interfaces, emissions from harvesting and changes in the forest and wood product carbon pools can be assigned to the development of the woodworking industry by evaluating the reported produced volumes which are available in national statistics. For wood based panels, some accuracy

problems occur due to the unknown densities and the actual carbon content in the products. For solid wood products, the density of the species and the carbon content respectively might vary as well. A consistent approach needs to define densities and wood contents for each product.

The other aspect, the surveillance of current developments, is performed on different aggregation levels (forests and wood products in terms of carbon pools (LULUCF), emissions from harvesting and emissions from the woodworking industry within the industry sector monitoring, transports within the transportation sector monitoring). However, the development of the environmental impact of the actual production process of the wood products is aggregated within the indicators frequently published by the government (BMWi 2014) which report achievements in context with the political targets for energy and GHG emissions. Here, either the energy intensive industrial sectors are the singular focus (excluding the woodworking industry), or the woodworking industry is aggregated within "others" (Lechtenböhme et al., 2014; Fleiter et al., 2013; Wünsch et al., 2012) and is not part of the industry monitoring in context with the agreement between the German industry association and the government mentioned above (Frondel et al., 2013).
Of course, the achieved gains or losses as a result of policy tools will become visible at national or international level anyway, since the relevant monitoring systems report at this level. But although the potential rebounds are taken into account (as totals), the interrelations might stay hidden, preventing the understanding of cause and effect and a deliberate implementation of policy tools which are aware of these potential rebound effects.
Furthermore, the energy consumption and direct CO_2 emissions are only two aspects of the various environmental impacts potentially triggered by the woodworking industry. The generation of energy (CHP plants) on site, emissions which occur in the supply chain (other than wood) and other important emissions like NMVOC, SO_2 and NO_x are not holistically available for the woodworking industry in general.

1.3 TOOLS - ENVIRONMENTAL LIFE CYCLE THINKING

1.3.1 *General framework*

Life cycle thinking means to holistically understand the full life cycle of decisions. This includes decisions on policy, business, or any other level. The most prominent tool used for this approach is the Life Cycle Assessment (LCA).

LCA is a standardized method to quantify effects of the complete life cycle of a product or service on resource depletion, environmental impacts and health issues. The approach is a structured method to comprehensively analyze all relevant aspects from the extraction of resources along the product or service life of the product to the disposal of the remaining waste, usually referred to as *from cradle to grave*.
The underlying standards are ISO 14040 and ISO 14044 which provide a robust framework for the application of LCA but also leave high flexibility to adjust certain issues for the specific cases. While those adjustments are needed to gain relevant results for all possible cases, this high level of freedom can also lead to biased results if chosen blindfold.
Some typical applications for LCA, studies are product improvement by identification of key issues, weak point analysis or eco design. Products can be compared in order to benchmark them against the average or competitive products. Another large field of application is communication of environmental issues and therefore encouraging life cycle thinking by means of life cycle based eco labels or carbon footprints. LCA can also supply information for environmental management systems. At policy level, the tool is used to supply strategic decision support and after the decision has been made, it can be used to monitor changes in environmental issues of sectors, nations, supply chains and others (European Commission, 2010b).
The structure of every LCA is given by ISO 14044 and consists of five steps:

THE GOAL DEFINITION is an essential part, as it ensures an unambiguous statement on the intended application and audience of the results. Understanding the goal of the study and the reason for carrying it out is essential for choosing a well-balanced LCA approach.

THE SCOPE DEFINITION is a clear description of the specific decisions made where ISO 14044 is flexible. This includes the description of limitations of the LCA and the implications for the targeted audience. This step is crucial in terms of the applicability of results to answer the questions addressed in the goal definition.

THE INVENTORY ANALYSIS is a detailed description of elementary flows which result from the system under study as defined in the scope definition. The result is referred to as the Life Cycle Inventory (LCI)

THE IMPACT ASSESSMENT aggregates the identified elementary flows of the LCI in support by assumption (European Commission, 2010b). Several methods are available.

THE INTERPRETATION of the results is essential for translating results from the impact assessment to results directly answering questions addressed in the goal definition. Again, the description of limitations is essential in this context.

1.3.2 *The scope of the study*

The essential approaches

ISO 14044 offers several possible ways of adopting the LCA methodology to the specific case under study. While this is indispensable for an ISO standard which offers a methodology for possibly all LCA studies, the standard also requests the practitioner of the study to supply a comprehensive and transparent documentation of the specific choices that were made. Furthermore, choices with a major impact on the results should be the subject of sensitivity analysis.

One of the most controversially discussed aspects in this context is the attribution of environmental burdens in case of multi-functional systems. Those systems typically supply more than one service or product. Burdens connected to the product under study have to be separated from those connected to the other products.

In this context it is important to understand which question was addressed in the goal definition. Questions on "what was" and "what is" have to be treated differently than questions on "what if". While the two former questions address information about the current status of a life cycle, "what if" addresses possible consequences which result from a change of the current status. Ekvall and Weidema (2004) argue that considering the consequences of an action is necessary to make a rational decision, but the actual way of how to build a model for this to get robust results for decision making has been discussed intensively. The two modeling principles are commonly called "attributional modeling" and "consequential modeling", also referred to as Attributional Life Cycle Assessment (ALCA) and Consequential Life Cycle Assessment (CLCA).

The two ways of LCA modeling can be differentiated by how the modeled life cycle of a product deals with multi-functional systems and the change in demand or supply as a consequence of a decision. The comparison of two products or - more precisely - the comparison of consuming one product instead of another are dealt with differently.

The attributional approach aims to isolate the environmental impact of the primary service (the functional unit) provided by the product system from those of any secondary services of the system. For the comparison, two isolated systems are compared with each other and the system with less impact can be argued to be the better choice.

The consequential approach instead tries to avoid any allocation procedure but strives to include all secondary services of a product system by system expansion. Further on, changes in demand are dealt with by analyzing the most possible reaction of a supply market to the change in demand (called "marginal supply") rather than assuming the reaction reflects the typical proportion of the market share of each supplier. Typically, both choices are modeled in one system.

The advantages of an idealized ALCA are straight forward modeled systems and the availability of basically well-established databases supplying generic data. The disadvantages are certainly that market reactions are not considered and relevant impacts that might be triggered in by-product systems are not detected.

CLCA models, on the other hand, tend to be rather more abstract models as the relevant impact might take place in the secondary systems. Furthermore, the background data used for the models (e.g. electricity supply) are different from those used in ALCA since they reflect the marginal production and not the average status quo (Weidema et al., 1999). The differences occur since some technologies are subject to constraints (Ekvall and Weidema, 2004) and cannot be up-scaled linearly to the average. Lund et al. (2010), for example, showed that the difference between the environmental impacts of the average Danish electricity mix can vary drastically from the marginal energy production.

Choosing the right approach

While it is not clear which approach should be used, it is generally understood that both approaches yield valuable insights (Plevin et al., 2014a; Suh and Yang, 2014; Brandão et al., 2014) and that some aspects are visible in one method yet obscured in the other (Earles and Halog, 2011). The value of mixing the approaches is also unclear.Suh and Yang (2014) argue that there is no real life LCA that matches the ideals of a true ALCA or CLCA therefore, there is never a case in which the approaches do not mix. Plevin et al. (2014b), on the other hand, argue that ALCA answers fundamentally different question. In ALCA the question is "which portion of total pollution can be attributed to product system X" and in CLCA it is "what is the net effect of an action". A mixed approach therefore gives answers to neither of them.

In conclusion, there is a strong argument for using ALCA for monitoring purposes and CLCA for policy decision support. Anything in between such as identification of key issues, weak point analysis, eco design, life cycle based eco labels, carbon footprints and many other applications should include a discussion not only of the generated results, but also on the applicability of the methodological choices made, knowing that instead of preferring one approach to another, one should recognize the strength and weaknesses of both approaches to best support a decision (Suh and Yang, 2014).

Practical implications

Beside the question of which general approach is to be used for a certain case, the practical implications of building the LCA model according to the type of approach need to be further determined. It is especially important to choose and document the type of allocation procedures (Weidema and Schmidt, 2010; Werner et al., 2007b; Jungmeier et al., 2002), cut-off rules and applied background data (Ekvall and Weidema, 2004) and to interpret their implications. A comprehensive harmonization effort in this context has been conducted by the Joint Research Center, Institute for Environment and Sustainability (IES) on EU level (European Commission, 2010b), which lead to the International Reference Life Cycle Data System (ILCD), a series of LCA handbooks, established by the European Commission, giving technical guidance to many LCA situations.
Many situations can be dealt with within the scope of an LCA. The European Commission (2010b) differentiates between micro-level decision support, meso- and macro-level decision support and accounting.

Micro-level decision support - example of wood products in building applications

The micro-level decision support is used to analyze the environmental impacts of decisions which are assumed to have no or only negligible consequences outside the decision context. Especially consequences that influence the characteristic structure of, for example, a production process are not expected. Typical applications are product comparison and communication. For wood products, labels and footprints are typical applications.
At least 66 % of the produced sawnwood and 34 % of the wood based panels produced in the woodworking industry are used in the construction sector (in 2007, Mantau and Bilitewski, 2010). Hence, on the product level, producers have to deal with environmental assessment schemes that rate the environmental quality of their products.
Schemes like DGNB and BNB typically include the evaluation of the environmental, economic and social performance of buildings and cumulate the results to a single sustainability indicator. With mandate M/350 EN in 2004, the CEN Technical Committee 350 (CEN/TC 350) was set up to develop "horizontal standardized methods for the assessment of the integrated environmental performance of buildings". Thereafter, for the assessment of environmental aspects on building level (CEN, 2011, EN 15978:2011), environmental information for the

construction products are required based on Type III Environmental Product Declarations (EPD) (ISO, 2007, ISO 14045:2006). Developing EPD is typically based on additional specific rules, requirements and guidelines called Product Category Rules (PCR). For the construction sector, EN 15804:2012-04 supplies general rules for building products (core PCR) and every program holder develops additional PCR on top of this for specific construction products (like doors, flooring, wood based panels in case of wood products). All EPD based on ISO 14025 include environmental information based on product life cycle assessment in accordance with ISO 14044:2006 (ISO 14044:2006, 2006).
Besides the named DGNB and BNB systems other sustainability assessment schemes for construction works are in place. Starting in 1990, "BREEAM" (Building Research Establishment Environmental Assessment Method) has been developed in the UK and LEED (Leadership in Energy and Environmental Design) has been developed in North-America since 1993. Although several other schemes are available, DGNB, BREEAM and LEED have the highest penetration in Europe (McGraw-Hill Construction, 2013). All three build upon environmental information of building products in accordance with ISO 14025.
The actual decision support is typically available on building level only. DGNB and BNB for example express the total environmental impacts of a building in relation to the results of a fictive building. The distance is than expressed in ratings which can be compared between buildings. But on these grounds, it can also be argued that if sustainability labels are targeted within the design phase of a building, the choice for building products will be governed by their environmental impacts from cradle to grave on product level.
It should be stated at this point, that the environmental aspects are only one aspect within the sustainability assessment schemes described above. Further considering the fact that the use phase of a building typically has a larger environmental impact than the production phase, the difference in environmental impacts assigned to different building products is not always a decisive factor for the total result of the sustainability assessment.

Micro-level decision support - example of wood products in non-building applications

Besides the EN 15804:2012-04 methodology which is applied within the construction sector, other environmental assessment methods or guidelines for products in general are available which all build upon LCA in accordance with the ISO 14040 series. The French environmental footprint guidance BPX 30-323 provides general guidance for product specific assessment with a focus on climate change. Others exclusively take climate change into account. The ISO product carbon footprint ISO/TS 14067:2013, the UK's products carbon footprint

(BSI, 2011, PAS 2050:2011) and the GHG Protocol developed by the World Resource Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) provide information on the life cycle greenhouse gas emissions of goods and services.
Finally with the Product Environmental Footprint (PEF) (Annex II of European Commission, 2013a), the European Commission's Joint Research Centre together with DG Environment developed an environmental footprint which builds upon the named approaches, especially the ILCD with the intention of a harmonization.
The decision support based on labels outside the building context is typically available by comparing the results for two (comparable) functional units, either directly or within more comprehensive comparative studies. Some of them adapt and document specific aspects of ISO 14044 apart from the established footprints and labels to best fit their needs. For example, González-García et al. (2011) analyzed different options for furniture manufacturing and Benetto et al. (2009) analyzed the environmental benefit of different drying technologies for Oriented Strand Board (OSB).

Accounting - product and company level

LCA is used for accounting to purely describe a system under study without analyzing any type of consequences. Examples are sector monitoring, corporate or site specific environmental reporting. This can be done based on ILCD and the GHG Protocol offers a company level approach as well. ISO 14064:2006 supplies principles to quantify GHG emissions on company level and other approaches are available (e.g. the "Guidance on how to measure and report your greenhouse gas emissions" Defra, 2009). Some methodologies include life cycle assessment by definition (e.g. ILCD), others offer guidelines for the inclusion of Scope 2 and Scope 3 emissions (i.e. adopting the WRI/W-BCSD methodology Scope 1 are direct emissions, Scope 2 emissions are indirect emissions from energy supply and Scope 3 emissions are all other emissions happening along the supply or waste chains). Mentionable in this context is that the international standard for environmental management systems is currently being revised. With regard to Lewandowska and Matuszak-Flejszman (2014), the revised version ISO 14044:2015 is likely to move towards LCA as well.

Accounting - sector level

For sector level *accounting*, standardized reporting procedures are not available, but with regard to the holistic monitoring procedures on national level in terms of GHG emissions reduction, reduction of energy consumption and the increase of the share of renewable

energy in the energy mix, some requirements can be derived.
For reports which disseminate results on national level, the single results of sectors must be summarized to national level without double counting. The system boundaries (used in the reporting) of sectors therefore circumscribe the site specific rather than products specific aspects. Examples are the GHG reporting (UBA, 2014) and energy reporting (BMWi, 2014) on national level.
A different approach is conducted by the ODYSSEE-MURE Project (Department of Energy and Climate Change, 2012), especially focusing on the energy efficiency development in the EU. The indicators on sector level (e.g. industry, or even one level below e.g. pulp and paper industry) include all energy consumed by the industrial sector (excluding transports).

Meso- and macro-level decision support

Decision support on meso- and macro-level is described to support decision making where structural consequences are expected outside the decision context. Typical applications are strategic decision support for policy development, policy information and the assessment of environmental benefits of different value-, process- or product-chains applicable to the same type of resource material or products. For forestry residues and by-products of the woodworking industry the potential benefit of shifting from material to energetic utilization, or the other way around, was discussed (Helin et al., 2014; Cespi et al., 2013). The environmental impacts of forest management has been analyzed and decision support for different forest management options, especially in context with GHG emissions and carbon storage issues, have been discussed extensively (Lippke et al., 2005; Poudel et al., 2012; Werner et al., 2010; Nabuurs et al., 2007; Osterburg et al., 2009). On product level, carbon storage issues are also relevant (Ingerson, 2011; Lippke et al., 2010; Tsunetsugu and Tonosaki, 2010; Rüter, 2010) and some effort has been made to evaluate the benefit of substitution of products derived from steel and plastics with wood products (Gustavsson et al., 2006; Sathre and O'Connor, 2010). Finally, benefits of cascade chains and other end of life options have been discussed (Osterburg et al., 2013; Gärtner et al., 2013; Frühwald et al., 2010).

From the viewpoint of the woodworking industry this means, LCA data is needed for the average products of the woodworking industry to be disseminated in public databases (e.g., the Oekobau.dat supplied by the BBSR) to supply the relevant information for sustainability schemes.
Furthermore, the impact of producing wood products, using them and treating them at their end of life are essential aspects for

environmental evaluations on policy level. Transparency and well documented data is necessary to make it adaptable to the broad range of methodologies used and in addition, eco design processes and environmental optimization efforts should be analyzed in context of the schemes in which the products have to compete . Finally, on company level LCA data will help to communicate in connection with management systems, while data used on company level should be applicable on sector level as well. On sector level, the required data needs to be available for several points in time to show a trend and it needs to be detailed enough, to filter the causes of the trend.

1.3.3 *Life cycle inventory data*

Considering the chosen approach

The life cycle inventory represents the results of the data collection based on the methodological choices defined in the scope of the LCA and the requirements of the impact indicators which are intended to be disclosed to the audience of the LCA.

European Commission (2010b) provides a framework for the LCI modeling principles. Basically the background processes require aspects of marginal production if the consequences of a decision are expected to be large. The average market mix is used for decisions with no expected large structural changes or monitoring purposes. Multi-functionality is solved by following ISO 14044 recommendations, where subdivision is followed by system expansion and allocation is named as a last possible solution only.

For the collection of data in attributional modeling, European Commission (2010c) proposes starting from a central process which is usually the functional unit (the reference flow of the system) and then expanding the data collection from there. For a structured approach, the analyzed system is separated into a foreground system and a background system. Following the "specificity perspective" as defined by European Commission (2010b), the foreground system includes all processes which are specific to the system which are typically all processes from "gate to gate" of a production site. The background system then represents the homogeneous market behind the supply and waste chains of the foreground system delivering cradle to grave models (European Commission, 2010c). The "management perspective" as a second alternative to divide the systems, defines the foreground system to include all processes in direct influence of the driver of the central process and the background system which includes everything else.

For consequential modeling, European Commission (2010c) proposes identifying and modeling the processes needed to meet the additional demand and the required alternative processes to substitute the changed demand of co-functions in case of multi-functionality. Both reactions are referred to as "primary market consequences". Consequential models can also include "secondary market consequences" like an increased demand of a co-product where the price of the co-product is reduced and obviously the reduced consumption of the competing co-product. Moreover, consumer behavior changes and industrial behavior like increased efficiency due to higher prices can be included in the model.

Collecting data

After defining the central process according to the functional unit, LCI input and output flows are collected for every process which was identified to be relevant for the foreground system. Flows can be products, co-products, services, waste, emissions, natural resources and other elementary flows. Those modeled processes also referred to as unit processes are the essential elements for the model. Relevant processes identified in the background system are modeled with generic data. European Commission (2010b) proposes to use well-documented and pre-verified datasets with high quality if possible.
But collecting information on process level to construct the complete life cycle of a product is not the only way of gaining knowledge on the interrelations of a product supply and waste chain. For attributional models, and especially for gaining knowledge on the completeness of the model, Input Output Life Cycle Assessment (IOLCA) or mixtures of IOLCA and classical LCA also called "hybrid LCA" are applied. Seppäläa et al. (2005) for example presented an IOLCA-based method on how to measure and monitor the eco-efficiency of a region. The approach principally uses economic supply-use tables which supply information on the supply of goods and services from a sector (called activity) and the goods and services used by an activity. To isolate the goods and services that where needed in a sector to produce a certain product, all co-products which are produced by the sector as well are substituted by replacing them as negative input to the same activity (Weidema et al., 2009). The resulting tables are called "direct requirement" tables and offer unique insight into the product requirements of a sector to produce a specific product. Seppäläa et al. (2005) used economic input-output tables in combination with material flows according to Nomenclature Generale des Activites Economiques dans l'Union Europeene (NACE) sector categories.
One of the advantages of this approach is its ability to produce rapid screening-level inventories (Wright et al., 2008) but high variations occur due to the necessary assumptions on prices (Moberg et al., 2014) and monetary input output tables may violate the underlying mass balance and unless no detailed data on the difference in consumer

prices is available, information based on physical causality should be preferred before monetary input output tables are applied (Merciai and Heijungs, 2014). Furthermore, calculations are work intensive, do not produce annual data and the material flow based analysis always implicitly assumes that each ton of material has the same environmental impact (Seppäläa et al., 2005).
For example, in Germany the economic input-output tables are supplied every fourth year, published four years after the reference year (data available from 2010, 2006 and 2002, see for example Destatis (2014a)). As they are based on monetary units, the inherent assumption would be that every Euro in terms of a monetary flow from a specific activity has the same environmental impact.

Availability of LCI data in the wood sector

Wood products have been subject to many LCA studies in terms of status quo assessments (*what is*) and decision support (*what if*). Following the typical process chain of wood products, status quo LCI and LCA results for forestry operations producing roundwood and forest residues have been published by Dias (2013), Timmermann and Dibdiakova (2014), González-García et al. (2013) and Schweinle and Thoroe (2001). On product level, data for products from the SMI have been published for the US market (Bergman and Bowe, 2010b, 2008b, 2009, 2008a, 2010a; Puettmann and Wilson, 2005; Wagner et al., 2009), and for Switzerland (Werner et al., 2007a). Frühwald et al. (2000a) conducted the first comprehensive LCA for sawmill products in Germany. However, the specific energy consumption for the production of sawn wood, a key factor for many environmental impact categories (Diederichs, 2015), can be very different from sawmill to sawmill. This was shown for the German market in an earlier study by Ressel (1986) and was verified for modern sawmills (Diederichs, 2014a). Tables 1 and 2 summarize the energy consumption listed in published LCI data for modern sawmill groups from different regions and years. Although these numbers already show average data from more than one sawmill, the publications present very different specific energy consumption for the production of similar products. While the reasons for those differences can be manifold, it becomes clear, that generic and representative datasets for a country require a broad and up-to-date database.

Döring and Mantau (2012) counted a total of 2194 sawmills in Germany in the year 2010. Official, but less comprehensive numbers, are available from Destatis (2010a), identifying 404 sawmills in 2010, yet excluding companies with fewer than 20 employees. In addition, the market is served by a significant number of middle size companies: 37.4 % of the saw log input is handled by at least 803 medium-sized producers (2,500-200,000 m^3/ year saw log input) (Döring and Mantau, 2012). Hence, having a large relevant population (statisti-

Table 1: Published data on electricity consumption of sawmill processes [kWh/m^3 output]. A: Bergman and Bowe (2010a), B: Puettmann et al. (2010), C: Milota et al. (2005) West D: Milota et al. (2005) South, E: Werner et al. (2007a) F: Frühwald et al. (2000a)

PROCESS	A	B	C	D	E	F
Debarking (D)		1.80			4.5	
Milling (M)		19.00			28.20	
Total D + M	52.64	20.81	45.35	34.43	32.70	23.15
Kiln drying	24.54	16.71	26.69	28.66	25.00	20.28
Planing	19.53	34.09	16.75	13.92	31.00	27.72

Table 2: Published data on heat consumption of sawmill processes (coniferous) [MJ/m^3 output]. A: Bergman and Bowe (2010a), B: Puettmann et al. (2010), C: Milota et al. (2005) West D: Milota et al. (2005) South, E: Werner et al. (2007a) F: Frühwald et al. (2000a)

FUEL	A	B	C [1]	D [2]	E	F
Wood	1803	1066				471
Oil and Gas	263	966				432
Total	2066	2032	2739	3099	959	903

[1] Average use of fuel for kiln dried products, [2] Heating value of steam

cally) and probably high deviations between each element, the required sample size of a relevant survey is large. None of the available datasets for sawmill products fulfills these requirements.
LCA and LCI studies have also been conducted for all typical products produced by the wood based panels industry (WBPI). Rivela et al. (2006) conducted LCA for particleboard (PB) and fiberboard (FB) (Rivela et al., 2007) by analyzing one Spanish PB plant and two Spanish as well as one Chilean FB production facilities. Kline (2005) presented data from four production facilities for OSB. In the US, data for the production of PB, plywood (PW) and FB was calculated (Wilson, 2008; Wilson and Sakimoto, 2005; Wilson, 2010b,a) and LCA for Brazilian PB manufacturing mills that used eucalyptus as the wood resource was presented by Silva et al. (2013). In Germany, an analysis of five PB and three FB production lines as well as a production line for OSB was conducted (Hasch, 2002; Frühwald et al., 2000b). Data was gathered between 1997 and 1999.
Yet since then, the German market and production of wood based panels has changed drastically. PW production has decreased by 50 % and production of PB by 40 %. FB production increased by 125 % and during those years no considerable amount of OSB was produced (figures rely on statistics from the European Panel Federation (EPF) and Food and Agricultural Organization of the United Nations (FAO)). In addition, Diederichs (2014b) found substantial differences in the specific energy consumption for the production of very similar products, which shows that generic datasets need a broad base. Considering the importance of the German WBPI to the European and world market, the current status of publicly available, transparently documented, and up-to-date inventory data for these products is quite unsatisfactory. Analogously to sawmill products, today's available data does not fulfill the requirements for relevant generic LCI datasets.

1.3.4 *Impact assessment*

General

Within the context of an LCA, the inventory related to the life cycle of a functional unit (the LCI) is evaluated in terms of its potential impact on an area of protection like human health, the natural environment and natural resources.
Life Cycle Impact Assessment (LCIA) is a tool used to first classify the inventory flows in their ability to contribute to an environmental mechanism and then to quantitatively describe the contribution (its specific character) within that mechanism. The impact is finally expressed by means of an impact category. Its value is determined by adding all elementary flows which were *classified* to contribute to the impact multiplied by the specific *characterization* factor of each substance or flow.

Table 3: Impact categories evaluated in the status quo assessment and their abbreviations used in the text

IMPACT CATEGORY	ABBREVIATION
Global warming potential 100yr.	GWP
Acidification potential of soil and water	AP
Eutrophication potential	EP
Depletion potential of the stratospheric ozone layer	ODP
Formation potential of tropospheric ozone	POCP
Abiotic depletion potential (ADP-elements) for non fossil resources	ADPe
Abiotic depletion potential (ADP-fossil fuels) for fossil resources	ADPf

These two steps, classification and characterization, are the mandatory elements of an LCIA as it is defined in ISO 14044:2006. Two optional elements are described as well. By *normalization* the evaluated impact categories can be related to those caused by any chosen reference. Typical references are the population of a country or one single individual of a defined group of consumers. By *weighting* the impact categories, they can be emphasized according to any preference.
Within this dissertation only the mandatory steps defined in ISO 14044:2006 will be focused.

Today, there is a large variety of LCIA methodologies available (see for example European Commission (2010a)). The choice of impacts dealt within the context of this dissertation is distinguished by the intended application of the results. However, since one focus of this dissertation is the dissemination of results on the level of LCI rather than impact categories, the choice does not lead to an exclusion of information.
In the context of EN 15804:2012-04 7 mid-point impact categories are used to describe the environmental impact (Table 3). The term midpoint refers to an assessment model where the impact is expressed in the middle of the cause-effect chain between the release of the substance (or the consumption of a resource) and its impact on the area of protection.

THE GLOBAL WARMING POTENTIAL - GWP calculates the radiative forcing ability of greenhouse gases for different time spans and discloses the result in terms of CO_2 equivalent emissions (CO_2-eq.). The GWP100yr indicator as it is used in the context of this dissertation uses a 100 year perspective before the cumulative radiative forcing is cut off. The most prominent substances with the ability to absorb infrared radiation in the atmosphere are CO_2, CH_4 and N_2O.

Since the CO_2 uptake of plants is inventoried in the LCI as an input to the system (emission to air) and as an output if the biomass is burned or if it leaves the system as a product (e.g., recycling), the total mass of this so called biogenic CO_2 is balanced in the system. Figure 1 shows the typical carbon balance of sawnwood products (a) and wood based panels (b). In contrast to the cradle to grave totals, cradle to gate totals include the "negative" biogenic CO_2 inputs.

For transparency reasons, biogenic CO_2 is not taken into account in this dissertation when CO_2-eq. are disclosed. The disclosure would not give additional information but rather superimpose the fossil based carbon emissions. However, they can be easily calculated based on information on the mass of wood in the products (e.g. in the description of the functional units as disclosed in Original Scientific Paper (OSP) I and II.) or the fuel quantity.

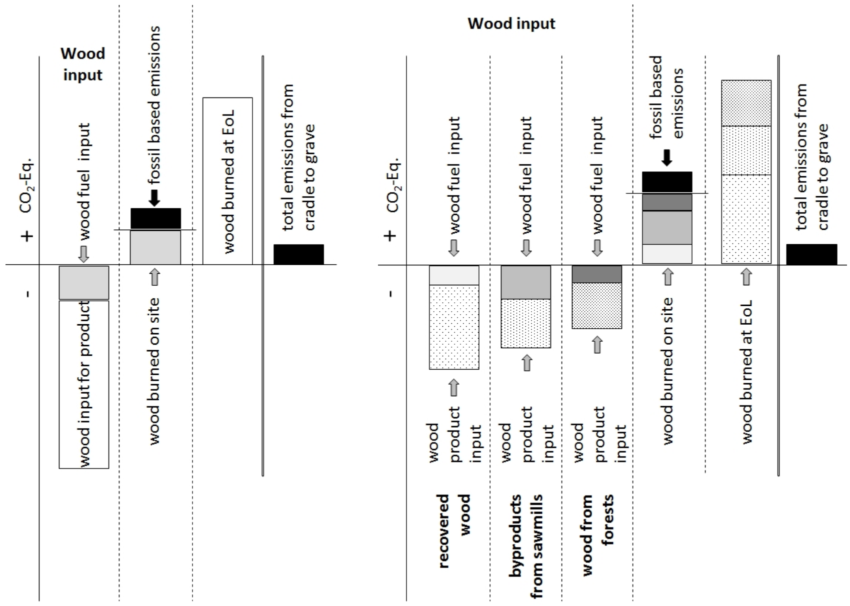
THE ACIDIFICATION POTENTIAL - AP indicates the ability of airborne emissions to affect the concentration of hydrogen ions in water and soils. Typical substances are NO_x, SO_2 and NH_3. The impact on mid-point level is expressed in NO_2-eq.

THE EUTROPHICATION POTENTIAL - EP addresses the reaction of an ecosystem to the addition of nutrients. Emissions of NO_x from combustion plants and NH_3 from agricultural processes are typical substance which lead terrestrial eutrophication, especially for marine and freshwater systems the availability of phosphorus as a nutrient is important as well. The impact on mid-point level is expressed in $PO_4{}^{-3}$-eq.

THE STRATOSPHERIC OZONE DEPLETION POTENTIAL - ODP indicates the ability of an airborne emission to deplete the ozone layer in the stratosphere. To do this, the substances need to be persistent to reach the stratosphere and disrupt the continuous procedure of the forming and destroying of ozone. Chlorine and bromine atoms in airborne emissions like dichlorodifluoromethane (R-12) and bromotrifluoromethane (Halon 1301), typically used as cooling fluids have this ability. The impact on mid-point level is expressed in R11-eq. (trichlorofluoromethane).

THE TROPOSPHERIC OZONE FORMATION POTENTIAL - POCP indicates the ability of a substance to trigger the photochemical generation of ozone in the troposphere. The essential reaction takes place under the present of volatile organic compounds (VOC), NO and radiation of ultraviolet light (daylight). The impact on mid-point level is expressed in C_2H_4-eq. (ethene).

THE ABIOTIC DEPLETION POTENTIAL - ADPE/ADPF addresses the depletion of abiotic resources (e.g. minerals, fossil fuels). The characterization takes the total availability of the resource into account in relation to the availability of the resource antimony. In the case of fossil fuels (ADPf) a general characterization factor for fossil fuels is multiplied by the heating value of the fuel. The impact on mid-point level is expressed in antimony-eq. for ADPe and heating value for ADPf.



(a) Sawnwood products

(b) Wood based panels

Figure 1: Typical (schematic) carbon balance of wood products from cradle to grave (for some wood based panels not all resources shown in the figures are used), EoL: End of Life

1.4 OBJECTIVE OF THE DISSERTATION

1.4.1 *Motivation*

From the presented stakeholder framework it can be derived that the achievement of mandatory EU targets in context with energy and environmental issues is endangered. The effort of the industry members in contributing to reach these targets needs to be increased. The woodworking industry is a relevant stakeholder for the achievement of several of those targets and needs to contribute in line with other sectors.

In this context it needs to be recognized that

1. The woodworking industry is confronted with new challenges by a variety of policy instruments (i.e. ETS, Effort Sharing Decision, Energy Efficiency Directive). Therefore, the interrelations between the targets, possible competing aspects, specifically appearing in the woodworking industry, and possible rebound effects to other parts of the forest wood chain or vice versa need to be fully understood.

2. The woodworking industry changes as the affecting policy frameworks change (i.e. profitability of CHP plants, obligatory implementation of energy management systems). Therefore the effectiveness of these policy frameworks in terms of reaching national targets needs to be analyzed based on an understanding of how the woodworking industry has developed in relation to the political targets.

3. LCA in accordance with ISO 14044 is a well-established tool used to comprehensively supply the relevant background information for accounting purposes and making decisions on micro-, meso- and macro-level. The tool is deeply embedded within several policy tools and supplying information to serve the application of life cycle assessment is a necessity for companies today and even more in the future.

4. LCA typically evaluates environmental aspects from cradle-to-grave of a product life cycle. Therefore, understanding the gate-to-gate impacts of the production step in context with the complete life cycle of the products requires well-defined system boundaries and interfaces to the other phases of the life cycle. This ensures the ability of the process-specific results to be applicable for studies with a wider view and allows a sector-wide assessment with transparent boundaries.

5. Available LCA and LCI data does not suffice the requirements stated above.

6. The assessment of representative LCI data for a wide range of products within the woodworking industry is a comprehensive and complex procedure. Monitoring approaches, therefore, need to be supported by simplified or streamlined LCI results based on sector-level data, combining it within a hybrid LCA.

Fully recognizing that possible contributions to reach the political targets can vary significantly depending on the stakeholder, the following tasks can be derived for the different stakeholder levels:

COM panies of the woodworking industry on the one hand need to declare the environmental impacts of their processes and products in accordance with the available product and corporate assessment schemes and labels. On the other hand, to contribute to reaching the political targets they need to understand how technical developments influence the outcome of LCA which is applied in these assessment schemes and labels.

POL icy tools focusing on environmental and energy aspects need to be evaluated in terms of their effectiveness. This evaluation requires an understanding of the woodworking industry's reaction to those policy tools based on a comprehensive monitoring approach of the wood sector.

ASS ociations within the woodworking industry need to understand the impact of policy tools and give advice to policy actors and their members based on scientific findings.

USE rs of sustainability assessment schemes require representative up-to-date LCI data on building products to run sustainability assessment schemes based on high quality information required to make better choices regarding materials and to push producers to improve their processes and products.

RES earchers and LCA practitioners need to understand problems like uncertainties and data gaps connected to the results produced with the established tools to proceed with the development of the methodologies. Furthermore, they need transparently documented background data to be used in studies apart from sustainability assessment schemes.

1.4.2 *Aim*

With regard to this motivation, the targets of this dissertation are:

A. calculation of representative, average LCI and LCA status quo data for all core products of the woodworking industry - *stakeholder level: COM, USE, RES*

B. introduction of a monitoring approach to follow the development of the woodworking industry based on a simplified, hybrid LCA - *stakeholder level: COM, POL*

C. identification of options of decision support for technology improvements by analyzing the ability of the presented tools to holistically address all potential environmental impacts - *stakeholder level: COM, ASS*

D. disclosure of future research and activity fields to improve and apply the presented tools - *stakeholder level: COM, POL, ASS, USE, RES*

2 SUMMARY OF PUBLICATIONS

2.1 HOLISTIC ABSTRACT

For the three essential aims (A - C) the methodology and underlying data will be described in Sections A (3.1), B (3.2) and C (3.3). Figure 2 displays the general approach.

In Section A (3.1) the status quo of the life cycle inventory of wood products is determined and analyzed in detail in terms of quality, representativity and applicability. OSP I and II supply this information for all core products of the sawmill and wood based panels industry. In addition, two case studies (OSP III and CP I) are conducted to test various aspects of the methodology before it was applied (CP I) and to test the applicability of the data for EPD based on EN 15804:2012-04 (OSP III).

In Section B (3.2) a monitoring approach is presented. It builds upon OSP IV, which combines the comprehensive product related inventory data with data available on sector level. This hybrid approach aims to provide information on the development of the sector required by associations and policy actors to evaluate the effectiveness of policy instruments.

Furthermore, a procedure to simplify the elaboration of LCI and LCA results for wood products is presented, helping companies in the woodworking industry to efficiently create the results needed for future monitoring tasks.

In Section C (3.3), two case studies (OSP V and CP II) are presented which allow inferences to the ability of the applied methodology to support decisions on micro-, meso- and macro level. For micro-level decision support in particular, OSP I, II and IV supply valuable infor-

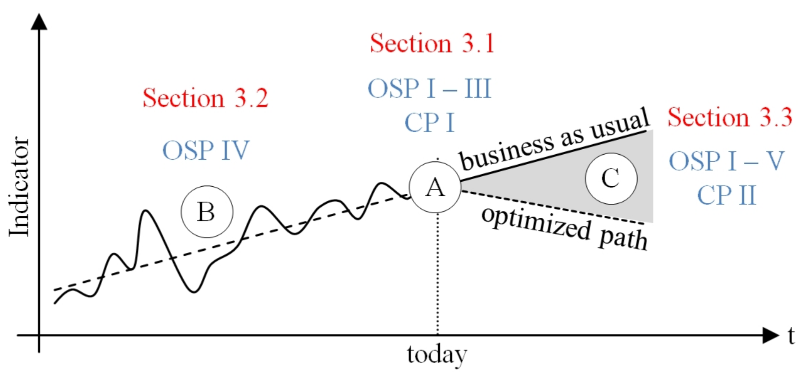


Figure 2: General approach of the dissertation and link to publications, OSP: Original Scientific Paper, CP: Conference Proceeding

mation as well.
In Section 4.4.1, recommendations for the stakeholders will be presented based on the results of this dissertation.

2.2 SINGLE ABSTRACTS

Original Scientific Paper I

Diederichs, S. (2014). 2010 Status quo for life cycle inventory and environmental impact assessment of the core sawmill products in Germany. Wood And Fiber Science, 46(1), pp.65-84

Based on a representative survey, the paper presents detailed life cycle assessment data for the core products of the German sawmill industry for the year 2010. It provides average inventory datasets for each product, assessment results based on the average and variations within the inventory datasets and their potential impact. For each product, the hot spots and the effect of uncertainties within each impact category are discussed. The presented data is compared to results published in other studies.

Original Scientific Paper II

Diederichs, S. (2014). 2010 Status quo for life cycle inventory and environmental impact assessment of wood-based panel products in Germany. Wood And Fiber Science, 46(3), pp.1-16

The paper presents detailed life cycle assessment data for the core products of the German wood based panels industry for the year 2010. Besides average inventory datasets for each product, the LCA results following the systematics of system boundaries used in EN 15804 are described. For each product or product group, the hot spots and the effect of uncertainties within each impact category are discussed. The presented data is compared to results published in other studies.

Original Scientific Paper III

Wenker, J., Achenbach, H. & Diederichs, S. (2014). Life cycle assessment of wooden interior doors in Germany - A sector representative approach for a complex wooden product according to EN 15804 methodology. Journal of Industrial Ecology. DOI: 10.1111/jiec.12296

The basic concept of the article was developed by Jan Wenker, Hermann Achenbach and Stefan Diederichs, the data was gathered by Jan Wenker and Hermann Achenbach, the manuscript was written by Jan Wenker, Hermann Achenbach and Stefan Diederichs.

The paper discusses the methodological challenges experienced during the calculation of a sector representative environmental product declaration from cradle to gate and the end of life (EoL) of wooden interior doors. The approach follows the requirements of EN 15804 and is in line with today's background information for sustainability assessment schemes for buildings such as the German Deutsche Gesellschaft Nachhaltiges Bauen e.V. (DGNB) or Bewertungssystem Nachhaltiges Bauen für Bundesgebäude (BNB) and others. The assessment builds upon LCI and LCA data presented in OSP I and II and demonstrates the applicability of the data for background information of environmental product declarations.

Original Scientific Paper IV

Diederichs, S. (2014). Monitoring Energy efficiency and environmental impact of the Woodworking industry in Germany. European Journal of Wood and Wood Products. DOI: 10.1007/s00107-015-0934-9.

Within this paper, the LCI information presented in OSP I and II is combined with national statistical data for the sawmill and wood based panels industry within a hybrid LCI model, setting the basis for a holistic monitoring of the SMI and WBPI sectors.
The approach initially scales the available values up to sector level based on the reported production volumes for 2010. Secondly, the data is simplified based on a sensitivity analysis and for those aspects which have been identified to be relevant, sector level data is inserted instead of the product level LCI data, combining it to a hybrid sector LCI. Since the sector level data is available on a yearly basis, the development of environmental effects of the complete sector can be monitored based on this approach.

Original Scientific Paper V

Ganne-Chédeville, C. & Diederichs, S. (2015). Potential environmental benefits of ultralight particleboards with bio-based foam cores. International Journal of Polymer Science, Volume 2015, DOI: 10.1155/2015/383279

The concept, conclusions, and recommendations were written by Christelle Ganne-Chédeville and Stefan Diederichs. The model, calculations and results in context with the EPD approach were conducted and elaborated by Christelle Ganne-Chédeville, the model, calculations and results in context with the holistic approach were conducted and elaborated by Stefan Diederichs

The paper reports on the comparison of LCA results of three types of ultra-lightweight particleboard (ULPB) containing foam, based on 100 % polylactic acid (PLA), 100 % expandable polystyrene (EPS) and 50 % PLA/50 % polymethyl methacrylate (PMMA), as well as a conventional particleboard (PB).
The assessment follows two different approaches, an *EPD approach* in accordance with EN 15804:2012-04 and a *holistic approach* with expanded system boundaries, allowing forecasting of the consequences of a broader replacement of PB with ULPB.
Both approaches show that the exchange of PB with ULPB with a foam core based on PLA is beneficial in terms of a reduction of greenhouse gas emissions and both approaches supply information for complementary advisories for environmental impact reduction addressed to the developers.

Conference Proceeding I

Diederichs, S., & Rüter, S. (2011). Deviation of LCI results from primary industry data and application of derived LCA in the framework of sustainable construction certification schemes using the example of glue laminated timber. In F. Caldeira, J. V. Ferreira, M. Petric, & R. M. Rowell (Eds.), Minimizing the environmental impact of the forest product industries (pp. 17-24). Porto. ECOWOOD 2010. Conference Proceedings

In this paper, the early stage results of the survey conducted for the status quo assessment (OSP I and II) were used to decompose each step of the production of gluelam. The challenge in this study was to combine data from sawmills which produced several different products (green, kiln-dried and planed) with those from producers of gluelam (LCI data from this survey was later published by Rüter and Diederichs (2012) which bought different types of raw materials (roundwood, green, kiln dried and planed sawnwood). Each product had to be regarded separately.
The total demand of supplied timber for each product was calculated on the basis of demand and supply matrices. This approach allowed the calculation of the specific wood residues that appeared as consequence of the processing of one specific product, and gave information about the ratio at which each product uses the processes and machinery. Electricity data which was only available on site level (in most cases estimates were made by the sawmill personnel) was broken down to process level by measuring the time of total occupation of the machinery and engine types and then broken down to product level by using the matrices calculation.
Finally, different allocation procedures were tested in terms of their significance on the level of gluelam production and the mass related allocation of CO_2 from biomass when using the data as back-

ground information for studies on wood products made from the semi-finished wood products assessed in OSP I and II.

Conference Proceeding II

Diederichs, S. (2012). Ökobilanzierung zur Ermittlung von Umweltkennwerten von Holzprodukten. In 7. Europäischer TMT-Workshop (pp. 91-100). Dresden: IHD

In this paper, the environmental impacts of thermally modified timber (TMT) were compared to the production of standard kiln dried timber. The calculation was based on the datasets for kiln dried timber from the survey of the sawmill industry (OSP I) and literature data for the TMT process. The most influential parameters of the TMT process with regard to the complete life cycle of such a product were identified. The results allow producers of TMT to understand how their product will compete against standard kiln dried timber in the context of the EN 15804:2012-04 methodology.

LCA Report

Rüter, S. & Diederichs, S. (2012). Ökobilanz-Basisdaten für Bauprodukte aus Holz. Arbeitsbericht aus dem Institut für Holztechnologie und Biologie des Johann Heinrich von Thünen Instituts. Hamburg. pp.316

The basic concept was developed by Stefan Diederichs and Sebastian Rüter. The survey, data collection, modeling and calculations were developed and done by Stefan Diederichs. The report was written by Stefan Diederichs and Sebastian Rüter.

This publication comprehensively reports the detailed modeling, survey and calculation principles which were followed to establish a life cycle inventory database for wood products.

3 INTEGRATION OF PUBLICATIONS

3.1 A - STATUS QUO

3.1.1 *Link to publications*

The detailed method to analyze the product specific status quo is described in OSP I and II. OSP IV describes the method to calculate the sector specific status quo for the sawmill industry (SMI) and wood based panels industry (WBPI).
Two case studies in context with the application of the product specific status quo assessment have been conducted (OSP III and CP I).

3.1.2 *Product specific status quo*

General

The calculation procedure followed the five steps defined in ISO 14044:2006 (Section 1.3.1).
Within the goal definition, the transparent documentation of the data relevance and applicability (system boundaries, representativeness, methodology issues and limitations) was explicitly established and achieved in the study to allow a wide applicability of the results also apart from the building context applications (EN 15804:2012-04).

Scope

Within the scope definition an independent functional unit was chosen for each product (Table 4). Each unit refers to 1 m^3 of the specific product, finished and wrapped, lying at the gate of the production site, ready to be sold and shipped. For sawn wood products, each functional unit is an equivalent of 1 m^3 at a moisture content (MC) of 12 %. It should be noted that, for transparency reasons, LCI tables in OSP I and II include the byproducts.

The LCA results are disseminated for cradle to gate system boundaries. LCI results are disseminated for the border between foreground and background data, which equals a gate to gate assessment. Subsystem boundaries are defined for transports, on site foreground emissions and background emissions. The supply of wood and the connected impacts are disseminated separately to simplify the trace of carbon flows in biomass and also to enable an exclusion of these parts of the product life cycle for the monitoring approach.

Table 4: Functional units of the status quo assessment and their abbreviations used in the text, all units refer to 1 m^3 of product

FUNCTIONAL UNIT	ABBREVIATION
Sawnwood, coniferous, green or air dried	C g
Sawnwood, coniferous, kiln dried	C kd
Sawnwood, coniferous, kiln dried and planed	C pl
Sawnwood, nonconiferous, kiln dried	NC kd
Raw particleboard	PBr
Overlayed particleboard	PBm
Oriented strand board	OSB
Medium density fibreboard	MDF
High density fibreboard	HDF

In the case of wood based panels, which rely on sawmill byproducts, the impacts from sawmills are disseminated separately.

The foreground system is defined in accordance to the *specificity perspective* (Section 1.3.3). The foreground data for the unit processes in the foreground system was gathered by industry surveys. In total the survey supplied detailed datasets for 43 sawmills and 17 panel producers. The representativity in the case of sawmills can be described for each process step. Table 8 in OSP I shows, that the data is responsible for about 25 % of the total production of coniferous sawnwood and 4 % of non-coniferous sawnwood and in Germany.
In case of wood based panels, the survey covered approximately 80 % of the total production of particleboard, 30 % of the OSB production and 20 % of fiberboard in Germany.
Several more companies supplied additional but incomplete data. The LCI data was gathered during a three year period from 2009 until 2011 from companies situated in Germany. Missing data, especially emissions from the combustions on site were modeled according to literature data as described in Rüter and Diederichs (2012).

Case studies

Two case studies were conducted to test the applicability of the status quo data to be used in LCA studies for products derived from sawn wood and wood based panels. The first case study (CP I) connects LCI from producers of glue laminated timber with generic data for sawmill products. The case study aims to identify the relevance of the deviation of the generic data, the relevance of the allocation procedures and the implications of disregarding the CO_2 from biogenic resources.

The second case study (OSP III) uses generic status quo data of sawn wood products and panels for a life cycle assessment of wooden interior doors. The aim of the case study was to supply an LCA dataset for doors according to EN 15804:2012-04.

Impact assessment

An impact assessment was conducted for the six impact categories defined in EN 15804:2012-04 (Table 3). The Global Warming Potential (GWP) indicator only refers to CO_2 from fossil sources. CO_2 from biogenic sources is not taken into account (see section 1.3.4). They can be easily calculated based on information on the wood used for fuel and material purposes (see OSP I and II).

3.1.3 *Sector specific status quo*

Principle

The principle to calculate the sector specific status quo is based on the assumption, that a sector of industry can be defined holistically by the products or services it produces and that the energy consumption and environmental impacts which are caused by the production of those products and services can be quantified comprehensively by using the method of product LCA. Hence, multiplying both values for one specific year, expresses the environmental impact and energy consumption of the sector of industry in that specific year.
The data derived by this bottom-up upscaling procedure is compared to statistical data available on sector level (see below).

Definition of the sector and production quantities

Differentiation between the SMI sector and the WBPI sector was done analogously to the LULUCF accounting methodology, which differentiates between sawnwood and wood based panels (European Parliament and Council of the European Union, 2013). The sectors are defined by all products listed under Production Communautaire (PRODCOM) Codes 16.1 (NACE Rev. 2), 20.1 (NACE Rev. 1.1) and PRODCOM Codes 16.21 (NACE Rev. 2), 20.20.1 (NACE Rev. 1.1).
Information on annual production volumes for the core products are based on (Destatis, 2012b, ff.) and (Destatis, 2010b, ff.).

Statistical data on sector level

The yearly final energy consumption (FEC) is publicly available for the SMI and WBPI from 2003 until 2012 (Destatis, 2012a). Emission data is available from the European Pollutant Emission Register (EPER) based on directive 96/61/EC from 2003 until 2005 and from the Pollutant Release and Transfer Register (PRTR) based on regulation 166/2006/EC from 2007 onwards. Data is available for the WBPI only. For several companies, emissions of NO_x and non methane volatile organic compounds (NMVOC) are reported.

3.1.4 *Results*

Product specific status quo

LCI and LCA results were published for each core product of the SMI in Table 4, Table 6 and Table 7 in OSP I. The data was compared to existing data described in Section 1.3.3 on the basis of single processes (Table 1 and Table 2 in OSP I).
Uncertainties and data ranges were disseminated in Table 9 and Table 10, the representativeness of the status quo data was shown in Table 8, each in OSP I.

LCI and LCA results for each core product of the WBPI were published in Tables 3 and 4 in OSP II. Comparison to existing data was conducted and results were published in Table 7. Uncertainties (Table 5), data ranges (Figure 3) as well as the representativeness (Table 6) were disseminated, each in OSP II.

The underlying model of OSP I and II was successfully applied to calculate the cradle to gate and end of life LCA of glue laminated timber (GLT) in CP I. At the stage when CP I was published, no final data for sawn wood products as published in OSP I and II was ready. Hence, the data ranges (Figure 4, CP I) refer to milling processes located at the producers of GLT only. Although data was derived from several producers, the underlying procedure of modeling (the matrix inversion step was also used for the sawn wood products in OSP I and II, see Section "system boundaries" above) allowed the dissemination of the contribution of each process.
The impact of different allocation procedures (see Section 1.3.3) for the sawmill process was tested (Figure 1, CP I) to be of little relevance for the cradle to grave results when choosing between mass and price based allocations, but of significant relevance if system expansion was chosen.
Further on, in CP I, the modeling principle of separating biogenic CO_2 flows and those from fossil resources was tested successfully (Figure 3, CP I) and applied to the model used to calculate results in OSP I and II.

The applicability of the data published in OSP I and II for Environmental Product Declarations (EPD) based on EN 15804:2012-04 was successfully tested in OSP III.

Sector specific status quo

Gate to gate inventories for the SMI and the WBPI were calculated based on the bottom up approach described in OSP IV. Table 2 in OSP IV reports the differences of the bottom up approach to data available on sector level for the total consumption of electricity and fuels for the SMI and WBPI as well as the emission of NO_x and NMVOC for the WBPI.
The results comply with the expected results described in Section 3.3 in OSP IV.

3.2 B - MONITORING

3.2.1 *Link to publications*

A detailed description of the monitoring approach was published in OSP IV.

3.2.2 *Method and data*

Principle

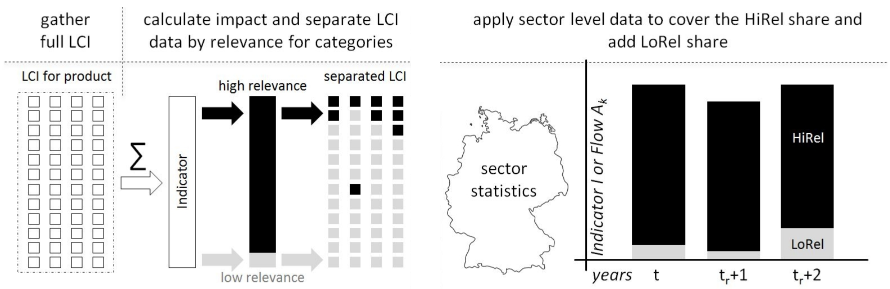
The fundamental principles of the monitoring approach build upon the principles of the sector status quo assessment (Section 3.1.3). In addition to this, the development can be monitored if the results which have been derived by multiplying product specific LCI data and production quantity data for one specific year to results from a different year.

System boundaries

The monitoring approach has two system boundary types, namely Scope 2 and Scope 3 system boundaries. The Scope 2 system boundaries include all emissions from gate to gate of the production. This includes i.e. emissions from the combustion on site and NMVOC from the drying process. The Scope 2 system boundaries also include the supply chain for all energy types used on site. This includes the generation of electricity, starting from the supply of fuels (coal, natural gas etc.) and ending with the utilization on site to process the wood. This equals Scope 2 boundaries described in Section 1.3.2 and those used by the *ODYSEE MURE* Project described in Section 1.3.2.
The Scope 3 system boundaries include all aspects included in the Scope 2 system boundaries and in addition all emissions arising in the supply chains, which equals Scope 3 boundaries described in Section 1.3.2. The wood chain is excluded from this, as the monitoring approach aims to analyze the woodworking industry isolated from forestry (see Section 1.4.1, 4th recognition).

Indicators

The relevant indicators for the monitoring approach mirror its aim in terms of generating knowledge about the development of the sector in the context with political targets for 2020 and the environmental assessment of building products in general (Table 1 in OSP IV.
The five impact categories disseminated in EPD based on EN 15804:2012-04 are included. Comparability to political targets is achieved by integrating absolute values for the total final energy consumption (FEC) (Parliament and Council of the EU, 2012), for the total primary energy consumption (PEC) (Parliament and Council of



(a) Simplification (b) Monitoring

Figure 3: Schematic view of the approach

the EU, 2012) and the total emissions of greenhouse gases (United Nations, 2012). The comparability to sector level targets is gained by disseminating the above absolute values relative to the total production volume of a sector (Frondel et al., 2013) and relative to the net value added generated by the sector, whereas the *Net Value Added* (NVA) is used as it is promoted by the United Nations to be used for eco-efficiency indicators (Sturm et al., 2002).

Evaluation of the approach

Unfortunately, as described in Section 1.3.3, the required LCI data is not available for every product and every year and therefore the monitoring approach is based on a hybrid LCA technique, combining simplified product LCI data with results of surveys on sector level. Figure 3(a) shows the essential idea of the simplifying procedure that underlies the monitoring approach:
Process based LCI data for all product groups is analyzed in terms of the sensitivity of every inventory flow quantity towards an indicator following the concept of a perturbation analysis. The approach is used to differentiate between inventory flows with high relevance (HiRel) for an indicator and inventory flows with low relevance (LoRel). The aim of this method is to cover at least 80 % of an impact category with as little information as possible.

Figure 3(b) shows the combination of the LCI data with the sector level data within the monitoring. In contrary to typical hybrid approaches, the most important part of the LCI, the HiRel, is covered by data on sector level and the quantities are based on physical flow information instead of monetary flow information from input-output tables as described with its specific challenges in Section 1.3.3.

For the reference year 2010, a plausibility test was conducted to compare data which was calculated by multiplying product specific LCI with production volumes for all products relevant for the sector, with sector data available from statistical offices (Table 2 in OSP IV).

The results demonstrate the plausibility as they correspond to the expected results. In addition, some conclusions can be derived from this for the general data quality for energy consumption figures available in companies of the woodworking industry. Section 4.2 deals with this in detail.

3.2.3 *Results*

General

The monitoring approach supplies reliable results especially for the cradle to gate GHG emissions of the SMI and the WBPI. Figures 4 and 5 show the development of the GHG emissions from the SMI and the WBPI from 2003 until 2012. The type of the graphs used for both sectors is the same and therefore explained in this general context. The top figures (a) show the development of the total GHG emissions from cradle to gate (without forestry) compared to the total production volume of the sector (dashed line). In the case of the SMI, the Scope 2 emissions and Scope 3 emissions are very similar, therefore Figure 4a only shows the Scope 3 emissions of that sector. The middle figures (b) show the total production of each sector differentiated by product types. The figures at the bottom (c) show the volume specific GHG emissions of the sectors. The dashed line shows the results according to the LCI data (reference 2010) extrapolated based on the production mix and energy mix reported by the statistical offices, the other line shows the results of the monitoring approach. In other word, the dashed line shows the development of 1 m^3 (average) produced in the sector with the assumption that the inventory for each product of the sector remained the same in ever year (the energy mix for the generation of thermal energy is set according to data from energy statistics of the sector). The continuous line shows the real GHG emissions of 1 m^3 (average) in each year. The distance between the lines therefore indicates the development of the efficiency compared to the year 2010.

The sawmill industry

In absolute quantities, the sawmill industry increased its GHG emissions from 664 kt CO_2-eq. in 2003 up to 912 kt CO_2-eq. in 2012 (+37 %). In the same time the total production increased by 11 % only (Figure 4). The specific GHG emissions to produce 1 m^3 of an average product from this sector increased from 35 kg CO_2-eq. up to 43 kg CO_2-eq. (Figure 4c). The main reason for this was the increased production of kiln dried sawn wood at the burden of green sawn wood in the product portfolio (Figure 4b).
In 2007 the total production of the SMI was at its highest level. A significant amount of the production increase before 2007 was due

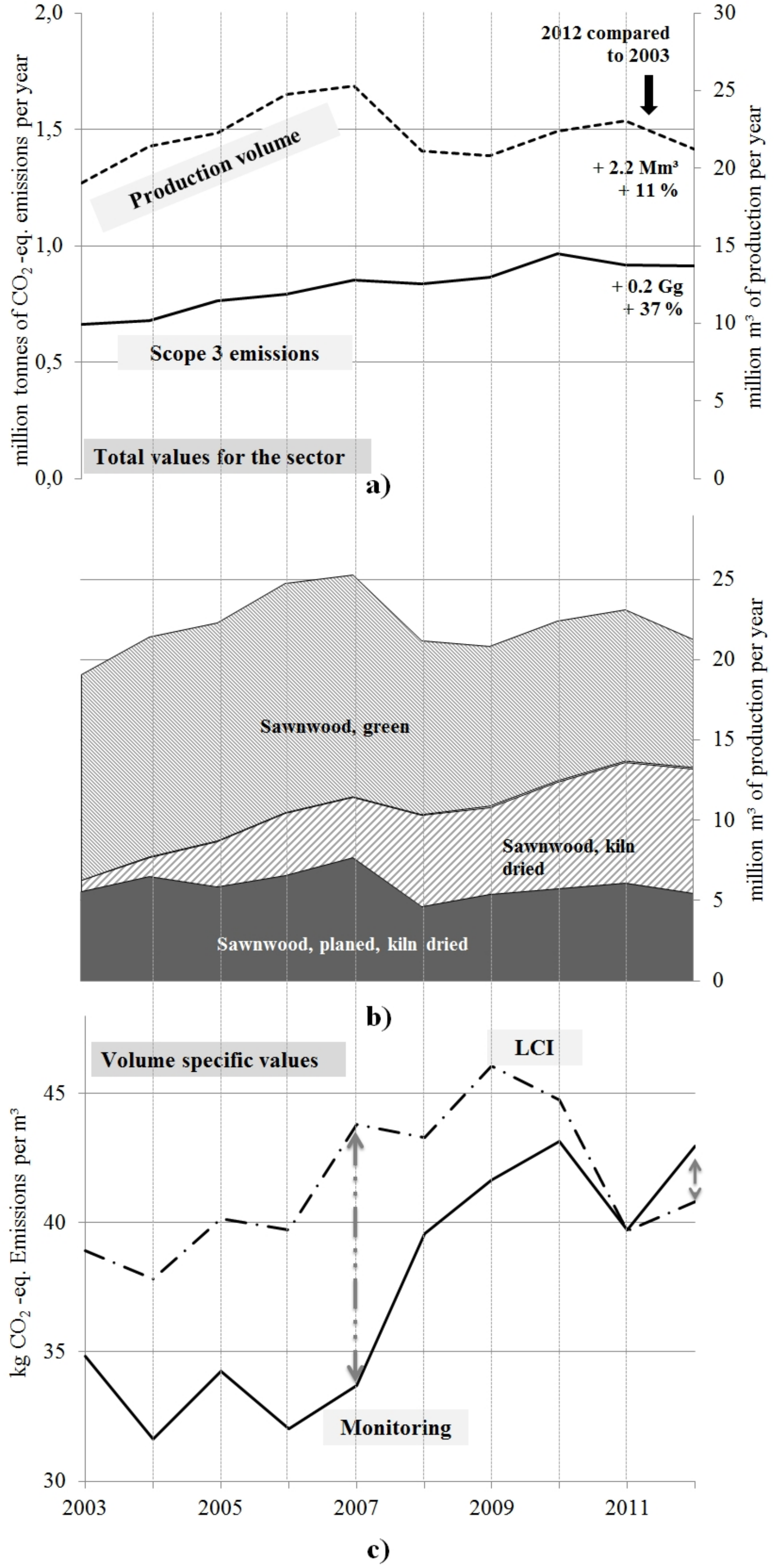


Figure 4: Development of GHG emissions from the SMI, a) Total GHG emissions (cradle to gate and energy related only) and total production volume, b) Total production volume of product portfolio, c) Average product specific GHG emissions calculated by the monitoring approach and by using LCI data only

to the extra production of kiln dried sawn wood (a product with high GHG compared the green sawn wood). From an LCA modeling perspective, the GHG emissions therefore should have increased accordingly. But they did not. The highest GHG emissions were reported in 2010 instead.
This indicates, that the GHG emissions efficiency to produce a specific product (not the average product of the sector but i.e. particle board or fiberboard) decreased. A reason for this could be the decrease in capacity utilization: in 2007 the production volume was about 20 % higher than in 2012. Since several infrastructural processes in the sawmill industry (lighting, transport chains etc.) consume the same amount of energy no matter if the capacity of the mill is fully utilized or not, the energy efficiency of a sawmill is likely to increase with an increased utilization of its capacity. Figure 4c indicates that from 2007 until 2012 the GHG efficiency (CO_2-eq per m^3) decreased by 35 %.
There is a reasonable amount of uncertainty in these figures due to the described data quality for the biomass quantities in the surveys from the statistical offices (see Section 4.2). The LCI based development (dashed line in Fig 4c) is based on the energy mix used to generate thermal energy in the SMI which is based on the share of fuels reported by the statistical office. If the amount of biomass used for the generation of thermal energy was actually higher than reported, the actual share of fossil fuels (relevant for GHG emission) would have been lower (and therefore closer to the other line which means that the efficiency loss was actually less than 35 %). However, the gravity of these uncertainties cannot not be quantified in this context.
From an economical point of view, the emitted GHG per value added (not shown in figure) increased from 1.05 to 1.24 kg CO_2-Eq./Euro (+18 %) between 2003 and 2011 (no figures available for 2012 at the time of calculation). This means the sawmill industry was not able to demand higher prices on the market in the same magnitude as CO_2 emission were increased.

The wood based panel industry

The wood based panels industry decreased its total GHG emissions from 4751 kt CO_2-eq. in 2003 down to 3885 kt CO_2-eq. in 2012 (- 18 % - Fig 5a). At the same time, the total production volume decreased by 11 % only. Also the product specific emissions of GHG (for the specific product mix) decreased from 353 to 325 kg CO_2-eq./m^3 (- 8 %) (Fig 5c). The emitted GHG per value added decreased as well, from 6.6 to 6.5 kg CO_2-eq./Euro (- 1.5 %) between 2003 and 2011 (not shown in Fig 5).
The production maximum in 2006 (please also see "The product statis-

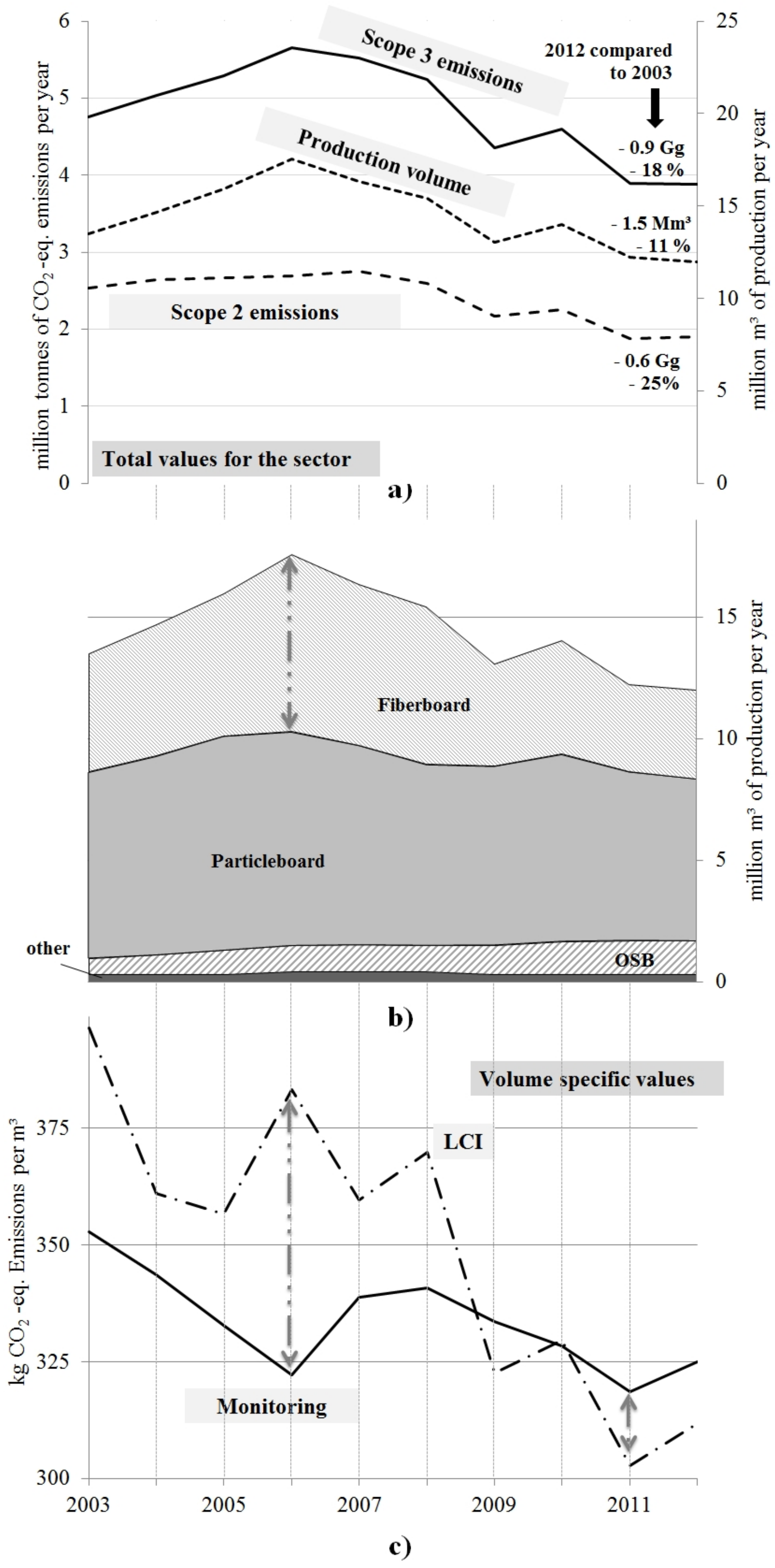


Figure 5: Development of GHG emissions from the WBPI, a) Total GHG emissions (cradle to gate and energy related only) and total production volume, b) Total production volume of product portfolio, c) Average product specific GHG emissions calculated by the monitoring approach and by using LCI data only

tics problem" on page 58) lead to total GHG emissions of about 5658 kt CO_2-eq. in that year, the highest value between 2003 and 2012. But as visible in 5a, the EGHG emissions did not increase much between 2004 and 2007.
This is caused by the high GHG efficiency for the specific product (i.e. 1 m^3 fiberboard) in 2006 which is also visible in Fig 5c: in 2006 the actual GHG emissions per m^3 were much lower than they would have been if the efficiency level of 2010 was assumed (which is known from the LCI data).
The lowest efficiency level was in 2011. This means between 2006 and 2011 the GHG efficiency (for the specific product, not for the mix) of the WBPI decreased by about 21 %.
Analogously to the SMI, the point of highest efficiency was calculated for the year with the highest capacity utilization. The uncertainties connected to the biomass fuel quantities also apply for the WBPI. Especially in the first year of the survey (2003) the amount of reported biomass used to generate thermal energy was very low. Hence, the share of fossil fuels in the energy mix (the LCI data is based on this) probably overestimates the GHG emissions in that year.

Simplification

OSP IV describes the relevant information within the product specific inventories of wood products. While the monitoring approach (Section 3.2) combines the relevant data with data on sector level, the results can also be used to simplify the data collection on site.

The simplification of the LCI collection procedure in the companies can be conducted by focusing on the inventory flows identified in OSP IV. Figures 3 and 4 in OSP IV show all inventory information needed to cover 80 % of each indicator result.
This simplified approach was integrated in an Environmental Management System (EnMS) by Sander (2014).

3.3 C - DECISION SUPPORT

3.3.1 *Link to publications*

Support for decisions on micro level can be derived from OSP I and II (Section 3.1) in combination with the sensitivity analyses conducted in OSP IV (Section 3.2).
The case study described in CP II uses aspects of the simplification procedure to give decision support to optimize the thermal modification process for the production of thermally modified timber (TMT) in a sawmill, a typical micro level decision.
Aspects to consider while giving decision support on meso- and macro level have been analyzed in OSP V. The latter publication shows the differences when conducting an LCA in accordance with EN 15804:2012-04 (for micro-level decision support) and when following a more "holistic approach" (for meso- and macro level decision support), which includes issues that are disregarded in the "EPD approach".

The description of method and data used within OSP I, II and IV have been described in Sections 3.1 and 3.2 of this dissertation. This Section will focus on method and data used within OSP V and CP II.

3.3.2 *Case study - simplified LCA for TMT*

The case study described in CP II utilizes LCI data for sawn wood products and adapts the kiln drying procedure (as a model) by several parameters to simulate the TMT process. These parameters are:

- consumption of thermal energy per m^3
- fuel type used to generate the thermal energy
- consumption of electricity per m^3
- reduction of the wood mass during the modification process
- utilization efficiency of the devolatilized organic substances when used for thermal energy generation

In addition, the reduced mass is recognized in the end of life of the TMT product.

3.3.3 *Case study - PB vs. ULPB*

General

The study aims to analyze the environmental benefits or drawbacks of using ULPB with a foam core processed on a continuous press, for

applications were commonly conventional PB is used.
It further aims to identify the parameters with the largest influence on environmental impacts, helping the developers to understand which decision in design might lead to better or worse results in the overall environmental impact of the new product. The approach is based on an Attributional Life Cycle Assessment (ALCA) and a second model which includes aspects typically focused in a Consequential Life Cycle Assessment (CLCA) but not claiming to be a full CLCA. Within this study, the name "holistic approach" is used. For the latter, only GWP aspects are analyzed.

Functional units

The exchange of PB with three types of ULPBs is analyzed from cradle to grave. The ULPBs represent panels with three different types of possible foam cores, EPS, PLA and a 1:1 mixture of PLA and PMMA. The final density of the ULPB is about 300 kg per m^3 compared to about 700 kg per m^3 in the case of PB. It should be noted, that the functional unit refers to applications were the described panels can be utilized with the same thickness. This may not be the case for some applications with high demands in terms of mechanical properties. Since the study is untented to emphasize the differences which result from the different modeling principles, this was accepted for the sake of simplicity.

System boundaries

The ALCA model is strictly based on the EN 15804:2012-04 methodology (Figure 2 in OSP V) and is therefore called "EPD approach" in the study. The "holistic model" includes further aspects (Figure 3 in OSP V). These are:

- the alternative use for sawmill by-products if not used in the wood based panels and for the generation of thermal energy
- the alternative use for corn if not used for PLA
- the land use change if extra corn has to be produced for the production of PLA

As it is not clear if additional corn is produced or -if not -, which feedstock is replaced, three scenarios for the corn production/displacement are analyzed:

SCENARIO 1 describes the impact, if additional corn has to be grown, including impacts of agricultural processes and the impact of land use change triggered by this extra production.

SCENARIO 2 describes the impact, if available corn is used for PLA which would have been used for the production of bio-ethanol to replace gasoline. This is a relevant question for the US, where bio-ethanol is produced from corn.

SCENARIO 3 describes a typical German case. Available corn which would have been used for the production of bio-gas (methane) is used for PLA instead. Hence the energy derived from the methane has to be substituted.

3.3.4 *Results*

For micro-level decision support (company level), OSP I and II (Section 3.1) in combination with the sensitivity analyses conducted in OSP IV (Section 3.2) filter the relevant information which should be taken into account primarily (Figure 3 and 4 in OSP IV).
For meso- and macro-level decision support, the system boundaries defined in EN 15804:2012-04 were not broad enough to include all essential aspects within the LCA. Especially effects triggered in the by-product chains or alternative routes for the bio-based products used were disregarded.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 A - STATUS QUO

The first target of this dissertation was the...

> **calculation of representative, average LCI and LCA status quo data for all core products of the woodworking industry** (see aspect A on page 26)

4.1.1 *Representative datasets*

Representative gate to gate LCI information and cradle to gate LCA results for the core products of the woodworking industry for the year 2010 have been published in the context of this dissertation. The results have been transparently documented in OSP I and OSP II and they are in accordance with the requirements of EN 15804:2012-04 as shown by Rüter and Diederichs (2012). They can be applied for average datasets in context of sustainability assessment schemes like the German BNB or DGNB and for background information for LCA studies which include semi-finished wood products.

For the core products of the SMI, Table 7 in OSP I, for the products of the WBPI, Table 4 in OSP II supply the relevant information to allocate the results into the modules A1 to A3 used in EN 15804:2012-04. "Foreground, gate to gate" and "background, gate to gate" results can be summarized into module A3, "transport" is to module A2 and "Forest" to module A1.
Since the carbon dioxide uptake in the forests is taken into account in EN 15804:2012-04, the values presented in Table 7 of OSP I and Table 4 of OSP II have to be adapted.
They can be easily calculated based on the mass of wood in the products. They need to be added to the GWP indicator as a negative value. For example green coniferous sawn wood with an oven dry density of 450 kg/m^3 has a carbon content of 225 kg/m^3 which oxidizes to 825 kg of CO_2. The cradle to gate GWP indicator for fossil CO_2-eq. emissions is 32.9 kg/m^3. The total value adds up to -792.1 kg CO_2-eq. from cradle to gate.
All values refer to the production of 1 m^3 of each product. Table 7 of OSP I and Table 4 of OSP II represent unallocated values, which means that they refer to inputs and outputs necessary to produce 1 m^3 of product and the by-products. Allocation by mass, price or others as well as system expansions can be done depending on

the methodology of the LCA study where the data is applied. In the context of EN 15804:2012-04, allocation based on price has been identified to be most appropriate as comprehensively described in Rüter and Diederichs (2012).
It should be noted at this point that attention has to be paid to the quantification of the volumes. As described in OSP I, 1 m^3 refers to an equivalent of 1 m^3 with an MC of 12 %.

4.1.2 *Limitations*

In terms of applicability of the LCI for studies which analyze toxicity indicators, attention has to be paid to data gaps especially concerning dioxins. The identified data gaps especially refer to emissions from combustion, namely selenium, polychlorinated biphenyls, polychlorinated dibenzodioxins, benzo(a)pyren, benzo(b)fluoranthene, benzo(k)fluoranthene, indeno(1,2,3-cd)pyrene and hexachlorbenzene. The heavy metals listed in Table 4 in OSP I and Table 3 in OSP II were compared with official data from Rentz et al. (2009), which are facilitated in the reporting to the UNECE Convention on Long-range Transboundary Air Pollution Emissions. Emissions of mercury and zinc are smaller by factor 5 to 8 in this study, emissions of copper and lead are higher by factor 5 to 2.5, but emission data for cadmium, arsenic, chromium, and nickel match very well with those reported by Rentz et al. (2009).
However, for the indicators presented in this study, those data gaps do not have an effect since the listed substances are not classified to have an effect in any of the indicators, which means that for the indicators presented in this dissertation, good compliance to official data from Rentz et al. (2009) was found.

4.1.3 *Comparison to other studies*

For sawmill products and wood based panels, the results for the process specific electricity and fuel consumption (average weighted by production volume) $\bar{x}_{volumeweighted}$ were compared to corresponding data from studies conducted in different years and/or other geographical context (Tables 1 and 2 in OSP I and Table 7 in OSP II).
Furthermore, for sawmill products the results were analyzed in terms of their distribution between companies. Here the 5 % fractile $Q_{0.05}$, the average between the companies (not weighted by production volume) $\bar{x}_{arithmetic}$ and the 95 % fractile $Q_{0.95}$ were looked at.
The results in Table 1 in OSP I show, that the specific energy consumption for each process differs widely between the companies

that took part in the study. Since $\bar{x}_{arithmetic}$ was higher than $\bar{x}_{volumeweighted}$ for debarking, milling and kiln drying, it can be concluded, that the larger companies typically have a lower specific energy consumption than the smaller ones. Moreover, the large differences between companies seems to be typical for the sawmill industry, since the results published by other authors also deviate heavily from each other.
Similar results were found for the consumption of fuels (Table 1 in OSP I). The values do not just deviate in terms of their totals but also in terms of the type of fuels used, which can have a large impact on some indicators derived from the LCI.

For wood based panels the product masses were also compared to results from other studies (Table 7 in OSP II).
For the production of PBr and OSB the other studies found higher values for the consumption of electricity and fuels but also considered products with high densities. The analyzed $\bar{x}_{volumeweighted}$ mass of the analyzed FB, ranks quite in the middle of the densities of the other studies. While fuel consumption also ranks in the middle, electricity consumption is lower than those published by other authors. The consumption of diesel is higher in the case of PBr and OSB and lower in the case of FB.
With regard to the survey sample base of LCI results for the products of the wood based panels industry (Table 6 in OSP II), the $\bar{x}_{volumeweighted}$ values for PB are quite reliable while the results for the FB only covered 18 % of the production. For OSB about 33 % of the total production was covered.

4.1.4 *Lessons learned*

The calculation of LCA datasets for products based on primary data from industry is labor intensive and time consuming. Based on experiences made during this dissertation, the most demanding task is the preparation of production data. The following aspects essentially contribute to this problem:

- The breakdown of electricity consumption - which is known on company level - towards the single products is in many cases based on assumptions. Typically, no measurement equipment is installed which would allow an accurate distribution. If data is available (physically), it is often not recorded or prepared in the required format.

- Quantity information for by-products is typically not available or imprecise. In many cases, the plausibility checks done during the surveys showed large inconsistencies of the data which was available on company level. Especially the combination of different methods of measurement (mass, solid volume, bulk volume) and the inaccurate measurement of MC above fiber saturation point lead to those inconsistencies.

- The process yields are not available for each product. Especially in sawmills, products arise bit by bit during production (i.e. chips, sideboards, main boards) and if these products need to be separated to conduct a product specific LCA, the yield has to be known for each process, which is not the case in most sawmills.

- For many combustion plants no continuous emission reporting is available. Instead, emission data has to be estimated for them based on technical specifications although the data is highly significant towards impact results and can deviate heavily.

In conclusion, the data availability in the companies of the woodworking industry needs to be improved drastically in order to provide representative LCI data for their products in the future. To update the data which has been elaborated in this dissertation different methods have to be used to keep the expected benefits of such data balanced with the cost of data acquisition, calculation and documentation. Chapter 4.4 recommends solutions to this problem for the relevant stakeholders.

4.2 B - MONITORING

The second target of this dissertation was the...

> **introduction of a monitoring approach to follow the development of the woodworking industry based on a simplified, hybrid LCA** (see aspect B on page 27)

4.2.1 *Evaluation of the approach*

Within this dissertation, a monitoring procedure for the woodworking industry is presented. The approach includes the relevant indicators used to express political targets and the relevant LCA indicators used in the context of schemes for the assessment of ecological sustainability of construction works.
The data needed for the calculation is publicly available and updated frequently (see EEA (2014) and Destatis (2014b)) which is in accordance to publicly accepted requirements for indicators (BMWi and BMU, 2012).
So far, reliable results are available for the global warming potential and the consumption of fossil fuels in context with the production of products of the sawmill industry and the wood based panels industry.
With the simplification of LCI data in terms of focusing on flows with high importance for an environmental indicator it was shown, that relevant LCA results can be derived from much smaller amount of data than the usual complexity of LCA studies would suggest. Therefore, the presented monitoring approach not only offers a way to monitor a sector, but the results from the simplifying procedure allow companies to focus on some single numbers to quantify the improvements they achieved individually. Results on company level need to be taken with caution though since the wood used for material was left outside the system boundary.

4.2.2 *Limitations*

Environmental aspects not covered

Limitations exist for some environmental aspects which could not be included satisfactorily into the monitoring. Results in terms of acidification potential, eutrophication potential and photochemical ozone creation potential heavily rely on information on emissions of NO_x and NMVOC. On sector level, the relevant data is not readily available to be used for monitoring as it lacks completeness. However, the available data already shows that both types of emissions are underestimated by available LCI data. For NMOVC, the underesti-

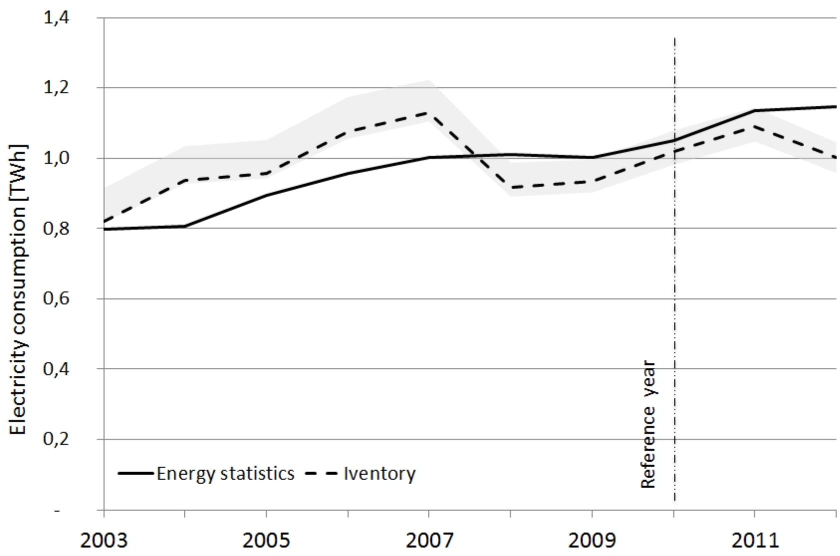


Figure 6: Electricity consumption of the SMI according to energy statistics and derived from up-scaling LCI data, the gray bar indicates the uncertainties that resolve from the information gap on the share of kiln dried products.

mation is severe.

For other impact categories (ODP, ADPe and toxicity indicators) no relevant results could be derived, since the relevant data on sector level is missing.

The biomass quantity problem

In OSP IV it was concluded, that data from the statistical office on energy consumption in the woodworking industry needs to be improved. Figures 6 and 7 show the electricity consumption of the sawmill and wood based panels industry according to data from DESTATIS and upscaled LCI data. The absolute height of the curves and the general trend are very similar. In contrast, Figures 8 and 9 show the heat consumption of the sawmill- and wood based panels industry according to data from DESTATIS and the data which was derived from upscaling LCI data. Especially in the early years of the surveys (starting in 2003), the differences are very high, getting smaller every year.

OSP IV concludes that official data probably does not reflect real circumstances and therefore, the average yearly increase of fuel consumption of approximately 15 % in case of the SMI and approximately 8 % in case of the WBPI is presumably much too high.

For the woodworking industry this means, if official data is used to calculate the development of energy efficiency of the woodworking industry, results will probably be incorrect and show values which

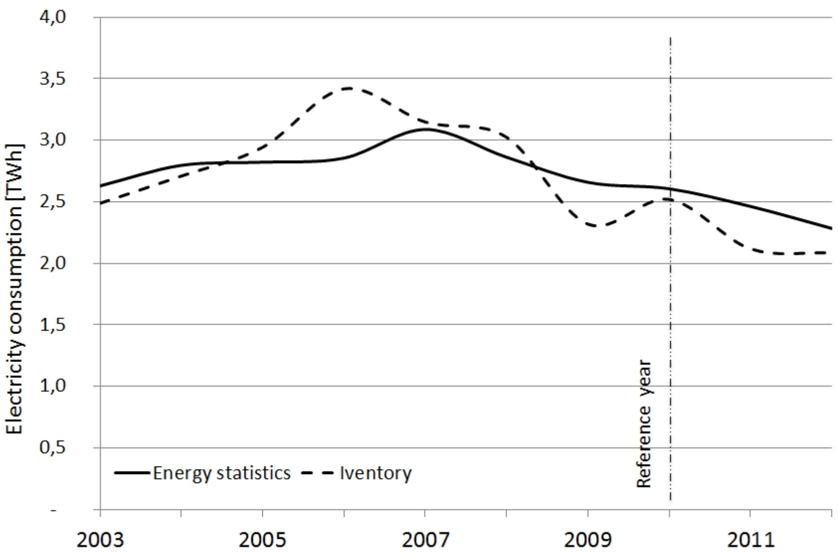


Figure 7: Electricity consumption of the WBPI according to energy statistics and derived from upscaling LCI data

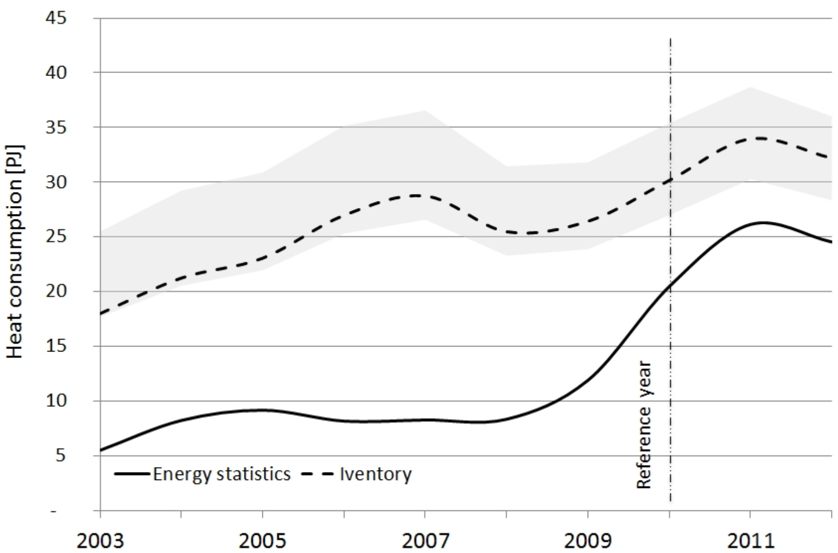


Figure 8: Heat consumption of the SMI according to energy statistics and derived from upscaling LCI data, the gray bar indicates the uncertainties that resolve from the information gap on the share of kiln dried products

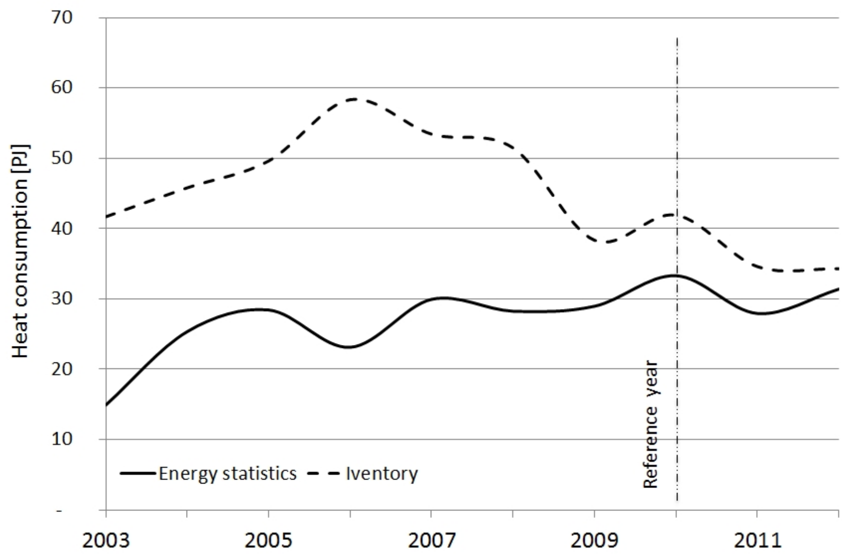


Figure 9: Heat consumption of the WBPI according to energy statistics and derived from uspacaling LCI data

are worse (in terms of reaching political targets) than they might be in reality. Today, official data shows a severe divergence between the behavior of the sector and the intended national final energy efficiency increase to reach 2020 targets. The results also indicate that the woodworking industry is most likely responsible for a larger share of the increase of renewable fuels in the final energy mix than shown by official data.

The product statistics problem

A large uncertainty within the upscaling procedures arises from the reported data for the production volumes. In this study, figures from DESTATIS were chosen to be consistent with energy statistics which are also published by DESTATIS and to use official data which will be reliably available in the future. However, other figures e.g., from the Statistical division of the Food and Agriculture Organization of the United Nations (FAO) and several publications from the University of Hamburg (e.g. Mantau and Bilitewski (2010)), exist which supply information that is not necessarily congruent with the statistics applied in this dissertation. Especially for the production statistics for fiberboard (see Figure 5 on page 45) the production peak in 2006 reported by the statistical office is inconsistent with data from the WBPI association (see for example EPF (2012)). This may explain parts of the efficiency loss described on page 46.

4.2.3 *Initial results derived from the approach*

The sawmill industry increased its average greenhouse gas emissions from 35 to 43 kg CO_2-eq./m^3 between 2003 and 2012. One aspects which lead to this increase was the increased production of kiln dried products. However, with a reduction of the total production volume since 2007 and the resulting overcapacity of many sawmills, a GHG efficiency loss starting in 2007 may have added a reasonable share to this total increase of product specific GHG emissions.
With regard to economic values, the sawmill industry was not able to compensate higher greenhouse gas emissions with an increased net value added. From 2003 to 2011 the emitted greenhouse gases per value added increased from 1.05 to 1.24 kg CO_2-eq./Euro.
The wood based panels industry decreased its average greenhouse gas emission from 353 to 325 kg CO_2-eq./m^3 from 2003 to 2012. This decrease is mainly explained by a change in the product portfolio. In fact, the share of fiberboard (very energy intensive production process and high glue content) decreased between 2006 and today.
In contrary, the GHG efficiency of a specific product (not the mix of the sector) (CO_2-eq per m^3) decreased as the capacity utilization of the production sites decreased, or the share of older, less efficient sites increased in the total mix. This efficiency loss was estimated to be approximately 20 % which means that a panel, which caused 200 kg CO_2-eq. in 2006, was responsible for approximately 240 CO_2-eq. in 2012. A share of this 20 % efficiency loss may also be attributed to data uncertainty as described above.
Unfortunately the efficiency loss cannot be allocated to a specific product, neither for the sawmill industry nor for the wood based panels industry. However, from the perspective of capacity utilization, the efficiency loss is probably located at the processes before the kiln drying process in the case of sawmills. In the case of wood based panels, the production of fiberboard decreased more than the production of other panels. Hence, the loss in efficiency is estimated to have happened especially here.
This obviously means that although the overall efficiency decreased, single products, like OSB whose production volume increased steadily since 2003 may not have experienced a decrease in their specific GHG efficiency.

4.2.4 *Lessons learned*

To understand the relevance of the development of process based emissions and energy consumption in the woodworking industry, the values can be compared to displacement factors for wood products substitution summarized by Sathre and O'Connor (2010).

Assuming a deliberate displacement factor of 0.8 t carbon emissions per 1 t of wood product, the monitored change in the specific GHG emissions per m^3 of products between 2003 and 2012 equals 12.6 % of the substitution effect in the case of panels and 1.2 % in the case of sawmill products. For panel products with lower displacement factors of about 0.5, the change already equals the displacement factor. For sawmill products a displacement factor of 0.3 leads to equal results. Sathre and O'Connor (2010) also found several studies which calculated factors below 0.3. Hence, the monitored development plays an essential role within decision oriented studies aiming to environmentally optimize the use of wood.

With regard to the political and social pressure of reducing environmental impacts and increasing energy efficiency, the results should urge the woodworking industry to improve the quality of the available data especially in terms of the quantities of biofuels. The data should also be supplied to the relevant databases.
In this context it seems to be reasonable to define a harmonized approach for the sector. With regard to data quality of emissions of NMVOC and NO_x, such an approach would seem productive as well.
In general, the presented approach can also be applied in other sectors. Especially for sectors with a high energy intensity (e.g. pulp and paper), the approach can be transferred provided that representative LCI data is available for the typical products.

4.3 c - decision support

The third target of this dissertation was the...

> **identification of options of decision support for technology improvements by analyzing the ability of the presented tools to holistically address all potential environmental impacts** (see aspect c on page 27)

4.3.1 *Micro level decision support*

General

For researchers and LCA practitioners, the status quo data can be used as background datasets for LCA where wood products are addressed. Table 4 in OSP I shows the gate to gate life cycle inventory for the production of the core products of the sawmill industry, Table 3 in OSP II shows the gate to gate life cycle inventory for the production of the core products of the wood based panels industry. All values refer to the production of 1 m^3 of each product regardless of the possible application (the functional unit). The tables represent unallocated values, which means that they refer to inputs and outputs necessary to produce 1 m^3 of product and the by-products. If the data is applied in LCA studies, allocation (or system expansion) has to be conducted only for those byproducts that are not used for fuel on site. Allocation by mass, price or others, as well as system expansions can be done depending on the methodology of the LCA study where the data is applied.
Since the data represents average values, adaption may be reasonable and necessary in some cases.

- For studies where the supply of wood products has a **low impact** compared to the total results of the study, and the product relies on one or very **few companies** of the woodworking industry, the worst case values $Q_{0.95}$ (Table 10 in OSP I and Figure 3 in OSP II) should be applied.
- For studies where the supply of wood products has a **relevant impact** compared to the total results of the study, and the product relies on one or very **few companies** of the woodworking industry, the data should be adapted to the respective circumstances as described below or if this is not possible, the worst case values $Q_{0.95}$ should be applied.
- For studies where the supply of wood products has a **low or relevant impact** compared to the total results of the study, and the product relies on the **market mix of wood products**, the average values $\bar{x}_{volumeweighted}$ in Table 4 in OSP I and Table 3 in OSP II should be applied.

Adapting data for sawmill products

If the data needs to be adapted to the respective circumstances, the following additional information can help to increase the reliability of the results for sawmill products:

- How is the yield of the sawmill process? The supply of wood is responsible for a large part of the total impacts. For sawmills with lower yields, the impacts may be higher.
- How long are the transport distances for the timber? The transports in the presented data make up to 15 % of an indicator result and increased transports may have a reasonable additive impact. (The specific transport distances can be found in (Rüter and Diederichs, 2012)).
- How much electricity is consumed by the sawmill? Comparing the total consumption to values in this study helps to understand if the sawmill is more or less efficient.
- How much diesel is consumed? Comparing the consumption of diesel to the presented results offers a way to correct the data.
- Are values available for the emissions of NO_x from the combustion plant? If so, they should be compared to those published in this study and the results may be adapted.
- What type of fuel is used? If fossil fuels are used, large changes in the GWP and ADPe indicators can be expected.
- How are exhaust gases of the drying procedure treated? Are they released without treatment (as found in this study) or is VOC reduced? This may have a relevant impact on the POCP indicator.
- How much steel is used for tools and wrapping materials? Compare to data in this study and correct the ADPe indicator.

Adapting data for wood based panel products

For the application of the average LCI and LCA data for wood based panels as background data, OSP II indicates a procedure to adapt the data to the respective densities of the products. For example, if the density of the PBr under study is 600 kg/m^3 the CO_2 eq. emissions can be taken as they are, since this is the density of the panels analyzed in the study. If the density is 730 kg/m^3 the CO_2 eq. emissions can be corrected according to Figure 3 in OSP II. The resulting emission for the complete product are than increased from 217 kg CO_2 eq. to 257 kg CO_2 eq. (+40 kg CO_2 eq.). Similar corrections can be done for fuel and electricity consumption as well as types of adhesives.

The following aspects should be addressed in detail when adapting the data to the respective circumstances:

- the specific electricity consumption of the panel production
- the types of glue and amount of glue used
- the types and amount of fuels used to generate thermal energy
- emissions of NO_x from combustion
- treatment of exhaust air from drying processes
- steel used for wrapping

4.3.2 *Meso- and macro-level decision support*

Choosing system boundaries

For meso- and macro level decision support, the system boundaries need to be broadened as shown in OSP V, including the alternative routes of by-products. This is essentially the case, if the greenhouse gas emissions resulting from of a reduced utilization of bio-based materials or fuels need to be taken into account.
The example of assessing the environmental implications of the decision to exchange a reasonable amount of conventional particleboard with ultralight particleboards with bio-based foam cores (OSP V), showed the potential explanatory power of the different LCA approaches. The EPD approach, which was based on the exigencies of EN 15804:2012-04 identified the change in electricity consumption and exchanging the urea-formaldehyde glue with core material to be the leading parameters of the comparison.
The holistic approach with its broadened system boundaries recognized these parameters as well but also the amount of biomass which has to be burned to dry the extra amount of chips in the PB is recognized as not available for other applications which means that reducing the amount of energy from biomass needed for the process has a much greater effect in the holistic approach than in the EPD approach. Moreover, the holistic approach takes into account the characteristics of the recovered wood at the end of life because the question whether the incineration process of the pure sawmill by-products would have been different from the process of burning the panels at their end of life is included in the model. Finally, as the production of PLA is included in the two LCA models in very different ways, different results can be derived here. In this context, the reaction of the corn-market to the increased demand of corn can be significantly for the total results of the comparison of the two panels. This is only recognizable if the holistic approach is applied.

4.3.3 *The marginal production*

Results from (OSP I) and (OSP II) indicate, that the larger production sites typically have lower specific environmental impacts than the smaller ones or those with an average size.
Above it was concluded, that the extra production of a single unit demanded on the market can lead to emissions much different from those connected to the production of an average unit. While the former aspect refers to a comparison of specific emissions of the same product and technology, the latter refers to a comparison of two very similar products but produced with different technologies and different specifications.
The latter aspect can be dealt with by following the procedures described in Section 4.3.1. The other aspect is the problem of identifying the marginal production, as it is not clear if an extra unit is produced by a small or large production site. Further on, results from the monitoring approach indicate, that the specific environmental impacts connected to the production of a specific wood product may also deviate heavily depending on the capacity utilization. Hence, the specific environmental impact of the marginal production technology is also influenced by the capacity utilization of this technology.
A potential solution for this problem, therefore, needs to include two aspects. On the one hand, the technology or size of production site which is most sensitive to a change in demand needs to be identified. As described by Weidema (2003) p.63, "[...] in an increasing market, the most sensitive supplier/technology is identical to the most competitive, while in a rapidly decreasing market [...], the most sensitive supplier/technology is the least competitive."
While the production capacity is rising, every additional product is produced by the newest and largest production site (and most efficient) since their variable costs are lowest. During a declining of capacities every additional unit is produced by older, smaller and less efficient sites.
On the other hand the effect of capacity utilization needs to be included by differentiating between the fixed environmental impact of a production site and the variable ones connected to each unit, as it is done in economics (fixed costs/variable costs, see also Guinée (2002) p.424).

4.4 D - FUTURE RESEARCH AND ACTIVITY FIELDS

The fourth target of this dissertation was the...

> **disclosure of future research and activity fields to improve and apply the presented tools** (see aspect D on page 27)

4.4.1 *Companies*

Updating the database

From the viewpoint of sustainability assessment schemes the SMI and WBPI supplied all relevant environmental information for all core products to be used as national average datasets for the assessment of construction works in 2010. However, the data should be updated regularly as the product specific impacts may considerably change over time.

The simplification procedure described in Section 3.3 and OSP IV supplies an ordered list for the relevant data to be collected at a production site to calculate the gate to gate LCI for each product. If the relevant data is implemented consistently in an energy management system, the expenditures and time consumption on data collection to supply the relevant gate to gate inventory information for the LCA practitioner will decrease heavily. The case study conducted by Sander (2014) gives a first impression on this.
Single companies can use the simplification procedure to elaborate the relevant data necessary to enable calculation of a company specific EPD in accordance with EN 15804:2012-04. The same procedure (if conducted by a representative amount of companies) can also be applied to update the average datasets that have been elaborated in this dissertation on a regular basis.
Further harmonization in terms of delivering reproducible and high quality LCI data from the companies of the woodworking industry has to be pushed on the level of associations (see Section 4.4.2).

Supporting decisions

Development and innovation activities (decisions) in the woodworking industry should be connected to LCAs to estimate the gains and losses to be expected. For decision support on company level, the initial assessment of environmental impacts should follow the exigencies of EN 15804:2012-04. However, since EN 15804:2012-04 turns a blind eye to market constraints, indirect land use change impacts and the substitution of alternative routes for limited resources, the initial assessment of environmental impacts should also include the results of a broadened analysis as described in OSP V.

The environmental assessment for decision support may start with a simplified approach as presented in CP II supported by the information supplied in the simplification procedure described in OSP IV including the relevant additional aspects found in OSP V.

Reporting results

After the decision has been taken (or the development has become a real product or process), the achieved improvements can be calculated by comparing the results from one year to another, albeit attention has to be paid to the inclusion of the correct modules (A - C).
The modules A1 to A3 (cradle to gate) shall be included as they reflect the essential aspects within the zone of influence of the company. The scenario Modules A4 and C2 to C4 shall be included as well, based on equal assumptions for the two years of the comparison (e.g. the end of life scenario described in Rüter and Diederichs (2012)). Furthermore, the function of the product at the gate of the production has to be equal for both years. All other modules shall be disregarded as they lie outside the zone of influence of the company. The calculated difference between the result from one year and another shall then be analyzed in terms of benefits which resulted from a decision within the management perspective (Section 1.3.2). Hence, benefits resulting from the changing framework outside this management perspective cannot be declared as gains initiated by the company.
Those types of benefits can be caused by a change in inventory detail (this must not be the case if the inventory acquisition system is consistent, e.g., changing from discontinuous to continuous measuring of NO_x) or due to a variety of changes in surrounding parameters such as the emission intensity of the electricity generation, changes within the production process of adhesives and other equipment material.
Typical gains which can be declared unambiguously are the reduction of electricity and fuel consumption, a shift towards adhesives with less environmental impacts and a general reduction of consumed wood, equipment, or adhesives, and finally the reduction of on-site emissions.

4.4.2 *Associations*

Support harmonization of data acquisition

For the consultation of members in terms of supporting their ability to reduce environmental impacts, associations can act as a platform to

find general solutions for their members and harmonize approaches. This refers to the data gaps and uncertainties in context with emission from the combustion and drying processes as well as those in context with the quantity of biomass used for thermal energy generation.
On the other hand, the data acquisition procedures in the companies need to be harmonized on sector level. The same applies for the reporting of annual production volumes and the consistent definition of products connected to these reported volumes.

The harmonization efforts should explicitly focus on

- installation points of measurement equipment
- calculation factors (mass to solid volume to bulk volume) for wood fractions
- default values for density and lower heating values
- measurement and reporting of emissions from combustion especially NO_x, SO_2 and CO
- measurement and reporting of emissions from drying especially formaldehyde and NMVOC
- measurement and reporting of biomass fuel quantities and qualities
- measurement and reporting as well as default values for moisture content (MC)
- consistent product definitions for reporting on sector level

Report the development of the sector

The presentation of environmental achievements due to optimizations as well as the proposition and evaluation of policy tools should be based on a comprehensive environmental reporting system on association or sector level. While the company level view and reporting should disregard impacts which are outside its field of action, a sector level report may supply a holistic view on the forest wood chain including Scope 2 and Scope 3 emissions as well carbon accounting procedures in context with forest management options and product storage. Substitution effects can be included as well.
Furthermore, a holistic view allows the explanation of efficiency losses (i.e. value added, quality increase, increase of product life expectancy) compared to cases where the processes of the woodworking industry are regarded singularly.
The proposition of effective policy which supports the woodworking industry to act in accordance with political targets set on national and international level needs to be based on a broad understanding

and transparent dissemination of environmental implications resulting from the implemented policy framework. This reporting should include monitoring results, status quo data, and potential effects of the decisions available today. In addition, in order to advise the woodworking industry on how best to tackle the challenges it faces in establishing a verifiable role in the achievement of national targets, the cause and effect of changes in the specific environmental impacts need to be understood in the context of their effect on the development of the complete sector.
A broadening of the applicability of the results presented in this dissertation could be achieved by including other European countries within the monitoring and by implementing other sustainability aspects beside environmental impacts.

4.4.3 *Policy*

From the viewpoint of political actors, the policy implementations need to be evaluated with regard to their effectiveness in reaching the respective targets. To improve the evaluation options, policy should separate the end use sector "woodworking" industry from the aggregated industry monitoring and recognize that this has been already found by European Commission (2011), stating that "the lack of detailed data in all end-use sectors is a major challenge" and that there are "no good data also of how much CO_2 emission are emitted by the end-use sectors because the current statistical reporting procedure assigns the emissions from electricity and heating to the energy sector".

BIBLIOGRAPHY

[ADEME 2013] ADEME: Energy efficiency in the European Union : trends and policies Lessons from the ODYSSEE MURE project . ODYSEE-MURE Project, Enerdata, ADEME. URL http://www.ademe.fr/, 2013. – 72 p

[BDEW 2013] BDEW: *Statistische Daten des Bundesverband der Energie- und Wasserwirtschaft e.V.: Brutto-Stromerzeugung 2012 nach Energieträgern in Deutschland.* 2013. – URL www.bdew.de. – Access date: 2014-03-06

[BDI et al. 2012] BDI ; BDEW ; BMWI ; BMU ; BMF: Vereinbarung zwischen der Regierung der Bundesrepublik Deutschland und der deutschen Wirtschaft zur Steigerung der Energieeffizienz vom 1. August 2012. IVB3 - 32 51 08 /2. Berlin : Bundesanzeiger, Bundesministerium der Justiz und für Verbraucherschutz, 2012. – 9 p. – URL http://www.bmjv.de

[Benetto et al. 2009] Benetto, Enrico ; Becker, Marko ; Welfring, Joëlle: Life cycle assessment of oriented strand boards (OSB): from process innovation to ecodesign. *Environmental science & technology* 43 (2009), August, Nr. 15, pp. 6003–9. – URL http://www.ncbi.nlm.nih.gov/pubmed/19731710. – ISSN 0013-936X

[Bergman and Bowe 2008a] Bergman, Richard D. ; Bowe, Scott A.: Environmental impact of producing hardwood lumber using life cycle inventory. *Wood And Fiber Science* 40 (2008), Nr. 3, pp. 448–458. – URL http://www.swst.org/publications/wfs/

[Bergman and Bowe 2008b] Bergman, Richard D. ; Bowe, Scott A.: Life-Cycle Inventory of Hardwood Lumber Manufacturing in the Northeast and North Central United States, CORRIM : Phase II, Final Report Module C . Consortium for Research on Renewable Industrial Materials. Seattle, WA, USA : University of Washington, 2008. – 54 p. – URL http://www.corrim.org

[Bergman and Bowe 2009] Bergman, Richard D. ; Bowe, Scott A.: Life-Cycle Inventory of Softwood Lumber Manufacturing in the Northeastern and North Central United States, CORRIM Phase II, Final Report Module D . Consortium for Research on Renewable Industrial Materials. Seattle, WA, USA : University of Washington, 2009. – 56 p. – URL http://www.corrim.org

[Bergman and Bowe 2010a] Bergman, Richard D. ; Bowe, Scott A.: Environmental impact of manufacturing softwood lumber in northeastern and north central United States. *Wood And Fiber Science*

42 (2010), Nr. CORRIM Special Issue, pp. 67–78. – URL http://www.swst.org/publications/wfs/

[Bergman and Bowe 2010b] Bergman, Richard D. ; Bowe, Scott A.: Life-Cycle Inventory of Hardwood Lumber Manufacturing in the Southeastern United States, CORRIM: Phase II, Final Report Module L . Consortium for Research on Renewable Industrial Materials. Seattle, WA, USA : University of Washington, 2010. – 56 p. – URL http://www.corrim.org

[BMWi 2014] BMWi: Zweiter Monitoring-Bericht Energie der Zukunft . Bundesministerium für Wirtschaft und Energie. Berlin, 2014. – 148 p. – URL http://www.bmwi.de/DE/Mediathek/publikationen,did=634268.html

[BMWi and BMU 2012] BMWi ; BMU: Monitoring Energie der Zukunft. Vorbereitung des ersten Berichtes 2012 für das Berichtsjahr 2011 - Indikatoren zur öffentlichen Diskussion . Bundesministerium für Wirtschaft und Technologie, Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. Berlin, 2012. – 10 p. – URL http://www.bmwi.de/DE/Themen/Energie/Energiewende/monitoring-prozess.html

[Brandão et al. 2014] Brandão, Miguel ; Clift, Roland ; Cowie, Annette ; Greenhalgh, Suzie: The Use of Life Cycle Assessment in the Support of Robust (Climate) Policy Making: Comment on Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation .... *Journal of Industrial Ecology* 18 (2014), Nr. 3, pp. 461–463. – URL http://doi.wiley.com/10.1111/jiec.12152. – ISSN 10881980

[BSI 2011] BSI: PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services . The British Standards Institution. London, 2011. – URL http://shop.bsigroup.com/en/forms/PASs/PAS-2050/

[CEN 2011] CEN: EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method . European Committee for Standardization. Brussels, 2011. – 55 p. – URL http://www.cen.eu

[Cespi et al. 2013] Cespi, Daniele ; Passarini, Fabrizio ; Ciacci, Luca ; Vassura, Ivano ; Castellani, Valentina ; Collina, Elena ; Piazzalunga, Andrea ; Morselli, Luciano: Heating systems LCA: comparison of biomass-based appliances. *The International Journal of Life Cycle Assessment* 19 (2013), June, Nr. 1, pp. 89–99. – URL http://link.springer.com/10.1007/s11367-013-0611-3. – ISSN 0948-3349

[Defra 2009] Defra: Guidance on how to measure and report your greenhouse gas emissions. London : Department for Environment, Food and Rural Affairs, 2009. – 75 p. – URL https://www.gov.uk/government/publications/guidance-on-how-to-measure-and-report-your-greenhouse-gas-emissions

[Department of Energy and Climate Change 2012] Department of Energy and Climate Change: *European Energy Efficiency, Analysis of ODYSSEE indicators*. 2012

[Destatis 2010a] Destatis: Produktion des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden . Statistisches Bundesamt. Wiesbaden, 2010. – 1–300 p. – URL https://www.destatis.de/DE/Publikationen/Thematisch/IndustrieVerarbeitendesGewerbe/Konjunkturdaten/ProduktionVj.html. – ISBN 2040310107004

[Destatis 2010b] Destatis: Rohholz und Holzhalbwaren, Arbeitsunterlage . Statistisches Bundesamt. Wiesbaden, 2010. – URL https://www.destatis.de/DE/Publikationen/Thematisch/IndustrieVerarbeitendesGewerbe/Fachstatistik/RohholzHolzhalbwaren.html

[Destatis 2012a] Destatis: Erhebung über die Energieverwendung. Wiesbaden. directly available at publisher : Statistisches Bundesamt, 2012

[Destatis 2012b] Destatis: Fachserie 4 Reihe 3.1, Produzierendes Gewerbe, Produktion des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden 2011 . Statistische Bundesamt. Wiesbaden, 2012. – 300 p. – URL https://www.destatis.de/DE/Publikationen/Thematisch/IndustrieVerarbeitendesGewerbe/Konjunkturdaten/ProduktionVj.html

[Destatis 2014a] Destatis: Fachserie 18 Reihe 2, Volkswirtschaftliche Gesamtrechnungen, Input-Output-Rechnung. Wiesbaden : Statistisches Bundesamt, 2014. – 116 p. – URL https://www.destatis.de/DE/ZahlenFakten/GesamtwirtschaftUmwelt/VGR/InputOutputRechnung/InputOutputRechnung.html

[Destatis 2014b] Destatis: *Statistic database: Energy use in the industry 2012*. 2014. – URL www.destatis.de/EN/FactsFigures/EconomicSectors/Energy/Use/Tables/EconomicBranch12.html. – Access date: 2014-03-06

[Dias 2013] Dias, Ana C.: Life cycle assessment of fuel chip production from eucalypt forest residues. *International Journal of Life Cycle Assessment* (2013), pp. 1–13. – URL http://link.springer.com/article/10.1007/s11367-013-0671-4. – ISSN 09483349

[Diederichs 2014a] DIEDERICHS, Stefan: 2010 Status quo for life-cycle inventory and environmental impact assessment of the core sawmill products in Germany. *Wood And Fiber Science* 46 (2014), Nr. 1, pp. 65–84. – URL http://www.swst.org/publications/wfs/

[Diederichs 2014b] DIEDERICHS, Stefan: 2010 Status quo for life cycle inventory and environmental impact assessment of wood-based panel products in Germany. *Wood And Fiber Science* 46 (2014), Nr. 3, pp. 1–16. – URL http://www.swst.org/publications/wfs/

[Diederichs 2015] DIEDERICHS, Stefan: Monitoring Energy Efficiency and Environmental Impact of the Woodworking Industry in Germany. *Submitted to European Journal of Wood and Wood Products* (2015)

[Diederichs and Rüter 2011] DIEDERICHS, Stefan ; RÜTER, Sebastian: Deviation of LCI results from primary industry data and application of derived LCA in the framework of sustainable construction certification schemes using the example of glue laminated timber. CALDEIRA, Fernando (Editor.) ; FERREIRA, Jose V. (Editor.) ; PETRIC, Marco (Editor.) ; ROWELL, Roger M. (Editor.): *Minimizing the environmental impact of the forest product industries*. Porto, 2011, pp. 17–24. – ISBN 9789896430832

[Diederichs and Rüter 2012a] DIEDERICHS, Stefan ; RÜTER, Sebastian: Ökobilanzen für Holz-Bauprodukte : Voraussetzung für die Nachhaltigkeitsbewertung von Gebäuden. *Holzbau* (2012), Nr. 2, pp. 17–19

[Diederichs and Rüter 2012b] DIEDERICHS, Stefan ; RÜTER, Sebastian: Ökobilanzierung zur Ermittlung von Umweltkennwerten von Holzprodukten. *7. Europäischer TMT-Workshop*. Dresden : IHD, 2012, pp. 91–100

[Döring and Mantau 2012] DÖRING, Przemko ; MANTAU, Udo: Standorte der Holzwirtschaft -Sägeindustrie - Einschnitt und Sägenebenprodukte 2010 . Universität Hamburg, Zentrum Holzwirtschaft, Arbeitsbericht Ökonomie der Holz- und Fortwirtschaft. Hamburg, 2012. – 50 p

[Earles and Halog 2011] EARLES, J. M. ; HALOG, Anthony: Consequential life cycle assessment: A review. *International Journal of Life Cycle Assessment* 16 (2011), March, pp. 445–453. – URL http://www.springerlink.com/index/10.1007/s11367-011-0275-9. – ISBN 0948-3349 1614-7502

[EEA 2014] EEA: *European PRTR and EPER Database*. 2014. – URL http://prtr.ec.europa.eu. – Access date: 2014-01-01

[Ekvall and Weidema 2004] Ekvall, Tomas ; Weidema, Bo P.: System boundaries and input data in consequential life cycle inventory analysis. *The International Journal of Life Cycle Assessment* 9 (2004), May, Nr. 3, pp. 161–171. – ISSN 0948-3349

[EN 15804:2012-04 2012] EN 15804:2012-04: *Nachhaltigkeit von Bauwerken, Umweltdeklarationen für Produkte, Grundregeln für die Produktkategorie Bauprodukte*. 2012

[EPF 2012] EPF: *Annual Report 2011-2012*. 2012

[European Commission 2010a] European Commission: ILCD Handbook, Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessement . European Commission, Joint Reserach Centre, Institute for Environment and Sustainability. Ispra, 2010. – 115 p. – URL http://eplca.jrc.ec.europa.eu/

[European Commission 2010b] European Commission: ILCD Handbook, General Guide for Life Cycle Assessment - Detailed Guidance . European Commission, Joint Reserach Centre, Institute for Environment and Sustainability. Ispra, 2010. – 414 p. – URL http://eplca.jrc.ec.europa.eu/

[European Commission 2010c] European Commission: ILCD Handbook, Specific guide for Life Cycle Inventory data sets . European Commission, Joint Reserach Centre, Institute for Environment and Sustainability. Ispra, 2010. – 139 p. – URL http://eplca.jrc.ec.europa.eu/

[European Commission 2011] European Commission: Impact assessment, communication from the Commission to the European Parliament, The Council, the European Economic and Social Committee and the Committee of the regions Commission Staff Working Document, Energy Efficiency Plan 2011, SEC(2011) 277. Official Journal of the European Union, 2011. – URL http://eur-lex.europa.eu/

[European Commission 2013a] European Commission: Commisson recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. Official Journal of the European Union, 2013. – 210 p. – URL http://eur-lex.europa.eu/

[European Commission 2013b] European Commission: Progress towards achieving the Kyoto and EU 2020 objectives, COM(2013) 698 . Report from the Commission to the European Parliament and the Council. Brussels : Official Journal of the European Union, 2013. – URL http://eur-lex.europa.eu/

[European Commission 2013c] European Commission: *Renewable energy progress report, COM(2013) 175 final*. 2013. – URL http://eur-lex.europa.eu/

[European Commission DG A.3 2012] European Commission DG A.3: *Guidance Document Biomass issues in the EU ETS, MRR Guidance document No. 3, Final Version of 17 October 2012*. 2012. – URL http://ec.europa.eu/

[European Parliament and Council of the European Union 2013] European Parliament ; Council of the European Union: Decision No 529/2013/EU of the European Parliament and of the Council of 21 May 2013 on accounting rules on greenhouse gas emissions and removals resulting from activities relating to land use, land-use change and forestry and ... Brussels : Official Journal of the European Union, 2013. – 18 p. – URL http://eur-lex.europa.eu/

[Fleiter et al. 2013] Fleiter, Tobias ; Schlomann, Barbara ; Eichhammer, Wolfgang: *Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien - Einsparpotenziale, Hemmnisse und Instrumente*. 2013

[Frondel et al. 2013] Frondel, Manuel ; Timmen, Ronald Janß en ; Ritter, Nolan: Statusbericht 2011 und 2012 zur Umsetzung der Vereinbarung zwischen der Bundesrepublik Deutschland und der deutschen Wirtschaft zur Klimavorsorge vom 9. November 2000 . Rheinisch-Westfälisches Institut für Wirtschaftsforschung. Essen, 2013. – 21 p. – URL http://www.rwi-essen.de/forschung-und-beratung/umwelt-und-ressourcen/projekte/157/

[Frühwald et al. 2000a] Frühwald, A ; Speckels, Lutz ; Scharai-Rad, M ; Welling, J.: Ökologische Bilanzierung von Bauschnittholz und veredelten Vollholzprodukten, Ordinariat für Holztechnologie der Universität Hamburg, Hamburg . Universität Hamburg. 2000

[Frühwald et al. 2010] Frühwald, Arno ; Diederichs, Stefan ; Morgan, Ruth: Verwendungspotentiale heben durch Kaskadennutzung am Beispiel Holz. *Erneuerbare Energie, Band 4*. TK Verlag - Fachverlag für Kreislaufwirtschaft, 2010, pp. 37–50

[Frühwald et al. 2000b] Frühwald, Arno ; Scharai-Rad, M ; Hasch, Joachim: *Ökologische Bewertung von Holzwerkstoffen Schlußbericht März 2000 Ergänzt in den Bereichen Spanplattenrecycling und OSB- Bilanzen*. 2000

[Ganne-Chedeville and Diederichs 2014] Ganne-Chedeville, Christelle ; Diederichs, Stefan K.: LCA of an in-development ultralight particleboard. Kutnar, Andreja (Editor.) ; Humar, Miha (Editor.) ; Burnard, Michael (Editor.) ; Zlahtic, Mojca (Editor.) ; Jones, Dennis (Editor.): *Proceedings of COST FP1303-meeting in Kranjska Gora (23-24.10.2014), Performance and maintenance of bio-based building materials influencing the life cycle and LCA*. Ljubljana : University of Ljubljana, 2014, pp. 61–62. – ISBN 978-961-6822-22-0

[Ganne-Chédeville and Diederichs 2015] Ganne-Chédeville, Christelle ; Diederichs, Stefan K.: Potential environmental benefits of ultralight particleboards with bio-based foam cores. *Int J Polymer Science* 2015 (2015), Nr. ID 383279, pp. 14

[Gärtner et al. 2013] Gärtner, Sven ; Hienz, Gunnar ; Keller, Heiko ; Müller-Lindenlauf, Maria: Gesamtökologische Bewertung der Kaskadennutzung von Holz - Umweltauswirkungen stofflicher und energetischer Holznutzungssysteme im Vergleich . ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH. Heidelberg, 2013. – 110 p. – URL `https://www.ifeu.de/`

[González-García et al. 2011] González-García, Sara ; Gasol, Carles M. ; Lozano, Raúl G. ; Moreira, María T. ; Gabarrell, Xavier ; Rieradevall i Pons, Joan ; Feijoo, Gumersindo: Assessing the global warming potential of wooden products from the furniture sector to improve their ecodesign. *The Science of the total environment* 410-411 (2011), December, pp. 16–25. – URL `http://www.ncbi.nlm.nih.gov/pubmed/22000917`. – ISSN 1879-1026

[González-García et al. 2013] González-García, Sara ; Krowas, Inga ; Becker, Gero ; Feijoo, Gumersindo ; Moreira, María T.: Cradle-to-gate life cycle inventory and environmental performance ofÂ Douglas-fir roundwood production in Germany. *Journal of Cleaner Production* 54 (2013), September, pp. 244–252. – URL `http://linkinghub.elsevier.com/retrieve/pii/S0959652613003193`. – ISSN 09596526

[Guinée 2002] Guinée, Jeroen B. (Editor.): *Handbook on Life Cycle Assessment, Operational Guide to the ISO Standards*. New York, Boston, Dordrecht, London, Moscow : Kluwer Academic Publishers, 2002. – 687 p. – ISBN 1-4020-0228-9

[Gustavsson et al. 2006] Gustavsson, Leif ; Pingoud, Kim ; Sathre, Roger: Carbon dioxide balance of wood substitution: Comparing concrete- and wood-framed buildings. *Mitigation and Adaptation Strategies for Global Change* 11 (2006), pp. 667–691. – ISBN 1102700672071

[Hasch 2002] Hasch, Joachim: *Ökologische Betrachtung von Holspan- und Holzfaserplatten*, Universität Hamburg, Dissertation, 2002

[Helin et al. 2014] Helin, Tuomas ; Holma, Anne ; Soimakallio, Sampo: Is land use impact assessment in LCA applicable for forest biomass value chains? Findings from comparison of use of Scandinavian wood, agro-biomass and peat for energy. *The International Journal of Life Cycle Assessment* 19 (2014), February, Nr. 4, pp. 770–785. – URL http://link.springer.com/10.1007/s11367-014-0706-5. – ISSN 0948-3349

[Ingerson 2011] Ingerson, Ann: Carbon storage potential of harvested wood: Summary and policy implications. *Mitigation and Adaptation Strategies for Global Change* 16 (2011), Nr. 3, pp. 307–323. – URL http://link.springer.com/10.1007/s11027-010-9267-5. – ISBN 1102701092

[ISO 2007] ISO: *ISO 14025:2006, Environmental labels and declarations - Type III environmental declarations - Principles and procedures (ISO 14025:2006); Text in German and English.* 2007. – URL www.iso.org

[ISO 14044:2006 2006] ISO 14044:2006: *Environmental management - Life cycle assessment - Requirements and guidelines*. 2006. – URL www.iso.org

[Jungmeier et al. 2002] Jungmeier, Gerfried ; Werner, Frank ; Jarnehammar, Anna ; Hohenthal, Catharina ; Richter, Klaus: Allocation in LCA of wood-based products experiences of cost action E9. *The International Journal of Life Cycle Assessment* 7 (2002), Nr. 6, pp. 369–375. – URL http://www.springerlink.com/content/w5h3070684802251/. – ISSN 0948-3349

[Kline 2005] Kline, D E.: Gate-to-gate life-cycle inventory of oriented strandboard production. *Wood and Fiber Science* 37 (2005), Nr. Corrim Special Issue, pp. 74–84. – URL http://www.swst.org/publications/wfs/

[Lechtenböhme et al. 2014] Lechtenböhme, Stefan ; Knopf, Brigitte ; Bauer, Nico ; Durand, Antoine ; Hanke, Thomas ; Luhmann, Hans-Jochen ; Samadi, Sascha ; Schmid, Eva ; Schneider, Clemens: Kosten- und Modellvergleich langfristiger Klimaschutzpfade (bis 2050) . Umweltbundesamt. Dessau-Rosslau, Germany, 2014. – 353 p. – URL http://www.umweltbundesamt.de/publikationen/kosten-modellvergleich-langfristiger

[Lewandowska and Matuszak-Flejszman 2014] Lewandowska, Anna ; Matuszak-Flejszman, Alina: Eco-design as a normative element of Environmental Management Systems-the context of the revised ISO 14001:2015. *The International Journal of Life Cycle Assessment* (2014), July. – URL http://link.springer.com/10.1007/s11367-014-0787-1. – ISSN 09483349

[Lippke et al. 2005] Lippke, Bruce ; Comnick, Jeffrey ; Johnson, Leonard R.: Environmental Performance Index for the Forest. *Wood And Fiber Science* (2005), Nr. 37 Corrim Special Issue, pp. 149–155. – URL http://www.swst.org/publications/wfs/

[Lippke et al. 2010] Lippke, Bruce ; Wilson, Jim ; Meil, Jamie ; Taylor, Adam: Characterizing the importance of carbon stored in wood products. *Wood And Fiber Science* (2010), Nr. 42 Corrim Special Issue, pp. 5–14. – URL http://www.swst.org/publications/wfs/

[Lund et al. 2010] Lund, Henrik ; Mathiesen, Brian V. ; Christensen, Per ; Schmidt, Jannick H.: *Energy system analysis of marginal electricity supply in consequential LCA*. February 2010. – URL http://www.springerlink.com/index/10.1007/s11367-010-0164-7

[Mantau and Bilitewski 2010] Mantau, Udo ; Bilitewski, Bernd: Stoffstrom-Modell- Holz 2007, Rohstoffströme und CO2-Speicherung in der Holzverwendung, Forschungsbericht für das Kuratorium für Forschung und Technik des Verbandes der Deutschen Papierfabriken e.V. (VDP) . intectus, infro. Celle, 2010. – 77 p

[McGraw-Hill Construction 2013] McGraw-Hill Construction: *World Green Building Trends: Business Benefits Driving New and Retrofit Market Opportunities in Over 60 Countries SmartMarket Report Executive*. 2013. – URL http://www.worldgbc.org/

[Merciai and Heijungs 2014] Merciai, Stefano ; Heijungs, Reinout: Balance issues in monetary input-output tables. *Ecological Economics* 102 (2014), June, pp. 69–74. – URL http://linkinghub.elsevier.com/retrieve/pii/S0921800914000962. – ISSN 09218009

[Mertens et al. 2014] Mertens, Oliver ; Diederichs, Stefan ; Meyer, Melanie: Energiemanagement und Ökosteuer Anforderungen und monetäre Bedeutung am Beispiel der deutschen Sägeindustrie . Thünen Institute of Wood Research. Braunschweig : Thünen Institut, 2014. – 36 p. – URL https://www.econstor.eu/dspace/bitstream/10419/95867/1/781017513.pdf

[Milota et al. 2005] Milota, Michael R. ; West, Cynthia D. ; Hartley, Ian D.: Gate to gate life cycle inventory of softwood lumber production. *Wood And Fiber Science* (2005), Nr. 37 CORRIM Special Issue, pp. 47–57. – URL http://www.swst.org/publications/wfs/

[Moberg et al. 2014] Moberg, Å s. ; Borggren, Clara ; Ambell, Christine ; Finnveden, Göran ; Guldbrandsson, Fredrik ; Bondesson, Anna ; Malmodin, Jens ; Bergmark, Pernilla: Simplifying a life cycle assessment of a mobile phone. *The International Journal of Life Cycle Assessment* 19 (2014), February, pp. 979–993. – URL http://link.springer.com/10.1007/s11367-014-0721-6. – ISBN 0948-3349

[Nabuurs et al. 2007] Nabuurs, G.J. ; Masera, O. ; Andrasko, K. ; Benitez-Ponce, P. ; Boer, R. ; Dutschke, M. ; Elsiddig, E. ;

Ford-Robertson, J. ; Frumhoff, P. ; Karjalainen, T. ; Krankina, O. ; Kurz, W.A. ; Matsumoto, M. ; Oyhantcabal, W. ; Ravindranath, N.H. ; Sanchez, M.J. S. ; Zhang, X.: Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA., 2007. – URL http://www.ipcc.ch/publications_and_data/ar4/wg3/en/contents.html

[Osterburg et al. 2009] Osterburg, Bernhard ; Röder, Norbert ; Elsasser, Peter ; Oef, Matthias D. ; Krug, Joachim: Analyse ausgewählter internationaler Studien und Dokumente über Kosten und Potentiale der Minderung von Treibhausgasemissionen sowie des Aufbaus und der Erhaltung von C-Senken im deutschen Agrar- und Forstsektor . Johann Heinrich von Thünen-Institut. Braunschweig und Hamburg, 2009

[Osterburg et al. 2013] Osterburg, Bernhard ; Rüter, Sebastian ; Freibauer, Annette ; De Witte, Thomas ; Elsasser, Peter ; Kätsch, Stephanie ; Leischner, Bettina ; Paulsen, Hans M. ; Rock, Joachim ; Röder, Norbert ; Sanders, Jürn ; Schweinle, Jörg ; Steuk, Johanna ; Stichnote, Heinz ; Stürmer, Wolfgang ; Welling, Johannes ; Wolff, Anne: Handlungsoptionen für den Klimaschutz in der deutschen Agrar- und Forstwirtschaft . Johann Heinrich von Thünen-Institut. Braunschweig, 2013. – 158 p. – ISBN 9783865761163

[Parliament and Council of the EU 2009] Parliament and Council of the EU: DIRECTIVE 2009/29/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community. Brussels : Official Journal of the European Union, 2009. – URL http://eur-lex.europa.eu/

[Parliament and Council of the EU 2012] Parliament and Council of the EU: *Directive 2012/27/EU on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC*. 2012. – URL http://ec.europa.eu/

[Plevin et al. 2014a] Plevin, Richard J. ; Delucchi, Mark a. ; Creutzig, Felix: Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers. *Journal of Industrial Ecology* 18 (2014), February, Nr. 1, pp. 73–83. – URL http://doi.wiley.com/10.1111/jiec.12074. – ISBN 10881980

[Plevin et al. 2014b] Plevin, Richard J. ; Delucchi, Mark A. ; Creutzig, Felix: Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers.

Journal of Industrial Ecology 18 (2014), May, Nr. 3, pp. 73–83. – URL http://doi.wiley.com/10.1111/jiec.12153. – ISBN 10881980

[Poudel et al. 2012] Poudel, Bishnu C. ; Sathre, Roger ; Bergh, Johan ; Gustavsson, Leif ; Lundström, Anders ; Hyvönen, Riitta: Potential effects of intensive forestry on biomass production and total carbon balance in north-central Sweden. *Environmental Science and Policy* 15 (2012), January, Nr. 1, pp. 106–124. – ISBN 1462-9011

[Puettmann et al. 2010] Puettmann, Maureen E. ; Wagner, Francis G. ; Johnson, Leonard: Life cycle inventory of softwood lumber from the inland northwest US. *Wood And Fiber Science* (2010), Nr. 42 CORRIM Special Issue, pp. 52–66. – URL http://www.swst.org/publications/wfs/

[Puettmann and Wilson 2005] Puettmann, Maureen E. ; Wilson, James B.: Life-cycle analysis of wood products: cradle-to-gate LCI of residential wood building materials. *Wood And Fiber Science* (2005), Nr. 37 CORRIM Special Issue, pp. 18–29. – URL http://www.swst.org/publications/wfs/

[Rentz et al. 2009] Rentz, Otto ; Oertel, Dagmar ; Woodfield, Mike ; Stewart, Robert: Manufacturing industries and construction (combustion). Chapter 1.A.2. *EMEP/EEA air pollutant emission inventory guidebook 2009*. Copenhagen, Denmark : European Environmental Agency, 2009, pp. 34

[Ressel 1986] Ressel, Jörg: Energieanalyse der Holzindustrie der Bundesrepublik Deutschland . Bundesforschungsanstalt für Forst- und Holzwirtschaft, Institut für Holzphysik und mechanische Technologie des Holzes. Universität Hamburg, 1986

[Rivela et al. 2006] Rivela, Beatriz ; Hospido, Almudena ; Moreira, MÂª T. ; Feijoo, Gumersindo: Life Cycle Inventory of Particleboard : A Case Study in the Wood Sector. *International Journal of life cycle assessment* 11 (2006), Nr. 2, pp. 106 – 113

[Rivela et al. 2007] Rivela, Beatriz ; Moreira, Ma T. ; Feijoo, Gumersindo: Life cycle inventory of medium density fibreboard. *The International Journal of Life Cycle Assessment* 12 (2007), Nr. 3, pp. 143–150. – ISSN 0948-3349

[Rüter 2010] Rüter, Sebastian: Consideration of Wood Products in Climate Policies and its Linkage to Sustainable Building Assessment Schemes. *Proceedings of the 53rd International Convention of Society of Wood Science and Technology and United Nations Economic Comission for Europe - Timber Committee October 11-14*. Geneva : UNECE/FAO Timber Section, 2010, pp. 88–101

[Rüter and Diederichs 2012] Rüter, Sebastian ; Diederichs, Stefan: Ökobilanz-Basisdaten für Bauprodukte aus Holz . Johann Heinrich von Thünen Institut, Institut für Holztechnologie und Holzbiologie. Hamburg, 2012. – 299 p

[Sander 2014] Sander, Julian: *Bereitstellung von Grundlagendaten zur Erstellung von Umwelt-Produktdeklarationen (EPD) für Holzprodukte der Binderholz Deutschland GmbH - Erweiterung des Energiemanagementsystems zur Erfüllung der Datenanforderung der Umweltbewertung durch EPD.*, Dissertation, 2014

[Sathre and O'Connor 2010] Sathre, Roger ; O'Connor, Jennifer: Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science and Policy* 13 (2010), April, Nr. 2, pp. 104–114. – ISBN 1462-9011

[Schweinle and Thoroe 2001] Schweinle, Jörg ; Thoroe, Carsten: Vergleichende Ökobilanzierung der Rundholzproduktion in verschiedenen Forstbetrieben . Bundesforschungsanstallt für Forst und Holzwirtschaft. Hamburg, 2001

[Seppäläa et al. 2005] Seppäläa, Jyri ; Melanen, Matti ; Mäenpää, Ilmo ; Koskela, Sirkka ; Tenhunen, Jyrki ; Hiltunen, Marja-Riitta: How Can the Eco-efficiency of a Region be Measured and Monitored? *Journal of Industrial Ecology* 9 (2005), October, Nr. 4, pp. 117–130. – URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-84876901083&partnerID=tZOtx3y1`. – ISBN 1088-1980

[Silva et al. 2013] Silva, Diogo Aparecido L. ; Lahr, Francisco Antonio R. ; Garcia, Rita P. ; Freire, Fausto Miguel Cereja S. ; Ometto, Aldo R.: Life cycle assessment of medium density particleboard (MDP) produced in Brazil. *The International Journal of Life Cycle Assessment* 2013 (2013), May, Nr. 18, pp. 1404–1411. – ISSN 0948-3349

[Stassen et al. 2012] Stassen, Oliver ; Tirschmann, Johannes ; Barbu, Marius C. ; Hoepner, Wolf-Dieter ; Rüter, Sebastian: Einsparmöglichkeiten nicht ausgeschöpft. *Holz-Zentralblatt* (2012), Nr. 28, pp. 734–735

[Sturm et al. 2002] Sturm, Andreas ; Mueller, Kaspar ; Upasena, Suji: *A Manual for Preparers and Users of Eco-efficiency Indicators: Conceptual Framework and Guidelines*. Geneva, 2002. – 126 p. – ISBN 92-1-112620-7

[Suh and Yang 2014] Suh, Sangwon ; Yang, Yi: On the uncanny capabilities of consequential LCA. *International Journal of Life Cycle Assessment* 19 (2014), April, pp. 1179–1184. – URL `http://link.springer.com/10.1007/s11367-014-0739-9`. – ISBN 0948-3349

[Timmermann and Dibdiakova 2014] Timmermann, Volkmar ; Dibdiakova, Janka: Greenhouse gas emissions from forestry in East Norway. *The International Journal of Life Cycle Assessment* (2014), July, pp. 1593–1606. – URL http://link.springer.com/10.1007/s11367-014-0773-7. – ISBN 0948-3349

[Tsunetsugu and Tonosaki 2010] Tsunetsugu, Yuko ; Tonosaki, Mario: Quantitative estimation of carbon removal effects due to wood utilization up to 2050 in Japan: effects from carbon storage and substitution of fossil fuels by harvested wood products. *Journal of Wood Science* 56 (2010), April, Nr. 4, pp. 339–344. – URL http://www.springerlink.com/index/10.1007/s10086-009-1107-4. – ISSN 1435-0211

[UBA 2014] UBA: Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto-Protokoll 2014, Nationaler Inventarbericht Zum Deutschen Treibhausgasinventar 1990 - 2012. Dessau-Rosslau, Germany : Umweltbundesamt, 2014. – 964 p. – URL http://www.umweltbundesamt.de/publikationen/berichterstattung-unter-der-klimarahmenkonvention

[UNFCCC 2011] UNFCCC: Land use, land-use change and forestry (Decision 2/CMP.7) . United Nations Framwork Convention on Climate Change. URL http://unfccc.int/resource/docs/2011/cmp7/eng/10a01.pdf, 2011

[United Nations 2012] United Nations: Doha amendment to the Kyoto Protocol. United Nations Framework Convention on Climate Change, 2012. – 6 p

[Wagner et al. 2009] Wagner, Francis G. ; Puettmann, Maureen E. ; Johnson, Leonard R.: Life Cycle Inventory of Inland Northwest Softwood Lumber Manufacturing, CORRIM : Phase II Final Report Module B . Consortium for Research on Renewable Industrial Materials. Seattle, WA, USA : University of Washington, 2009. – 72 p. – URL http://www.corrim.org

[Weidema 2003] Weidema, Bo: Market information in life cycle assessment . 2.-0 LCA Consultants, Danish Environmental Protection Agency, Environmental Project. 2003

[Weidema et al. 2009] Weidema, Bo P. ; Ekvall, Tomas ; Heijungs, Reinout: Guidelines for application of deepened and broadened LCA . ENEA, The Italian National Agency on new Technologies, Energy and the Environment Project. 2009. – 49 p

[Weidema et al. 1999] Weidema, Bo P. ; Frees, Niels ; Nielsen, Anne-Merete: *Marginal production technologies for life cycle inventories*. January 1999

[Weidema and Schmidt 2010] Weidema, Bo P. ; Schmidt, Jannick H.: *Avoiding Allocation in Life Cycle Assessment Revisited*. April 2010. – URL http://doi.wiley.com/10.1111/j.1530-9290.2010.00236.x

[Wenker et al. 2015] Wenker, Jan L. ; Achenbach, Hermann ; Diederichs, Stefan ; Rüter, Sebastian: Life cycle assessment of wooden interior doors in Germany - A sector representative approach for a complex wooden product according to EN 15804 methodology. *Accepted at Journal of Industrial Ecology* (2015)

[Werner et al. 2007a] Werner, Frank ; Althaus, Hans-Jörg ; Künniger, Tina ; Richter, Klaus ; Jungbluth, Niels: Life Cycle Inventories of Wood as Fuel and Construction Material, ecoinvent report No.9 . EMPA, ESU. Dübendorf, 2007. – 176 p

[Werner et al. 2007b] Werner, Frank ; Althaus, Hans-jörg ; Richter, Klaus ; Scholz, Roland W.: Post-Consumer Waste Wood in Attributive Product LCA Context specific evaluation of allocation procedures in a functionalistic conception of LCA. *International Journal of life cycle assessment* 12 (2007), Nr. 3, pp. 160 – 172

[Werner et al. 2010] Werner, Frank ; Taverna, Ruedi ; Hofer, Peter ; Thürig, Esther ; Kaufmann, Edgar: National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. *Environmental Science and Policy* 13 (2010), pp. 72–85. – ISBN 1462-9011

[Wilson 2008] Wilson, James B.: Particleboard : A Life-Cycle Inventory of Manufacturing Panels from Resource through Product, CORRIM Phase II, Final Report Module F . Consortium for Research on Renewable Industrial Materials. Seattle, WA, USA : University of Washington, 2008. – 57 p. – URL http://www.corrim.org

[Wilson 2010a] Wilson, James B.: Life-cycle inventory of medium density fiberboard in terms of resources, emissions, energy and carbon. *Wood And Fiber Science* 42 (2010), Nr. CORRIM Special Issue), pp. 107–124

[Wilson 2010b] Wilson, James B.: Life-cylce inventory for particleboard in terms of resources, emissions, energy and carbon. *Wood And Fiber Science* (2010), Nr. 42 CORRIM Special Issue, pp. 90–106. – URL http://www.swst.org/publications/wfs/

[Wilson and Sakimoto 2005] Wilson, James B. ; Sakimoto, Eric T.: Gate-to-gate Life-Cycle Inventory of Softwood Plywood Production. *Wood And Fiber Science* (2005), Nr. 37 Corrim special Issue, pp. 58–73. – URL http://www.swst.org/publications/wfs/

[Wright et al. 2008] Wright, Heather E. ; Zhang, Qiong ; Mihelcic, James R.: Integrating economic input-output life cycle assessment with risk assessment for a screening-level analysis. *International Journal of Life Cycle Assessment* 13 (2008), April, Nr. 5, pp. 412–420. – ISBN 0948-3349\r1614-7502

[Wünsch et al. 2012] Wünsch, Marco ; Seefeld, Friedrich ; Schlomann, Barbara ; Fleiter, Tobias ; Gerspacher, Andreas ; Rohde, Clemens ; Geiger, Bernd ; Kleeberger, Heinrich: Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 . Umweltbundesamt. Dessau-Rosslau, Germany, 2012. – 91 p. – URL `http://www.umweltbundesamt.de/publikationen/datenbasis-zur-bewertung-von`

Part II

PUBLICATIONS

2010 STATUS QUO FOR LIFE-CYCLE INVENTORY AND ENVIRONMENTAL IMPACT ASSESSMENT OF THE CORE SAWMILL PRODUCTS IN GERMANY

*S.K. Diederichs**

Research Associate
Thuenen Institute of Wood Research
21031 Hamburg, Germany
E-mail: stefan.diederichs@ti.bund.de

(Received June 2013)

Abstract. Product life-cycle assessment (LCA) is an established tool for supporting decisions on the consumer, business, and policy levels. LCA practitioners are in need of continuously updated average LCA data in line with current methodological developments and consensus for supporting decisions with environmental information. For sawmill products, where large deviations in terms of environmental impact among the many single sawmills are known to exist, detailed surveys on LCA data with high sector representativeness are needed to yield reliable average data. Based on a representative study on German sawmills, this article provides detailed environmental average life-cycle inventory and impact assessment data and variations for the production of the four core products of the German sawmill industry setting a status quo for 2010.

Keywords: Life-cycle inventory, LCI, life-cycle assessment, LCA, lumber, energy, emissions, carbon.

INTRODUCTION

Environmental Impacts of Products

Environmental product life-cycle assessment (LCA) in accordance with ISO 14044 (ISO 2006a) is an established tool for supporting decisions on the consumer, business, and policy levels. It has been extensively used as a scientific tool and its methodology has continuously been optimized and adapted. Three stakeholder levels can be distinguished.

On the consumer level, benchmarking and eco-labeling based on LCA results and ISO 14025 (ISO 2006b) have been introduced and standardized internationally over the last decades. Carbon footprints in accordance with ISO/DIS 14067 (ISO 2013) or PAS 2050 (BSI 2011) using a similar methodology have been introduced, and the most widely used tools in Europe for sustainable constructions—"Deutsche Gesellschaft für Nachhaltiges Bauen" (DGNB) and "BRE Environmental Assessment Method" (BREEAM)—rely on LCA.

On the manufacturing or business level, costs are the commanding variable for decisions. The bottom line is that environmental issues will only be considered if the return of investment occurs early enough. This can be indirectly achieved if labels based on LCA can succeed in convincing the discerning consumer to ask for the environmentally friendly product. Further on, LCA combined with material flow analysis can provide valuable information for hot spot analysis of environmental impacts and energy efficiency measures.

On the policy level, LCA has been used as a tool, especially to justify decisions on the choice of biofuels, packaging, construction material and food, and their production systems, respectively. Databases for LCA data on building products have been introduced at national levels and databases for a wider spectrum of processes and products have been introduced on the European level. The German government's "National Action Plan on Material Use of Renewable Resources" (BMELV 2009) entitles LCA to serve as the essential tool for measuring the sustainability of renewable products, while the

* Corresponding author

implementation and development of LCA databases is found to be crucial to estimate the CO_2-emission reduction for a new climate regime.

Sawmill Products and Life-Cycle Assessment

Available life-cycle assessment data for sawmill products. In 2010, Germany was the world's fifth largest producer of sawnwood behind Brazil, the Russian Federation, China, Canada, and the United States (FAO 2010). Wood products from German sawmills are broadly used in the construction sector but also for packaging and furniture, while the byproducts are either used as raw material for wood-based panels or for paper or fuel.

Due to this distinctive conjunction of sawmill products and byproducts with many sectors of industry, private consumers, and exports, information on sawmill products is needed for a variety of life-cycle considerations with LCA as one of the most appropriate tools to evaluate environmental aspects.

LCA for sawmill products has been conducted in several studies. Recently, major research efforts were done for US sawmills (Puettmann and Wilson 2005; Bergman and Bowe 2008a, 2008b, 2009, 2010a, 2010b; Wagner et al 2009). Werner et al (2007) conducted LCA for wood products in Switzerland. Fruehwald et al (2000) conducted the first comprehensive LCA for sawmill products in Germany.

Requirements of life-cycle assessment for sawmill products. Classical, comparative LCA, in terms of decision support for potentially environmentally friendly options, can only be conducted successfully if its methodological framework is chosen well and its data requirements can be satisfied. As a rule, the targeted application of the LCA results determines its system boundaries. Therefore it also defines the required boundary and representativeness of the raw data needed to conduct the LCA. Since the methodological choices are often unique, especially for comparative LCA studies, practitioners need updated, transparently documented and disaggregated life-cycle inventory (LCI) data. Particularly the system boundaries and representativeness of the LCI data need to be described clearly to enable a consistent combination of several LCI data sets.

LCA raw data can be applied in the form of site-specific or average data. Site-specific data are certainly applied in studies for specific manufacturers, where identification of hot spots and optimization potentials is based on site-specific detailed information. If choices affect several companies, site-specific data cannot be applied, though.

Average data are required for most LCA studies. This applies for company-independent product labeling at the consumer level, where site-specific data (eg as published in some environmental product declarations [EPD]) is usually not available for all production facilities of a product (BMVBS 2011).

On the policy level, average data with high representativeness are indispensable. The role of wood as a building material and/or fuel plays a significant role within the scope of national CO_2-emission reduction potentials in the shape of product substitution, carbon storage in wood products, and substitution of fossil fuels. Not less important but more a side show of LCA are bottom-up approaches to account for environmental impacts of complete industry sectors. For example, in Germany, essential industrial tax benefits are tied to energy efficiency developments of an industry sector (EU 2011; BDI BDEW, BMWI, BMU, BMF 2012; StromStG 2012). In this context, average sector LCA data help uncover efficiency measures which are primarily based on outsourcing energy consumption to other sectors or countries.

Challenges of average data acquisition for sawmill products. Doering and Mantau (2012) counted a total of 2194 sawmills in Germany in the year 2010. Official but less comprehensive numbers are available from DESTATIS (2010a), identifying 404 sawmills in 2010, but excluding companies with fewer than 20 employees. It becomes obvious that the German sawmill sector is characterized by a large number of sawmills. With regard to information on production volumes from Doering and Mantau (2012), where 37.4% of the sawlog input is handled by at least 803 medium-sized producers (2,500-200,000 m^3/year sawlogs input), it can further be assumed that the sector is characterized by a large number of small- and medium-sized companies.

Due to the need of average data for products, the variance between site-specific LCA data, which is the basis for average LCA data, becomes important. Although most studies do not offer this kind of information, differences in specific parts of production processes offer an insight to the variances. Ressel (1985) documented the differences in the context of energy consumption issues in the sawmill sector. A comparison of the specific energy consumption of sawmill processes published in several studies from different countries showed large differences on the country level (Tables 1-3). It can therefore be concluded that reliable average data for the sawmill sector need a sound data basis.

Project Background

With this problem background, the OekoHolzBauDat project was launched in 2009. Detailed LCA data were gathered by surveys and site visits at 43 German sawmills which produced a total of 5 million m^3 per year sawnwood in 2009/2010/2011 (survey was done over a period of 3 years), which equaled 26% of the total German production in 2010. Later, data were gathered from 27 other sawmills, which were not able to supply full data sets but provided useful complementary information. The OekoHolzBauDat project focused on supplying highly aggregated LCA data for building products following requirements of the EPD core product category rule EN 15804 (EN 2012; Rueter and Diederichs 2012).

It is the aim of this article to supply average detailed LCI and Environmental Impact Assessment (LCA) data on the production of the core wood-based products of the German sawmill sector. The data are presented in a disaggregated form, allowing a wide range of applications and is transparently documented, allowing consistent combination with other LCI data sets.

DATA AND METHODOLOGY

General Claim

The results within this article are described in terms of their representativeness, system boundaries, limitations, and methodological issues. They can be used as background data in the context of today's typical environmental assessment tasks, namely carbon footprints based on PAS 2050 or IS0 14067, environmental LCA based on ISO 14044, and EPD based on ISO 14025. The data can also be considered as valid for EPD based on the core product category rule for building products EN 15804 and

Table 1. Electricity consumption (kWh/m^3 output) of processes in comparison with other studies (coniferous), $\bar{x}_{volume\,weighted}$: average electricity consumption weighted by production volume (margin represents different electricity consumption for different products), and $Q_{0.05}/\bar{x}_{arithm}/Q_{0.95}$: 5% fractile/arithmetic average/95% fractile of distribution of company results (not weighted by production volume).

	Reference	Debarking (D)	Milling (M)	Total D + M	Kiln-drying	Planing
Study	$\bar{x}_{volume\,weighted}$	2.2-2.7	15.3-17.7	19.4-21.8	21.6-22	22.8
	$Q_{0.05}/\bar{x}_{arithm}/Q_{0.95}$	1.1/3.0/5.3	9.9/20.3/30.0	12.3/25.2/40.9	5.7/22.5/50.4	2.7/20/56.2
Other studies	Bergman and Bowe 2010a			52.64	24.54	19.53
	Puettmann et al 2010	1.80	19.00	20.81	16.71	34.09
	Milota et al 2005 (West)			45.35	26.69	16.75
	Milota et al 2005 (South)			34.43	28.66	13.92
	Werner et al 2007	4.50	28.20	32.70	25.00	31.00
	Fruehwald et al 2000			23.15	20.28	27.72
	Average of other studies	3.15	23.60	34.85	23.65	23.83

Table 2. Fuel consumption (MJ/m^3 output) ([%] from total) of drying and heating in comparison with other studies (coniferous), $\bar{x}_{volume\,weighted}$: average electricity consumption weighted by production volume, and $Q_{0.05}/\bar{x}_{arithm}/Q_{0.95}$: 5% fractile/arithmetic average/95% fractile of distribution of company results (not weighted by production volume).

	Reference	Wood fuel	Oil and gas	Total
Study	$\bar{x}_{volume\,weighted}$ [a]	2052 (99.5)	11 (0.5)	2063 (100)
	$Q_{0.05}/\bar{x}_{arithm}/Q_{0.95}$	(79.8/94.5/100)	(0/5.5/20.2)	713/2864/6505 (100)
Other studies	Bergman and Bowe 2010a	1803 (87.3)	263 (12.7)	2066 (100)
	Puettmann et al 2010	1066 (52.5)	966 (47.5)	2032 (100)
	Milota et al 2005 (West)[b]	—	—	2739
	Milota et al 2005 (South)[b]	—	—	3099
	Werner et al 2007	—	—	959
	Fruehwald et al 2000	—	—	903
	Average of other studies	—	—	1966

[a] Average use of fuel for kiln-dried products.
[b] Heating value of steam.

as background data sets for attributional modeling approaches described in the ILCD Handbook (EC 2010). Last but not least, the described products present the main outputs of the German sawmill sector defined in national statistics, allowing input–output LCA studies for the sector.

Survey

The LCI and LCA results in this article are based on surveys done during the OEKOHOLZBAUDAT project. More than 70 sawmills supplied data; 43 of these supplied information for a complete LCI. Several site visits were conducted comparing emission protocols and electricity consumption bills. The survey was conducted over a period of 3 years.

The Functional Units

The sawmill sector was defined by including all utilized processes necessary to convert sawlogs (received at the gate of the sawmill site) into one of the following core products that leave the sawmill sector:

Sawnwood, coniferous, green or air-dried;
Sawnwood, coniferous, kiln-dried;
Sawnwood, coniferous, kiln-dried, planed; and
Sawnwood, nonconiferous, kiln-dried.

In each case, the production of 1 m^3 of product is defined as the functional unit of the system under study. To be precise, each functional unit is an equivalent of 1 m^3 at a MC of 12%. Therefore 1-m^3 equivalent of green sawnwood actually is slightly larger than 1 m^3. The oven-dry mass is not affected by this. Undried, nonconiferous sawnwood is not considered, since there is no relevant market for it. Planed nonconiferous sawnwood is not considered, since the process of nonconiferous wood planing was assigned to the flooring, furniture, or solid wood products industry.

Table 3. Electricity consumption of processes in comparison with Bergman and Bowe (2008b) (nonconiferous) (kWh/m^3 output).

Process	Study	Bergman and Bowe 2008b
Debarking	6	
Milling	49.7	
Debarking and milling	55.7	62.27
Kiln drying	57.8	31.13

Sawmill Processing

The essential process steps in the sawmill industry are debarking, sawing, drying, and planing. The auxiliary processes are the combustion of fuels for heat supply, compressors supplying pressurized air, extraction to remove dust and equipment to withdraw byproducts from the main processes, and other infrastructural energy-consuming processes such as electric lighting. Products leaving the site are stacked and—for dried products—wrapped in plastic.

Debarking. This is the first on-site process. Logs are brought from the log yard to the stationary debarking unit by forklift or rail crane. They are scanned for metal (screws, shrapnel, etc.), butt ends are reduced if necessary, and logs are debarked and cut to length. They are sorted by diameter and conveyed to sorting boxes or directly to the sawing process. Byproducts are reducer chips, a mixture of large chips and bark, pure bark from debarking, and minor amounts of sawdust from cutting.

Debarking consumes electricity and large amounts of pressurized air in some cases. Additionally, diesel and engine oil is needed for the forklifts, or electricity for the cranes, respectively. Lubricants and cutting tools are needed for the machines. On-site emissions arise from diesel combustion. The intermediate product is debarked sawlogs.

Sawing. Coniferous sawlogs are sawn (or milled) by a chipper canter in combination with circular saws. On rare occasions, gang and band saws are used.

Sawing of nonconiferous sawlogs is primarily done by gang or band saw, sometimes in combination with circular saws. The applied technologies differ mainly in terms of the alignment (chaining) of processes, feeding speed, yield, and quality of the byproducts. These can be hogged chips, chips, sawdust, and edgings or rejected core products. The latter two are mostly chipped down to smaller pieces and can be summarized as chips.

Besides lubricants and cutting tools, the process consumes electricity and pressurized air. Extraction removal by vacuum is usually not needed since particles are mainly withdrawn by conveyer belts. Only for nonconiferous sawmills is the sawdust occasionally withdrawn with exhaust systems. Since particles are not considered in this study (see chapter Data Gaps), no relevant on-site emissions are connected to the process.

The core or intermediate products are undried or air-dried coniferous and nonconiferous sawnwood.

Drying. This is done in convection driers with only a few marginal exceptions. Sawnwood is piled up with kiln stickers and loaded into the kilns with forklifts. After the drying procedure, which reduces the MC down to an average of 14% or down to 8% for some nonconiferous products, the stacks are brought to the next process step by forklifts. They are destacked and kiln stickers are removed for reuse. The drying procedure consumes water and thermal energy for evaporation of water, diesel for the forklifts, and electricity for the fans. Byproducts are generated insofar as small parts of the load are rejected in the following sorting procedure and chipped down to wood chips. On-site emissions arise directly from diesel combustion and kilns.

The core or intermediate products are kiln-dried coniferous and nonconiferous sawnwood.

Planing. In this article, we only consider planing of coniferous sawnwood. Kiln-dried coniferous sawnwood is planed in conventional or planar calibrating processes on at least one side of the product, but mostly on all four sides. Planing in this context includes the generation of profiles and grooves (tongue and groove) as well.

The process consumes electricity, lubricants, cutting tools, and pressurized air. Planing chips (byproducts) are extracted by vacuum. The core product is kiln-dried, planed coniferous sawnwood. No relevant on-site emissions are connected to the process.

Auxiliary processes. All auxiliary processes consume electricity. Heat and on-site electricity generation consume wood fuels and fossil fuels. Wood fuels are brought to the combustion with either conveyer belts or forklifts which consume diesel and engine oil or electricity. On-site emissions arise from combustion of diesel, wood fuels, and fossil fuels.

System Boundaries

The primary (foreground) system boundaries include debarking, milling, sawing, and drying as well as auxiliary processes. Transportation on site as well as heating of the buildings and electric lighting is likewise included.

From an environmental point of view, the foreground system includes all relevant emissions that evolve directly on the production sites as there are emissions from the diesel burned in the vehicles used on site, emissions that directly evolve from the kilns, and obviously all emissions that come from the combustion processes (Fig 1).

The secondary (background) system boundaries include all other emissions which are not directly emitted on site. The background system is further divided into forestry, transport of sawlogs and all other generic background data for material, and energy consumed by the sawmill industry (sawmill, gate-to-gate).

A differentiation between the supply of sawlogs and the supply of (for example) fuels in terms of different system boundaries is made. This is based on two considerations.

While inputs and outputs of an industrial sector are always linked to several other sectors, there are sectors that are linked very closely to each other and others that are linked not as closely. The closeness is best described by pointing out the relevance of products from one sector to the needs of another. For example, chances are low that the oil-refining industry would go through structural changes because the amount of diesel used by sawmills differs or even doubles, while the structure of forestry is likely to change if sawmills only needed half as many sawlogs. This context has been comprehensively described by Weidema and Frees (1999).

Hence, monitoring changes of the sawmill industry based on the changes of consumption of energy and other products by the sawmill sector imply that every unit consumed more or

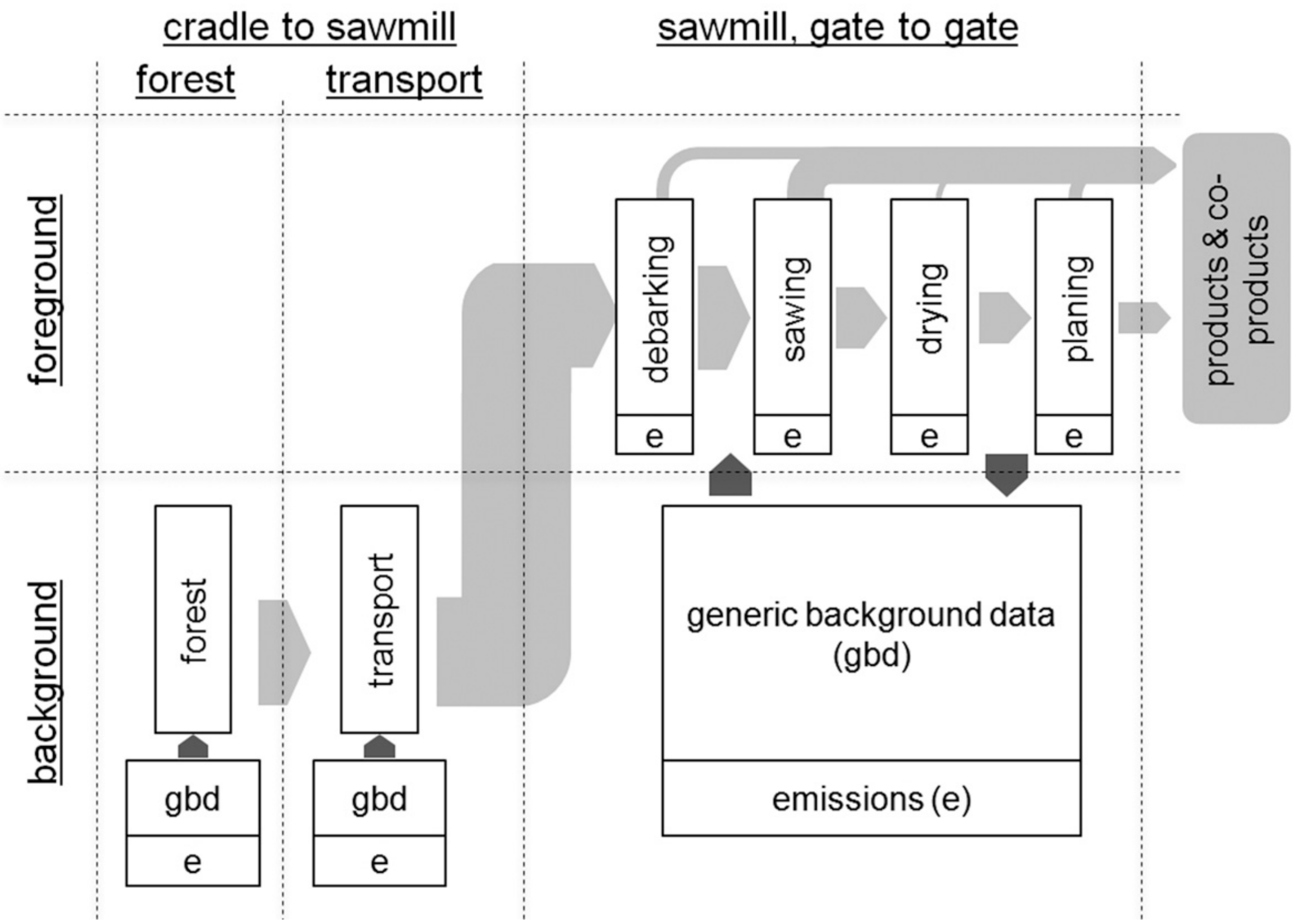


Figure 1. System boundaries and subsystem boundaries of the analyzed production system.

less by the sawmill industry has the same environmental impact, further implying that no structural change is forced by the change in demand. Since this is particularly ambiguous for the consumption of wood, it was separated from other inputs to the sawmill sector in terms of system boundaries. This will help to use the presented data for change-oriented LCA studies.

Second, the forestry system boundaries include all processes needed to produce sawlogs processed by the sawmill either as material or fuel. All material-inherent characteristics, like carbon or calorific value of dry mass, are balanced among forestry products, wood burned on site, and sawmill products.

Figure 2 shows the typical carbon balance of solid wood products. The carbon dioxide, captured in the trees which are harvested for material or energetic use, is accounted for as negative "emission." Wood burned on site and all other carbon dioxide emissions based on the combustion of fossil fuels are accounted for as emissions. Since it is assumed that all wood products will be burned at the end of life (EoL) (or given to another product life cycle), the carbon stored in the product will be released as carbon dioxide (or accounted for as positive output within this system and negative input in the next product system). The total carbon balance of the life cycle therefore equals the emissions of carbon dioxide resulting from combustion of fossil fuels and other greenhouse gas emissions from nonbiomass. It also includes the emissions resulting from combustion of wood, but since in this case, the carbon dioxide is captured from the atmosphere and given back within the same system boundary, it has no effect on the cradle-to-grave emissions of the wood products. In passing it should be noted that a potential effect on the total amount of greenhouse gases in the atmosphere due to the carbon stored in the wood products needs to be considered separately from this.

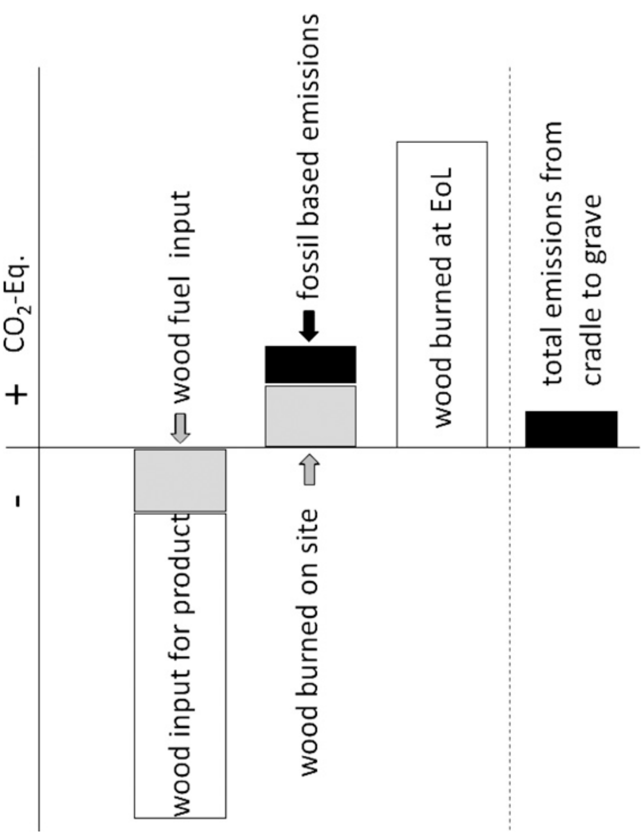


Figure 2. Carbon balance of sawmill products.

Therefore it is absolutely necessary to keep carbon dioxide emissions as a result of burning wood separate from "negative" emission resulting from carbon stored in wood. Separating forestry by subboundaries as done in this article precludes potential calculation errors.

Background Data

Generic background data for sawlog production was taken from Schweinle (1996) and Albrecht et al (2008). The wood species used for coniferous sawnwood were assumed to be pine (*pinus sylvestris*) and spruce (*picea abies*) with a weighted medium density of 450 kg/m^3 (oven-dry mass); nonconiferous sawnwood was assumed to be beech (*fagus sylvatica*) and oak (*quercus*) with weighted medium density of 680 kg/m^3 (oven-dry mass) (FNR BMELV 2004; BMELV 2010).

Sawlogs transport models are based on Borcherding (2007) and EC (2010). The model for emissions from the kiln-drying process is based on Wagner et al (2009), who reported several emissions to air from which volatile organic compound with 0.167 kg/m^3 was the leading emission. The electricity grid mix model is based on AG Energiebilanzen e V. (2010) and

PE International (2012). It results in 572 kg CO_2-Eq./kWh, which is in the range of official data from UBA (2012) which calculated 577 kg CO_2-Eq./kWh for 2009 and estimated 562 kg CO_2-Eq./kWh for 2010. Information on emissions from burning of wood is based on Reitberger et al (2001), Speckels (2001), Tsupari et al (2005), and Boehmer et al (2010). For each emission reported in the cited literature, its contribution to the indicators global warming potential (GWP), acidification potential (AP), photochemical ozone creation potential (POCP), and eutrophication potential (EP) was analyzed. All substances which were responsible for more than 15% of at least one indicator were modeled as a function of filter technique, fuel type, and combustion size according to data from Kaltschmitt and Hartmann (2009). Those substances are CO_2, CO, CH_4, SO_2, and NOx. If companies did not supply information on their combustion technique, the worst (but still legal) case was assumed for these substances. For emissions responsible for 1-15% of at least one indicator, the average value from the literature was chosen. All substances which were responsible for less than 1% are based on data from Speckels (2001) who analyzed the emissions of 18 wood combustion plants in detail. All together, 68 substances are taken into account. A comparison of the resulting average emissions to emission published by Rentz et al (2009) resulted in high confidentiality for emissions relevant for the environmental indicators published in this article. All of them are within the 95% confidence interval for typical emissions from "combustion in industry using biomass" listed in Rentz et al (2009). All other data were based on PE International (2012). Detailed information about the modeling principles is documented in Rueter and Diederichs (2012).

Allocations

Product-specific results refer to a specific unit of a product. However, since the production of sawnwood also leads to byproducts (bark, chips, etc.) that can be used in other product systems (eg wood-based panels), input and output flows need to be allocated to core and byproducts. This allocation can be done on the basis of mass, economic value, or other physical or nonphysical relationships and has been broadly discussed for sawnwood (see Jungmeier et al 2002)). Because the type of allocation used limits the applicability of the LCI data, the inventory in Table 4 shows the unallocated LCI. It describes the quantities of all material and energetic flows which enter or leave the foreground gate-to-gate system boundary. This includes all byproducts that evolve in the processes. Exceptions apply for electricity as one of two products from combined heat and power plants (see subsequently).

An allocated LCI, which was used for the impact assessment, only includes those inputs and outputs that were allocated to the functional units (the core products of the sawmill sector). The allocation procedures were based on different systematics and comply with ISO 14044 and EN 15804 (Rueter and Diederichs 2012).

Allocation inside gate-to-gate boundaries. Within the foreground system, processes that produce core products and byproducts at the same time are debarking, sawing, drying, and planing. The input of wood as a raw material to a process that produces core and byproducts was allocated on the basis of oven-dry mass of the wood (allocation by physical relationship).

The input of heat and electricity to a process (and its supporting auxiliary processes like extraction and pressurized air) that produces core and byproducts was allocated on the basis of market prices of the products (Table 5). For example, the price of 1 m^3 bark is 10% of the price of 1-m^3 debarked sawlogs. If 8% of a log consists of bark, 0.8% of the electricity used for debarking is allocated to the bark, while 99.2% is allocated to the logs. This reflects the intention of the process to have maximum economic yield while producing the core products and complies with EN 15804 and suggestions of EC (2010).

Thermal energy for heating and electric energy for illumination of the buildings was completely

Table 4. Life-cycle inventory for the declared units (unallocated).

Flow	Unit	C g	C kd	NC kd	C pl
Inputs					
Material					
Sawlogs	m^3	1.82	2.03	2.06	2.21
Fuels					
Residues (on site)	MJ	—	1677	4913	2031
Residues (off site)	MJ	—	72.6	1285	42.7
Recovered wood	MJ	—	217	—	199
Fuel oil (light)	MJ	—	1.9	—	1.5
Gas	MJ	—	0.0	—	3.7
Plant oil	MJ	—	3.5	—	5.7
Logistics on site					
Diesel	kg	0.9	1.3	1.6	1.7
Engine oil	g	15.6	25.4	40.7	28.7
Electricity (from grid)					
Process	kWh	18.7	36.8	105.5	58.4
Infrastructure	kWh	3.1	6.6	18.7	13.8
Equipment					
Lubricants	g	90.8	114.3	170.6	137.9
Steel	g	5.8	13.0	44.8	22.4
Drinking water	kg	2.4	19.2	13.6	25.5
Surface water	kg	6.7	32.1	19.9	33.5
Wrapping					
Polymers	g	—	312.0	168.0	677.0
Wood	g	1471	1760	3125	3871
Paper and cardboard	g	24.0	34.0	—	81.0
Steel	g	88.0	341.0	997.0	228.0
Outputs					
Product (wrapped)					
Sawnwood product	m^3	1	1	1	1
Byproducts					
Bark	m^3	0.172	0.202	0.206	0.220
Chips, dust, and cuttings	m^3	0.655	0.825	0.854	0.990
Waste					
Solid waste	kg	0.097	0.127	0.215	0.160
Water	kg	9.079	51.31	33.45	59.01
Emissions (direct)					
CH_4	g	—	19.6	96.1	23.4
CO	g	13.1	73.4	320	97.3
CO_2 (from fossil fuels)	kg	2.60	4.37	4.97	5.69
N_2O	g	—	0.460	1.95	0.486
NMVOC	g	4.36	49,1	109	55.1
SO_2	g	3.29	28,6	121	34.9
NOx	g	42.0	328	1376	403
Lead	mg	—	308	1539	371
Cadmium	mg	—	0.693	3.46	0.835
Mercury	µg	—	62.9	310	75.2
Arsenic	mg	—	14.4	72.1	17.4
Chromium	mg	—	13.3	66.4	16.0
Copper	mg	—	148	744	179
Nickel	mg	—	73.5	363	88.7
Zinc	mg	—	0.318	1.52	0.372

C g, coniferous sawnwood, green; C kd, coniferous sawnwood, kiln-dried; NC kd, nonconiferous sawnwood, kiln-dried; C pl, coniferous sawnwood, planed; NMVOC, nonmethane volatile organic compounds.

Table 5. Relative price of byproducts to core products (Rueter and Diederichs 2012) (large chips refer to typical chips from chipper canters, small chips are all chips smaller than this).

Core product	Byproduct	Relative price
Sawlogs	Industrial wood	60%
Sawlogs debarked	Bark	10%
Sawnwood, green	Large chips	30%
	Small chips	25%
	Dust	25%
Sawnwood, kiln dried	Chips and other	16%
Sawnwood, planed	Chips	12%

allocated to the core products, since they would not have been installed for the productions of byproducts only. Diesel, engine oil, and all other equipment were allocated to the core products for the same reason.

Allocation procedures for electricity produced on site by combined heat and power plants (CHP) was based on energy of the two products. As an exception, the unallocated LCI actually includes this CHP input allocation. The reason is the widespread decoupling of electricity production from the sawmill production process in terms of economic and fuel supply dependency. As a consequence of the available subsidies for electricity from biomass in Germany, the amount of electricity generated by the CHP is the crucial factor for the investment to be worthwhile. In some cases, the investment for the CHP is much higher than the investment for the sawmill. In other words, the production of electricity (by CHP) on site is not much or not at all influenced by more or less production of sawnwood or, respectively, byproducts. On-site electricity production by CHP and its supply with fuel is therefore defined outside the system boundaries.

Allocation procedures for background data. For the impact assessment, LCI results of the foreground system were connected to data on forestry, transport, and generic background data. Here, allocation procedures were applied as described in the accompanying documentations of the data sources. For forestry operations, allocation was based on market prices of sawlogs and industrial wood.

Cutoff Rules and Assumptions

Based on other LCA results for sawmill products, every flow exceeding 1% of the total used primary energy was included, whereas all neglected flows did not exceed 5% of this indicator. Obviously, flows that were below this threshold but were known anyway were included. Capital goods like buildings and machinery were not included in terms of their production, since the associated impacts were assumed to not exceed 1% of the total.

The transport distances for other materials than wood were assumed to be 50 km. The transport distances for wood were modeled specific for each company.

The on-site emissions from combustion of wood fuel were modeled to supply information for the impact categories published in this article. The indicator ODP was not used for the emissions sensitivity analysis, since the normalized result (Germany 2001 data from Universiteit Leiden 2010)) for wood combustion emissions was less than 1% of the result from the indicator EP. Therefore, it was assumed that ODP was sufficiently represented without being modeled as a function of filter technique, fuel type, and combustion size.

Data Gaps

Several other emissions without an influence on the presented impact categories, especially heavy metals, are listed in the LCI. They were compared with official data from Rentz et al (2009). Emission data for cadmium, arsenic, chromium, and nickel agree very well with those reported there. Emissions of mercury and zinc are smaller by factor 5 to 8 in this article; emissions of copper and lead are higher by factor 5 to 2.5. For other emissions to the atmosphere listed by Rentz et al (2009), no data were collected. These substances are selenium, polychlorinated biphenyls, polychlorinated dibenzodioxins, Benzo(a)pyren, Benzo(b)fluoranthene, Benzo (k)fluoranthene, Indeno(1,2,3-cd)pyrene, and hexachlorbenzene. If the LCI date is used to evaluate impact categories where these substances are relevant, special attention should be paid. The emissions from combustion of diesel only consider substances relevant for the reported impact categories.

No data were available for the wheels used on site as well as the wrapping material for the equipment. In other words, the equipment was assumed to enter the company without any wrapping since the impact was assumed to be negligible. Nevertheless, the wrapping of the products is included.

Impact Assessment

The impact assessment covers six impact categories defined in EN 15804, which are GWP for 100 yr, AP, EP, POCP, stratospheric ozone depletion potential (ODP), and abiotic resource depletion potential (ADP). For ADP, two subcategories exist. ADPe describes the depletion of elements of non-fossil resources and ADPf the depletion of fossil fuels. Classification and characterizations of emissions is based on definitions published by Universiteit Leiden (2010). Carbon dioxide emissions evolving from oxidization of carbon contained in biomass and photosynthetic capture of carbon dioxide to carbon contained in biomass are not included in the GWP100 category for the reason described previously (Fig 2). For the GWP indicator, this article focuses on carbon dioxide emissions based on the combustion of fossil fuels and other emissions that are not CO_2 from wood combustion. However, biogenic carbon dioxide uptake and emissions can be easily calculated based on LCI and dry mass of wood and the system shown in Fig 2.

RESULTS

Gate-to-Gate Life-Cycle Inventory

Table 5 shows the gate-to-gate foreground LCI of all functional units.

Coniferous sawnwood, green or air-dried. To produce 1 m^3 of the product, about 1.826 m^3 of sawlogs with bark enter the mill. Debarking consumes 3.7 kWh for the process and 0.6 kWh for infrastructural demands. Taking price allocation into account, the production of 1 m^3 of bark consumes 0.27 kWh of electricity. After sorting by dimension and/or quality, 1.58 m^3 of debarked saw logs are brought to the infeed of the mill and converted to 1 m^3 of sawnwood. The process consumes 17.5 kWh electricity from which 2.5 kWh is for infrastructural demands. Taking price allocation into account, the production of 1 m^3 of chips at this process consumes 4.01 kWh. Total yield from sawlogs with bark to sawnwood is 54.7%.

Direct on-site emissions arise mainly from combustion of diesel. Considering the impact categories within this article, the most relevant emissions are 2.6 kg of carbon dioxide (GWP), 42 g nitrogen oxide (AP, EP, POCP), and 4 g of nonmethane volatile organic compounds (NMVOC) (POCP).

Coniferous sawnwood, kiln-dried. This product is produced by technical drying of sawnwood. Despite the fact that more sawlogs are needed, the specific energy demand for debarking is very much the same as for undried sawnwood, while milling is slightly more energy-efficient (−12%). Although the same processes are applied for the production, not all sawmills produce dried sawnwood. Therefore the group of analyzed companies was different for the two products, resulting in different specific energy demand for the processes.

Kiln-drying is the most energy-consuming procedure of all sawmill processes. For the production of 1 m^3 kiln-dried coniferous sawnwood, 21.9 kWh of electricity and 1968 MJ of fuel are consumed; 85% of those are byproducts from on-site production (mainly bark). Eleven percent are recovered wood. Four percent are bought from other sawmills or landscaping, while only 0.2% are fossil fuels.

The drying chambers are loaded using forklifts which are mainly powered by diesel engines. This process step consumes about 0.4 kg of diesel/m^3 of kiln-dried coniferous sawnwood. Compared with on-site emissions from the production of green sawnwood, the emissions from the kilns and wood combustion outweigh diesel emissions in the context of AP, EP, and POCP. For GWP, methane emitted from wood combustion is only responsible for 7% of the on-site GWP relevant emissions. Diesel emissions still have the lead. Remember that carbon dioxide emissions from combustion of wood are not considered here.

Emissions relevant for the other impact categories (AP and EP) are predominantly 328 g of nitrogen oxide from wood combustion (79%) and diesel engines (20%) as well as 49.1 g of NMVOC from wood combustion (28%), drying kilns (52%), and diesel (13%).

Coniferous sawnwood, kiln-dried, planed. The planing of the kiln-dried sawnwood consumes 22.8 kWh of electricity. Diesel consumption for this step is at about 0.3 kg/m^3. Fuel consumption for kiln-drying here is higher than for kiln-dried sawnwood, since about 1.09 m^3 of kiln-dried sawnwood is needed to produce 1 m^3 of planed sawnwood and the group of analyzed companies was different. The specific fuel consumption is slightly higher for the same reasons. Compared with kiln-dried sawnwood, the share of recovered wood used for fuel (9%) was lower. The amount of fossil fuels again is negligible (0.3%). Since no on-site emissions arise from planing (except the surplus of diesel emissions), the distribution of emissions to their sources is very much the same as on-site emissions from kiln-dried coniferous sawnwood.

Non-coniferous sawnwood, kiln-dried. Production of non-coniferous sawnwood differs strongly from the production of coniferous sawnwood. Yield is only slightly higher, but consumption of electricity is close to three times as high. No definite statement can be made on the distribution of electricity consumption between processes. Since only two mills took part in the survey for nonconiferous sawnwood, and no process-specific consumption of electricity was measured on site, only total consumption for the product was determined.

A total of 6198 MJ of wood fuel is consumed by the kilns, from which 80% is taken from on-site production. While coniferous wood mills are in most cases able to meet their heat demand solely by combustion of bark produced on-site (this depends on the season of the year and moisture content of the bark, respectively), nonconiferous wood mills can cover only 50% to 60% of their fuel demand by bark produced on site. About 20-30% are nonbark residues from on-site production; another 20% are residues bought from other sawmills or landscaping.

Diesel consumption is slightly higher than for kiln-dried coniferous sawnwood, but specific consumption of engine oil (kilograms oil per kilogram diesel) is about 25% higher than in coniferous wood mills. The quantity of direct emissions on site is predominantly driven by the combustion of wood.

Equipment, wrapping, and waste. Lubricants and steel to maintain the equipment are used for all main products and therefore increase from green sawnwood to planed sawnwood. Water is used mainly for drying but also for wet storage of the wood. All inputs result in waste flows.

Regarding the mass, wood has the biggest share among the used wrapping materials. Besides this, polymers, especially polyethylene foil and steel, play a significant role.

Cradle-to-Gate and Gate-to-Gate Impact Assessment and Energy Demand

Primary energy demand. Table 6 shows the input of primary energy for each functional unit. From cradle to gate, 544 MJ of primary energy consumption is allocated to the production of 1 m^3 of green sawnwood. The consumption of primary energy for kiln-dried products is significantly higher due to high energy demand for drying processes. Drying coniferous sawnwood consumes four times more than producing green sawnwood. A total of 637 MJ is additively consumed if the kiln-dried coniferous sawnwood is planed. Kiln-drying in nonconiferous wood production consumes about three times more primary energy than drying of coniferous sawnwood.

Table 6. Primary energy consumption (MJ).

Source	C g	C kd	NC kd	C pl	Ren
Forestry and Transport					
Sawlogs (material)	8,672	8,672	13,104	8,672	100%
Forest operations	204	244	336	253	1%
Transport to mill	71	93	186	97	2%
Total (nonmaterial)	275	337	522	350	
Sawmill					
Diesel	41	66	79	88	0%
Electricity	227	514	1,515	806	13%
Wood fuel (on site)	—	1,677	4,913	2,031	100%
Wood fuel (off site)	—	290	1,285	242	100%
Fossil fuel	—	2	—	5	0%
Others (material)	7	48	39	58	0%
Total (nonmaterial)	268	2,549	7,791	3,173	
Total (nonmaterial)	544	2,886	8,313	3,522	
Total (all)	9,223	11,605	21,456	12,253	

C g, coniferous sawnwood, green; C kd, coniferous sawnwood, kiln-dried; NC kd, nonconiferous sawnwood, kiln-dried; C pl, coniferous sawnwood, planed; Ren: share of renewables.

Since drying chambers are predominantly run by heat, generated from wood fuel, the total share of primary energy from renewables is 70-80% for the three kiln-dried products, but only 6% for the green coniferous sawnwood.

Global warming potential. Table 7 shows total cradle-to-gate LCA results with the relative share of each subsystem defined in Fig 1.

For dried and planed products, greenhouse gas (GHG) emissions are caused mainly by the generation of electricity in the background gate-to-gate system and by the combustion of diesel for on-site logistics in the foreground gate-to-gate system. In contrary, cradle-to-gate emissions of green sawnwood originate mainly from the forest and transport systems (60%).

Figure 3 shows the relevance of every process from forest to dried planed sawnwood products for the GWP indicator based on the results for planed coniferous sawnwood. Most of the emission sources originate from background system (black), while major on-site emissions (gray) evolve mainly from on-site logistics (debarking) and drying (kilns and combustion).

For all products, 15 to 18 kg of CO_2-Eq. is emitted during forestry operations. About 95% of those emissions are carbon dioxide, 3% are methane emissions, and 2% are nitrous oxide emissions. Seventy-seven percent of the CO_2 emissions is emitted by forestry machinery and 15% by wet storage procedures.

Table 7. LCA results.

Flow	C g	C kd	NC kd	C pl
Foreground, Gate to Gate				
GWP	8%	11%	9%	11%
AP	17%	54%	74%	56%
EP	18%	58%	78%	60%
POCP	18%	79%	80%	78%
ODP	0%	0%	0%	0%
ADPe	0%	0%	0%	0%
ADPf	0%	1%	1%	0%
Background, Gate to Gate				
GWP	33%	46%	59%	55%
AP	13%	12%	10%	16%
EP	6%	6%	5%	8%
POCP	10%	4%	5%	6%
ODP	87%	92%	95%	95%
ADPe	100%	100%	100%	100%
ADPf	37%	52%	62%	61%
Transport				
GWP	15%	12%	11%	9%
AP	15%	8%	5%	7%
EP	17%	8%	6%	8%
POCP	12%	3%	3%	3%
ODP	1%	0%	0%	0%
ADPe	0%	0%	0%	0%
ADPf	17%	14%	14%	11%
Forest				
GWP	44%	31%	21%	24%
AP	55%	26%	11%	22%
EP	59%	27%	12%	24%
POCP	60%	14%	13%	13%
ODP	13%	7%	4%	5%
ADPe	0%	0%	0%	0%
ADPf	46%	34%	23%	27%
Total				
GWP (kg)	32.9	56.6	116.2	73.5
AP (kg)	0.15	0.37	1.16	0.45
EP (g)	30.6	78.7	245.3	92.1
POCP (g)	18.5	96.3	192.6	106.3
ODP (mg)	3.3	7.0	19.3	10.6
ADPe (mg)	294.3	1,105	3,258	874.2
ADPf (MJ)	410.8	664.4	1,305	848.4

LCA, life-cycle assessment; C g, coniferous sawnwood, green; C kd, coniferous sawnwood, kiln-dried; NC kd, nonconiferous sawnwood, kiln-dried; C pl: coniferous sawnwood, planed); GWP, global warming potential; AP, acidification potential; EP, eutrophication potential; POCP, photochemical ozone creation potential; ODP, ozone depletion potential; ADPe, nonfossil abiotic resource depletion potential; ADPf, fossil abiotic resource depletion potential.

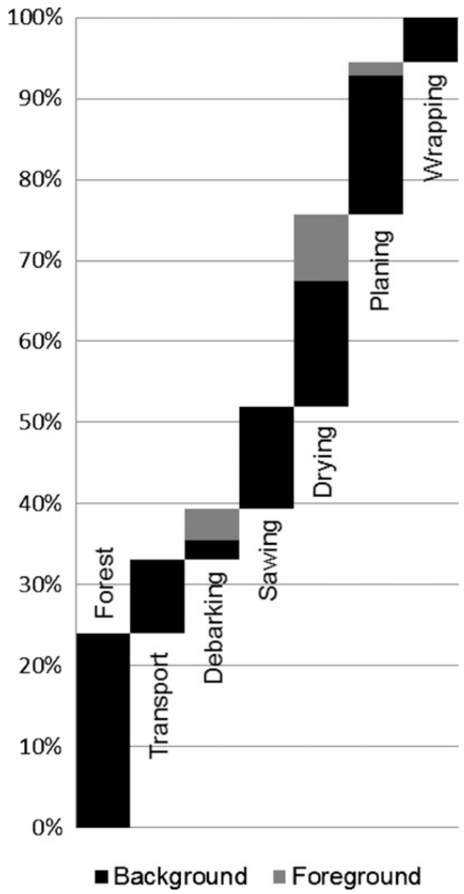


Figure 3. CO_2-Eq. emissions from processing planed sawnwood.

Transport distances for sawlogs are around 100 km for all products, which leads to emissions between 4 and 7 kg CO_2-Eq./m^3 of coniferous sawnwood and 13 kg CO_2-Eq./m^3 of nonconiferous sawnwood. The higher emissions for nonconiferous wood transports compared with coniferous wood transports result from the higher amount of wood fuels burned on site for nonconiferous wood production and the higher raw density of nonconiferous wood. More than 99% of the relevant emissions is carbon dioxide from burning of diesel in transportation vehicles.

On site, 3-10 kg of CO_2-Eq. is emitted by burning of diesel, fuels for heat supply, and the drying kilns. For the production of green coniferous sawnwood, these emissions evolve singularly from burning of diesel. For kiln-dried and planed coniferous sawnwood, about 49-54% of on-site GHG emissions evolve from diesel combustion, 32-33% from combustion of wood, 1-2% from combustion of fossil fuels, and 13-16% from the drying chambers. For kiln-dried nonconiferous sawnwood, 69% of the on-site GHG emissions arise from combustion of wood, 24% from combustion of diesel, and 7% from the kilns. The essential GHG emissions of the kilns are volatile organic compounds (VOCs). Gate-to-gate background emissions are responsible for 29-53% of the total cradle-to-gate emissions. For all products, generation of electricity is responsible for the major share of those emissions.

Focus on Acidification Potential, Eutrophication Potential, Photochemical Ozone Creation Potential, and Ozone Depletion Potential

Emissions which cause depletion of the ozone layer (ODP) originated mainly from the background gate-to-gate system for all products (generation of electricity). Other sources are of minor relevance for this indicator.

For the AP, EP, and POCP of green sawnwood production, 44-60% of the indicator results are caused by forestry operations and 12-17% by transports to the sawmill site. Only 28-40% of the results are caused by sawmill processes (foreground and background).

This is different for dried products. The drying process pushes the relevance of the indicator result of the foreground gate-to-gate system up to 54-80%. The primary substances here are nitrogen oxide and sulfur dioxide from the combustion of wood (AP and EP) and VOC emitted from the kilns and combustion of diesel (POCP).

Representativeness

Looking at the representativeness of the analyzed processes, the survey provided detailed data for 27.2-42.1% of the typical sawmill processes for coniferous wood. Less data were available for nonconiferous wood sawmills. Only 3.4%

Table 8. Processes and representativeness (fraction) of the analyzed volumes compared with national process utilization.

Process	Volume analyzed (million m^3/yr)[a]	Germany 2010 (million m^3/yr[a,b]
Debarking	9.08	34.00
Sawing	5.49	20.55
Kiln drying	3.32	12.21
Planing	1.36	3.23
Debarking (nc)	0.03	0.92
Sawing (nc)	0.02	0.55
Kiln-drying (nc)	0.02	0.50

[a] Process output volume.
[b] Based on DESTATIS (2010b) and survey results.
nc, nonconiferous.

of the total national process throughput was analyzed, which leads to a limitation of the informational value of nonconiferous sawnwood results (Table 8).

Other Studies

The results for the specific electricity consumption of the processes and the fuels used for heat production were compared with results from other studies listed in Tables 1, 2, and 3. The cited data were partially taken directly from publications or calculated on the basis of pieces of information in the study and assumptions. For coniferous sawnwood, the processes in this study had lower electricity consumption than the average of all cited studies, but values came closer to the average than most of the other studies. Heat consumption was also very close to the average (Table 2). Only one study for electricity consumption of nonconiferous wood processes could be compared (Table 3). The data supply further evidence of the large differences in environmental impacts of sawmill processes in general, but also validate the high representativeness of results in this article, since values of this study come very close to the average.

Uncertainties

Considerations on data uncertainty focus on the data collected in surveys or site visits conducted during this study.

Very reliable data were collected for any type of valuable (monetarily) input and output like electricity, fuel, sawlogs, products, byproducts, and others, since the quantities are usually well documented by the companies' bookkeeping. In the case of wood, inputs and outputs for material use were collected as volume flow. Quantities of fuel wood were collected as mass flow, which correlates to the typical approach of the companies' bookkeeping system. Therefore, the material flow and the energy flow are independent from variations in raw density of wood. Problems occur, if byproducts—where the volume is known only—are burned on site. Here the mass and moisture content were estimated by the companies. Therefore uncertainties exist for the quantification of energy content of the burned byproducts and the total mass of byproducts burned.

The product portfolio of a sawmill ranges from green sawnwood as a single output to several different products. Since only a few companies were able to allocate the total consumption of electricity to each process, the companies which only had data at the site level or process group level were asked to estimate the share of each process based on other information (net power and utilization time). Therefore uncertainties exist in terms of partitioning the electricity to each product or process.

As stated before, emissions from combustion of wood were not measured but estimated based on literature data. Since emissions from wood combustion are influenced by more parameters than those used in the model (size, fuel type, and filter technology of the plant), uncertainties arise from the estimated emissions.

To approximate the extreme results which arise due to the described uncertainties, it is assumed that the estimated raw density of wood and electricity consumption alternates by 10% each and emission factors for wood combustion alternate within the 95% confidence interval documented in Rentz et al (2009). VOC emissions from the drying kilns were estimated to alternate by 10% in relation to the values described in chapter background data.

Table 9. Uncertainties and their effect on impact categories (gate to gate) (%).

Uncertainty aspect Analyzed range	Mass of wood 10	Electricity consumption 10	Emission factors EEA[a]	VOC from drying 10
GWP	<0.1	6.9-8.4	<0.1	0.2-0.4
EP	<0.1-8.2	0.4-1.8	0-130	<0.1
AP	<0.1-6.9	1.1-3.6	0-110	<0.1
ODP	<0.1	9.4-9.7	<0.1	<0.1
POCP	<0.1-4.7	<0.1-2.1	0-1300	5.8-6.3
PE ren[b]	9.2-10	0.9-1.1	—	—
PE fos[c]	—	6.0-7.3	—	—
ADPe	—	—	—	—
ADPf	—	6.8-8.6	—	—

[a] Range is based on the 95% confidence interval for each emission documented in Rentz et al (2009).
[b] Primary energy from renewable sources.
[c] Primary energy from non renewable sources.
VOC, volatile organic compounds; GWP, global warming potential; AP, acidification potential; EP, eutrophication potential; POCP, photochemical ozone creation potential; ODP, ozone depletion potential; ADPe, nonfossil abiotic resource depletion potential; ADPf, fossil abiotic resource depletion potential.

Table 9 shows the effect of each identified uncertainty on the impact categories. Uncertainties in mass of wood primarily affect EP, AP, and consumption of primary energy from renewable resources, partially up to 1% impact for each percent of uncertainty. Uncertainties in electricity consumption primarily affect GWP, ODP, primary energy from nonrenewable resources, and ADPf since consumption of electricity has the main share in each of those impact categories. Uncertainties in VOC emissions from drying primarily affect POCP with about 0.5% for each percent of uncertainty. Very high effects due to uncertainty are recognized in context with emissions from wood combustion, especially for EP, AP, and POCP. The reason here is the high uncertainty in emissions of NO_X and NMVOC.

Data Range

The data range in the LCI is discussed for the softwood products only, since only two hardwood mills supplied data. As expected, the differences between site-specific data and average data are very concise. Besides the volume weighted average results, Table 1 also shows the 5% and 95% fractiles and the average value for the distribution of specific electricity consumption of all sites without weighting. Although the fractiles describe a large range of specific electricity consumption for each company, for debarking and milling, the majority of companies run their processes with a specific consumption quite close to the average. For the kiln-drying process and the planing process, the distribution is much wider. This might be reasoned by the large amount of parameters that can be changed in the drying and planing process compared with debarking and milling. Remember, that electricity consumption was estimated for each process by the company as a share of the known total consumption of the production site. Hence, the natural data range is mixed with uncertainties here. Table 2 shows the corresponding numbers for the consumption of thermal energy. The share of fossil fuels is low for most companies in the survey.

Average values and fractiles of the LCI results and the cradle-to-gate LCA impact results are documented in Table 10. Looking at the input side, a very high data range appears at the wrapping material. It seems that there are several different ways on how to wrap the sawnwood products and what wrapping material to use. The specific diesel and oil consumption can be very different for each company as well. The age of the machines and the structure of the log yard might a very big influence here. In some cases electric cranes were used.

On the output side, emissions of CH_4, CO_2, and NO_X can be very different for each company as a result of the combustion technique and the type of fuel used. CO_2 emissions obviously depend on

Table 10. Data range for LCI for the declared units (unallocated, coniferous only) and cradle-to-gate LCA results and $Q_{0.05}/\bar{x}_{arith}/Q_{0.95}$: 5% fractile/arithmetic average/95% fractile of distribution of company results.

		C g			C kd			C pl		
Flow	Unit	$Q_{.05}$	X_{arithm}	$Q_{.95}$	$Q_{.05}$	X_{arithm}	$Q_{.95}$	$Q_{.05}$	X_{arithm}	$Q_{.95}$
Inputs										
Material										
Sawlogs	m^3	1.38	1.78	2.17	1.46	1.95	2.47	1.60	2.13	2.70
Logistic on site										
Diesel	kg	0.090	0.780	1.40	0.140	1.07	1.96	0.130	1.34	2.67
Engine oil	g	1.80	11.8	21.7	2.50	16.6	31.2	0.700	20.2	40.9
Electricity (from grid)										
Total	kWh	12.3	25.2	40.9	26.8	51.3	96.2	41.4	81.3	157.6
Equipment										
Lubricants	g	20.8	88.8	173.9	22.8	99.1	197.8	28.4	126.3	297.4
Steel	g	0.400	5.10	8.40	0.500	11.1	14.8	10.0	19.1	24.9
Drinking water	kg	0	1.90	3.40	6.20	16.0	22.3	8.50	21.2	27.9
Surface water	kg	0.600	5.90	7.40	8.30	27.2	43.1	7.00	28.2	45.8
Wrapping										
Polymers	g				0	326	1690	17.0	893	2872
Wood	g	0	136	1583	1355	1674	1775	0	3873	7328
Paper and cardboard	g	0	28.1	81.6	0	42.2	101	0	97.0	198
Steel	g	8.70	91.4	130	0	319	366	0	188	241
Outputs										
Byproducts										
Total	m^3	0.377	0.781	1.17	0.457	0.950	1.47	0.595	1.13	1.70
Emissions (direct)										
CH_4	g				7.30	26.5	64.3	12.5	23.8	36.7
CO	g	1.50	12.6	22.8	27.0	78.4	112	50.2	89.2	127
CO_2 (from fossil fuels)	kg	0.318	2.69	4.86	3.10	7.32	19.8	5.39	8.72	13.1
N_2O	g				0.128	1.24	2.47	0.246	0.577	1.11
NMVOC	g	0.559	4.72	8.53	37.9	52.8	74.1	44.8	54.0	69.4
SO_2	g	0.528	4.44	8.03	12.9	34.8	68.5	22.9	34.2	55.0
NO_X	g	4.77	40.2	72.7	148	390	643	265	387	635
Lead	mg				90.8	371	627	185	353	588
Cadmium	mg				0.204	0.836	1.42	0.416	0.794	1.32
Mercury	µg				20.8	77.0	138	39.2	72.4	119
Arsenic	mg				4.25	17.4	29.4	8.66	16.5	27.5
Chromium	mg				3.92	16.0	27.1	7.98	15.2	25.4
Copper	mg				43.9	179	303	89.4	170	284
Nickel	mg				21.7	88.8	151	44.2	84.3	140
Zinc	mg				0.111	0.404	0.831	0.212	0.371	0.580
Gate-to-gate LCA impact category results										
GWP	kg	26.0	33.0	50.1	45.9	60.9	95.8	55.5	78.5	127.7
AP	kg	0.120	0.151	0.215	0.251	0.432	0.617	0.351	0.456	0.633
EP	g	24.2	31.4	44.2	50.7	92.3	146	69.9	93.6	129
POCP	g	14.7	18.8	25.4	81.1	102	124	90.2	106	125
ODP	mg	1.68	3.25	4.44	4.04	7.30	12.4	6.22	10.8	18.2
ADPe	mg	54.6	303	426	47.0	1015	1330	86.8	907	1654
ADPf	MJ	331	410	627	506	676	1055	607	873	1454

LCI, life-cycle inventory; LCA, life-cycle assessment; C g, coniferous sawnwood, green; C kd, coniferous sawnwood, kiln-dried; C pl, coniferous sawnwood, planed; NMVOC, nonmethane volatile organic compounds; GWP, global warming potential; AP, acidification potential; EP, eutrophication potential; POCP, photochemical ozone creation potential; ODP, ozone depletion potential; ADPe, nonfossil abiotic resource depletion potential; ADPf, fossil abiotic resource depletion potential.

the use of fossil fuels. Relatively steady values are visible for emissions of NMVOC. Uncertainty analysis though showed high values here, which means that real emissions might be much higher than those reported in Table 5.

Naturally the high deviation in the LCI results becomes also visible in the impact assessment. At this point two aspects become clear. First, for the assessment of other products (eg glulam, cross-laminated timber) made of products discussed in this article, information on which sawmill supplied the wood might be of environmental interest. Second, representative average values can only be calculated based on a broad survey.

CONCLUSIONS

In this article, detailed environmental LCI and impact assessment data for the production of the four core products of the German sawmill industry are provided. The data are presented as unallocated data sets and can be applied for a broad range of LCI, LCA, energy and mass flow studies in need of data for sawmill products. The data have high representativeness for Germany and identify the environmental status quo for sawmill products in the year 2010. Besides average results, uncertainties and the range of results are discussed. In this context, high uncertainties exist for the amount of emissions from wood combustion, especially those that potentially trigger acidification, eutrophication, and photochemical ozone creation. More reliable data are needed here to reduce uncertainties. As expected, the data range found in this article is quite high for every product. Assuming that the main reason for the differences is caused by process-specific aspects and only a small share is caused by differences between the actual products, a high optimization potential in the sawmill industry in terms of reduction of environmental impacts is very probable.

ACKNOWLEDGMENTS

Thanks to all companies that supplied data via questionnaires and during on-site visits. Thanks also to Norbert Buddendick and Norbert Burkart “Bundesverband der Deutschen Säge- und Holzindustrie” (sawmill association) for their invaluable assistance in organizing communication networks between science and the German sawmill industry. Financial assistance for this research was provided by the Fachagentur Nachwachsende Rohstoffe (22028808). Special thanks to Sebastian Rüter and Johannes Welling for making this research possible.

REFERENCES

AG Energiebilanzen e V (2010) Auswertungstabellen zur Energiebilanz Deutschland, Daten für die Jahre 1990 bis 2009. AGEB, Berlin, Germany. 13 pp.

Albrecht S, Rueter S, Welling J, Knauf M, Mantau U, Braune A, Baitz A, Weimar H, Soergel S, Kreißig J, Deimling S, Hellwig S (2008) Oekologische Potentiale durch Holznutzung gezielt foerdern.Holz u Klima, BMBF project Ökopot, Final Report, Johann Heinrich von Thünen-Institut, Braunschweig, Grmany, 298 pp.

BDI BDEW, BMWI, BMU, BMF (2012) Vereinbarung zwischen der Regierung der Bundesrepublik Deutschland und der deutschen Wirtschaft zur Steigerung der Energieeffizienz vom 1. August 2012. Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (Federal Ministry of Food, Agriculture and Consumer Protection), Berlin, Germany. 9 pp.

Bergman RD, Bowe SA (2008a) Environmental impact of producing hardwood lumber using life cycle inventory. Wood Fiber Sci 40(3):448-458.

Bergman RD, Bowe SA (2008b) Life-cycle inventory of hardwood lumber manufacturing in the northeast and north central United States, CORRIM: Phase II, Final Report Module C. University of Washington, Seattle, WA. 54 pp.

Bergman RD, Bowe SA (2009) Life-cycle inventory of softwood lumber manufacturing in the northeastern and north central United States, CORRIM: Phase II, Final Report Module D. University of Washington, Seattle, WA. 56 pp.

Bergman RD, Bowe SA (2010a) Environmental impact of manufacturing softwood lumber in the northeastern and north central United States. Wood Fiber Sci 42(CORRIM Special Issue):67-78.

Bergman RD, Bowe SA (2010b) Life-cycle inventory of hardwood lumber manufacturing in the southeastern United States, CORRIM: Phase II, Final Report Module L. University of Washington, Seattle, WA. 56 pp.

BMELV (2009) Aktionsplan der Bundesregierung zur stofflichen Nutzung nachwachsender Rohstoffe. Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (Federal Ministry of Food, Agriculture and Consumer Protection), Berlin, Germany. 40 pp.

BMELV (2010) Holzmarktbericht, Abschlussergebnisse für die Forst- und Holzwirtschaft des Wirtschaftsjahres 2010. Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (Federal Ministry of Food, Agriculture and Consumer Protection), Bonn, Germany. 33 pp.

BMVBS (2011) Leitfaden Nachhaltiges Bauen. Bundesministerium für Verkehr, Bau und Stadtentwicklung (Ministry of Transport, Building and Urban Development), Berlin, Germany. 97 pp.

Boehmer S, Gallauner T, Goessl M, Krutzler T, Moser G (2010) Biomassefeuerungsanlagen, Im Leistungsbereich von 400 kW bis 10 MW. Umweltbundesamt GmbH, Wien, Germany. 76 pp.

Borcherding M (2007) Rundholztransportlogistik in Deutschland – eine transaktionskostenorientierte empirische analyse. PhD thesis, Universitaet Hamburg, Hamburg, Germany. 266 pp.

BSI (2011) PAS 2050, Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institution, London, UK. 43 pp.

DESTATIS (2010a) Jahresbericht für Betriebe—Arbeitsunterlage. Number: 5422701107005. Statistisches Bundesamt, Wiesbaden, Germany (Excel Sheet).

DESTATIS (2010b) Produktion des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden. Statistisches Bundesamt, Wiesbaden, Germany. 300 pp.

Doering P, Mantau U (2012) Standorte der Holzwirtschaft - Saegeindustrie—Einschnitt und Saegenebenprodukte 2010. Universitaet Hamburg, Zentrum Holzwirtschaft, Arbeitsbereich: Oekonomie der Holz- und Forstwirtschaft, Hamburg, Germany. 50 pp.

EC (2010) ILCD handbook, general guide for life cycle assessment—Detailed guidance. European Commission, Joint Research Centre, Institute for Environment and Sustainability, Ispra, Italy. 414 pp.

EN (2012) 15804 Sustainability of construction works, environmental product declarations, core rules for the product category of construction products. European Committee for Standardization, CEN/TC 350—Sustainability of construction works. Brussels, Belgium. 50 pp.

EU (2011) Regulation (EU) No 305/2011 of the European parliament and of the council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. Official Journal of the European Union. EN. L 88/5-43. 39 pp.

FAO (2010) Sawnwood, production quantity, 2010. The Statistics Division of the Food and Agricultural Organisation of the United Nations, Domain Forestry, Forestry Production and Trade. Rome. http://faostat3.fao.org/faostat-gateway/go/to/home/E (28 January 2013).

FNR BMELV (2004) Leitfaden Bioenergie, Datensammlung, Kapitel 3 Eigenschaften von Bioenergieträgern, Umrechnungen, Fachagentur Nachwachsende Rohstoffe. Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz. Federal Ministry of Food, Agriculture and Consumer Protection, 70 pp. http://fnr-server.de/cms35/fileadmin/biz/pdf/leitfaden/datensammlung/ (31 January 2013).

Fruehwald A, Speckels L, Scharai-Rad M, Welling J (2000) Oekologische Bilanzierung von Bauschnittholz und veredelten Vollholzprodukten. Ordinariat für Holztechnologie der Universitaet Hamburg, Hamburg, Germany. 178 pp.

ISO (2006a) 14044, Environmental management—Life cycle assessment—Requirements and guidelines. German and English Versions. International Organization for Standardization, Geneva, Switzerland. 84 pp.

ISO (2006b) 14025, Environmental labels and declarations—Type III environmental declarations—Principles and procedures. Text in German and English. International Organization for Standardization, Geneva, Switzerland. 48 pp.

ISO (2013) ISO/DIS 14067 Carbon footprint of products—Requirements and guidelines for quantification and communication. International Organization for Standardization, Geneva, Switzerland.

Jungmeier G, Werner F, Jarnehammar A, Hohenthal C, Richter K (2002) Allocation in LCA of wood-based products experiences of cost action E9. Int J Life Cycle Ass 7(6):369-375.

Kaltschmitt M, Hartmann H (2009) Energie aus Biomasse. Springer, Dordrecht, The Netherlands; Heidelberg, Germany; London, UK; New York, NY. 1054 pp.

Milota MR, West CD, Hartley ID (2005) Gate to gate life cycle inventory of softwood lumber production. Wood Fiber Sci 37(CORRIM Special Issue):47-57.

PE International (2012) GaBi 4 Software and GaBi Professional Database Version 4.131. Leinfelden-Echterdingen. http://www.gabi-software.com (1 June 2013)

Puettmann ME, Wagner FG, Johnson L (2010) Life cycle inventory of softwood lumber from the inland northwest US. Wood Fiber Sci 42(CORRIM Special Issue): 52-66.

Puettmann ME, Wilson JB (2005) Life cycle analysis of wood products: Cradle-to-gate LCI of residential wood building. Wood Fiber Sci 37(CORRIM Special Issue):18-29.

Reitberger F, Huber S, Streit A, Schmoeckel G, Ebertsch G, Stoettner A, Zell B (2001) Energetische Nutzung nachwachsender Rohstoffe. Bayrisches Landesamt für Umweltschutz, München, Germany. 77 pp.

Rentz O, Oertel D, Woodfield M, Stewart R (2009) Manufacturing Industries and Construction (combustion). Chapter 1.A.2 *in* EMEP/EEA air pollutant emission inventory guidebook 2009. European Environment Agency, Copenhagen, Denmark. 34 pp.

Ressel J (1985) Energieanalyse der Holzindustrie der Bundesrepublik Deutschland. Bundesforschungsanstalt für Forst- und Holzwirtschaft, Institut für Holzphysik und mechanische Technologie des Holzes, Hamburg, Germany. 155 pp.

Rueter S, Diederichs S (2012) Oekobilanzbasisdaten für Bauprodukte aus Holz. Thünen Institut, Hamburg, Germany. 299 pp. In German with summary in English.

Schweinle J (1996) Analyse und Bewertung der forstlichen Produktion als Grundlage für weiterführende forst- und holzwirtschaftliche Produktlinien-Analysen. Bundesforschungsanstalt für Forst- und Holzwirtschaft, Hamburg, Germany. 139 pp.

Speckels L (2001) Oekologische Vergleich verschiedener Verwertungs- und Entsorgungswege für Altholz, Dissertation im Fachbereich Biologie, Ordinariat für Holztechnologie, Universitaet Hamburg, Hamburg, Germany. 403 pp.

StromStG (2012) Stromsteuergesetz vom 24. März 1999 (BGBl. I S. 378; 2000 I S. 147), das zuletzt durch Artikel 2 des Gesetzes vom 5. Dezember 2012 (BGBl. I S. 2436, 2725) geändert worden ist. BGB/German civil code, Bundesministerium der Justiz, Berlin, Germany.

Tsupari E, Monni S, Pipatti R (2005) Non-CO_2 greenhouse gas emissions from boilers and industrial processes. VTT, Espo, Finland. 110 pp.

UBA (2012) Entwicklung der spezifischen des deutschen Strommix 1990-2010 und erste Schätzungen 2011. Umweltbundesamt, Dessau-Rosslau, Germany. 5 pp.

Universiteit Leiden (2010) CML 2001, characterization and normalization data. CML-IA database. Universiteit Leiden. Institute of Environmental Science. Faculty of Science. Leiden. http://cml.leiden.edu/software/data-cmlia.html (19 November 2012).

Wagner FG, Puettmann ME, Johnson LR (2009) Life cycle inventory of inland northwest softwood lumber manufacturing, CORRIM: Phase II Final Report Module B. University of Washington, Seattle, WA. 72 pp.

Weidema B, Frees N (1999) Marginal production technologies for life cycle inventories. International J Life Cycle Assessment 4(1):48-56.

Werner F, Althaus H-J, Kuenniger T, Richter K, Jungbluth N (2007) Life cycle inventories of wood as fuel and construction material. ecoinvent report No. 9. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland. 176 pp.

2010 STATUS QUO FOR LIFE CYCLE INVENTORY AND ENVIRONMENTAL IMPACT ASSESSMENT OF WOOD-BASED PANEL PRODUCTS IN GERMANY

*S.K. Diederichs**
Research Associate
Thuenen Institute of Wood Research
21031 Hamburg, Germany
E-mail: stefan.diederichs@ti.bund.de

(Received December 2013)

Abstract. Considering the importance of the German wood-based panel industry, the current status of available life-cycle inventory (LCI) data for these products is quite unsatisfying. In this study, detailed disaggregated LCI and environmental life-cycle assessment (LCA) data and variation in data on production of the core products of the German wood-based panel sector are given. The data suit a wide range of applications and are transparently documented, allowing consistent combination with other raw data sets. The data are analyzed in terms of sensitivity of environmental impacts to the variations in LCI. Also, specific advice is given to LCA practitioners on how to narrow the presented variations with respect to the environmental impact category they are interested in. Results are presented for the typical midpoint environmental impact categories excluding toxicity indicators. For the latter, the relevant data gaps are discussed.

Keywords: Life-cycle inventory, LCI, life-cycle assessment, LCA, wood-based panels, energy, emissions, carbon.

INTRODUCTION

With the initial basic concept of moderating the anisotropic nature of solid wood through homogenization, wood-based panels (WBP) have come a long way through technical development. Today, the worldwide annual production of about 275 Mm^3 of WBP (FAO 2013) offers an almost continuous covering of any possible compromise among mechanical, optical, and emission properties that can be influenced by particle size and orientation, type of adhesives and additives, processing parameters, and panel dimensions.

Based on figures from EPF (2012) and FAO (2013), the five biggest producers of WBP are China with 38% of the world production, followed by the US (11%), Germany, Russia, and Canada with 4% each. About 21% of the world production is from the European Union (EU). Compared with world production, which is split into fiberboard, particleboard, and plywood with approximately 1/3 each, EU and Germany have large production volumes of fiberboard and particleboard with 93 and 98% of total production, respectively.

German WBP production of 12 Mm^3 in 2011 was composed of 48% particleboard, 30% dry-process fiberboard, and 10% oriented strandboard. In addition, 6% of the production was hardboard (high-density fiberboard from wet process), 4% softboard (low-density fiberboard from wet process), and 2% plywood panels (EPF 2012; FAO 2013).

Environmental life-cycle assessment (LCA) has been conducted for all typical WBP. In Spain, Rivela et al (2006, 2007) conducted LCA for particleboard (PB) and dry-process fiberboard (FB) by analyzing one Spanish PB plant and two Spanish as well as one Chilean FB production facilities. (EPF [2007] identifies a total of 14 PB producers and 7 FB producers in Spain in 2005.) Kline (2005) analyzed four production facilities for oriented strandboard (OSB) in the southeast region of the US (from a total of 22 in this region). Wilson (2008, 2010b, 2010c) surveyed five PB and four FB manufacturing mills

* Corresponding author

in 2004, representing 23 and 27% of the total US production. The latest results were published by Silva et al (2013) who analyzed three Brazilian PB manufacturing mills that used eucalyptus as the wood resource.

In Germany, Frühwald et al (2000) conducted an analysis of five PB and three FB production lines as well as a literature-based assessment for production of OSB. Data were gathered between 1997 and 1999. From then until today, German production of PB decreased by 40% and plywood production by 50%, whereas production of FB increased by 125%. No relevant volume of OSB was produced in Germany in those years.

Considering the importance of the German WBP industry to the European and world market, the current status of publicly available, transparently documented, and up-to-date inventory data for these products is quite unsatisfactory. LCA practitioners analyzing WBP from German producers used in construction, packaging, or furniture have to either use old or undocumented data or data from a different geographical context.

This study aims to supply average detailed life-cycle inventory (LCI) and environmental LCA data and variation in data on production of the core products of the German WBP sector. For data to be useful, they should be basically disaggregated, allowing a wide range of applications, and should be transparently documented, allowing a consistent combination with other raw data sets. The results of this study should thoroughly fill the described data gap.

DATA AND METHODOLOGY

Functional Units

The most relevant products of the German WBP industry in terms of production volume are PB, FB, and OSB. In the case of PB and FB, the panels are sometimes laminated with a decorative layer, typically melamine-treated paper.

Functional units represent the supply of 1 m^3 to the factory gates of the products listed in Table 1. The functional unit PBm is defined to analyze the additional emissions that occur as a result of a melamine face. Table 2 gives an overview of the average material content and density of the products behind the functional units.

System Boundaries

Several different system boundaries were defined for the analysis (Fig 1). For the classic cradle-to-gate LCA, the system boundaries include all information from the supply of raw materials to the finished product at the gates of panel production. For the gate-to-gate LCI, the system boundary includes only foreground data of the production.

To simplify the trace of carbon flows in biomass, the supply of wood (background, forest/sawmill/transport) was separated from the supply of everything else (background, panel production).

Foreground Data

Foreground data were primarily gathered during the OekoHolzBauDat project, which was launched

Table 1. Functional units of the life cycle inventory and their names used in this study.[a]

Name	Group	Description
PBr	PB	Production of raw (nonfaced) PB based on the weighted production volumes of industrial partners
PBm		Production of melamine-faced PB based on the weighted production volumes of industrial partners; the average thickness as relevant for the melamine face is 18.7 mm including melamine face
OSB		Production of raw OSB
MDF	FB	Production of raw MDF with medium based on the weighted production volumes of industrial partners
HDF		Production of raw MDF with high density based on the weighted production volumes of industrial partners

[a] PB, particleboard; PBr, raw, nonfaced particleboard; PBm, particleboard with melamine face; OSB, oriented strandboard; MDF, medium-density fiberboard; HDF, high-density fiberboard; FB, fiberboard.

Table 2. Functional units in terms of material content and mass (1 m^3).[a]

Content (kg)	PBr	PBm	OSB	MDF	HDF
Wood and water					
Stem wood and residues (odm)	428.1	415.7	530.9	590.3	669.3
Recovered wood (odm)	109.5	115.2	—	—	—
Water	37.6	37.2	27.0	47.0	61.7
Adhesive and others					
Adhesives	56.3	53.5	30.8	95.6	113.3
Additives	2.9	2.5	11.3	4.7	5.6
Lamination	—	32.9	—	—	—
Total	634.4	657.0	600	737.5	849.9
Total (kg odm)	596.8	619.8	573	690.6	788.2

[a] PBr, raw, nonfaced particleboard; PBm, particleboard with melamine face; OSB, oriented strandboard; MDF, medium-density fiberboard; HDF, high-density fiberboard; odm, oven-dry mass.

in 2009 (survey was conducted for 3 yr in which 17 panel mills were analyzed by surveys and site visits). In addition to results from the conducted surveys, the foreground data also include calculated results. On-site emissions at panel facilities mainly arise from diesel, combustion of fossil fuels and wood fuel, pressing, and drying. Emissions from burning of wood are modeled as a function of filter technique, size, and fuel type based on Reitberger et al (2001), Speckels (2001), Tsupari et al (2005), Kaltschmitt and Hartmann (2009), and Böhmer et al (2010). Emissions from drying and pressing at the panel manufacturing plant were calculated based on Milota (2000) and Wilson (2010a).

Background Data

Specific background data for sawmill byproducts are also calculated on the basis of surveys conducted during the ÖkoHolzBauDat project (Rueter and Diederichs 2012). The methodology follows the rules described by Diederichs (2014).

Generic background data for forestry operations was taken from Schweinle (1996) and Albrecht

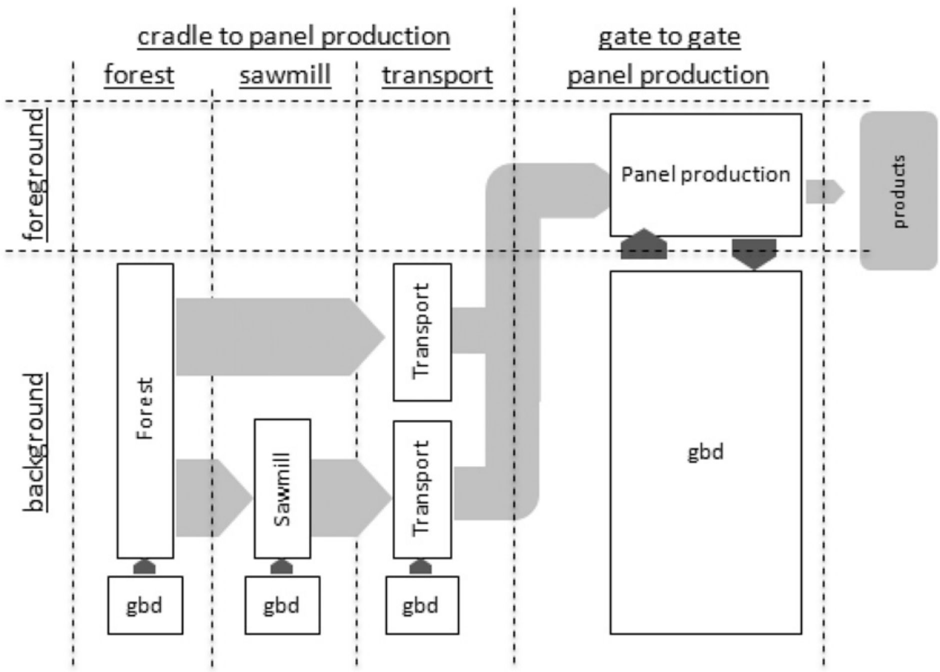


Figure 1. System boundaries and subsystem boundaries of the analyzed production system. gbd, generic background data.

et al (2008). Transport models are based on Borcherding (2007) and the European Commission (2010a). The electricity grid mix model is based on AG Energiebilanzen e.V. (2010) and PE International (2012). Indicated emissions were 572 kg CO_2-Eq/kWh, which is in the range of official data from UBA (2012), and in that study, greenhouse gas emissions of 577 kg CO_2-Eq/kWh for 2009 and estimated 562 kg CO_2-Eq/kWh for 2010 were reported. Background data for adhesive production were primarily based on Zeppenfeld and Grunwald (2005) for the production starting from basic chemicals and PE International (2012) for the production of basic chemical materials. Especially for the different mol ratios of formaldehyde and urea and phenol and melamine, feedback from experts from the panel industry completed the data. For formaldehyde-based resins, results from Wilson (2009) were used for plausibility checks. The detailed models and mol ratios are documented in Rueter and Diederichs (2012). The model used for OSB production was primarily based on information on the production of polymethylenediisocyanate (pMDI). The environmental impacts were calculated according to Zeppenfeld and Grunwald (2005), and a raw data set for diphenyl-methan-4.4-diisocyanate was supplied by PE International (2012).

Allocation Principles

Many forms of wood resources are used for panel production. Logs or sawmill residues as well as industrial wood residues and recovered wood can be used as material resources. For energy purposes, bark and residues from landscaping are used as well. Some of these wood resources are byproducts of other production systems. For a cradle-to-gate assessment of WBP, emissions that occur in those other production systems need to be partially allocated to those systems and the systems being studied. This calculation step is one of the most discussed aspects in LCA. It has a large effect on the results of the study (Jungmeier et al 2002) and the choice of the allocation type depends mainly on the purpose of the results (European Commission 2010b).

In this study, LCI is calculated from gate to gate. In other words, the LCI includes all flows that cross the boundary of the foreground gate-to-gate panel production system (Fig 1). Because all byproducts of the panel production are directly used as fuel or are recycled internally in a closed loop, no allocation procedure is needed for this step. Hence, the LCI results at the foreground gate-to-gate boundary are free of allocation procedures and can be used in a wide range of applications. An exception is when a combined heat and power plant is on-site. In this case, the power plant was considered outside the foreground system boundaries but inside the background gate-to-gate boundaries as reasoned by Diederichs (2014). The allocation procedure then was based on exergy.

In contrast, LCA results were calculated from cradle to gate. They include all subsystems shown in Fig 1. Hence, allocation procedures were necessary.

Forestry operations yield small-diameter logs, mostly used for pulp, paper, panels, and energy, as well as sawlogs with larger diameters. The choice for a procedure to allocate emissions from forestry operations to those products is based on recommendations of EN 15804 (EN 2012), in which allocation shall be based on economic values if the difference in revenue from the coproducts is high (more than 25%). Based on prices listed in NRW (2011) and StELF (2011) as well as deviation of assortments from the base scenario of Polley and Kroiher (2006), differences in revenue are 26% for pine and beech, 32% for oak, and 65% for spruce. Hence, the price of the products was chosen as the basis for allocation. Based on an LCA conducted by Zimmer (2010), the production of forest chips was estimated to have 17% of the environmental impact of small-diameter spruce. Bark from forest and landscaping wood was assumed to have the same impact as forest chips (always based on oven-dry mass of biomass).

Sawmill byproducts used in the WBP industry are assumed to arise exclusively from the milling process in the sawmills. Hence, the environmental impact is identical to that of green sawnwood described in Diederichs (2014), except that milling impacts are allocated to the byproducts instead. Allocation was based on price.

Recovered wood for material or fuel use does not carry an environmental burden when it enters the system. Only its inherent characteristics such as heating value and carbon content are traced in the flow. The reason for this is the definition of the "end-of-waste-state" in EN (2012), which is located at the retailer of the recovered wood (Rueter and Diederichs 2012). Hence, all process steps before this are allocated completely to the former product system. However, the environmental impact of transportation from the retailer of recovered wood to the panel factory is taken into account.

Flows of Carbon in Biomass

In contrast to allocation of, for example, electricity and thermal energy to products and byproducts (which is based on economic value), the wood resources are allocated to products and byproducts based on oven-dry mass as recommended by ISO 14044 (ISO 2006). Therefore, inputs and outputs of the material inherent characteristics of a production system are balanced. This also refers to the carbon content of the biomass. Figure 2 shows the carbon balance in a life cycle of a typical WBP. Wood resources used either as fuel or material are accounted for as "negative" emissions. If wood is burned on-site or at the end of its service life, emissions arise from combustion. If the wood is transferred to a second production system without being burned (in the case of recovered wood), its inherent characteristics are subtracted from the first system and added to the next. No amount gets lost.

The amount of carbon from biomass is causally determined by the wood mass within the products (Table 2) and the wood mass burned during production (Table 3). Figure 2 clarifies why, mathematically, carbon dioxide emissions from biomass vanish in cradle-to-grave assessments. In contrast, cradle-to-gate totals as published in this study actually include "negative" emissions from wood use. For transparency reasons, carbon flows of biomass were not taken into account in the environmental impacts assessment here. They would superimpose fossil-based emission while not giving any additional information.

Cut-Off Rules, Assumptions, and Data Gaps

Decisions regarding which flow to include in the LCI were based on previously published LCA results for WBP (see Introduction) and a sensitivity analysis performed by Rueter and Diederichs (2012). Hence, every flow exceeding 1% of an indicator result was included, whereas all neglected flows did not exceed 5% of this indicator result. Flows that were below this threshold but were known anyhow were included.

Assumptions were made regarding capital goods such as buildings and machinery. They were not included in terms of their production, because the associated impacts were assumed to not exceed 1% of the total. Further assumptions were made in context with adhesives and additives. As shown by comparing Table 2 with Table 3, the model defines that all flows listed under the categories adhesives and additives in Table 3 are assigned to the functional units in Table 2 with the identical amounts. Because no detailed data were available on the internal waste flows of the companies, all inputs of adhesives and additives were assumed to leave the company as content of the respective product.

Data gaps occurred in context with the wrapping material for the equipment. Hence, in the model, it was assumed that the equipment entered the company without any wrapping. The emission model for combustion of wood fuel was based on literature data. Comparing those with data listed by Rentz et al (2009), gaps occurred for emissions of selenium, polychlorinated biphenyls, polychlorinated dibenzodioxins, benzo(a)pyren, benzo(b)fluoranthene, benzo(k)fluoranthene, indeno(1,2,3-cd)pyrene, and hexachlorbenzene. Implications of the described data gaps are discussed later in the text.

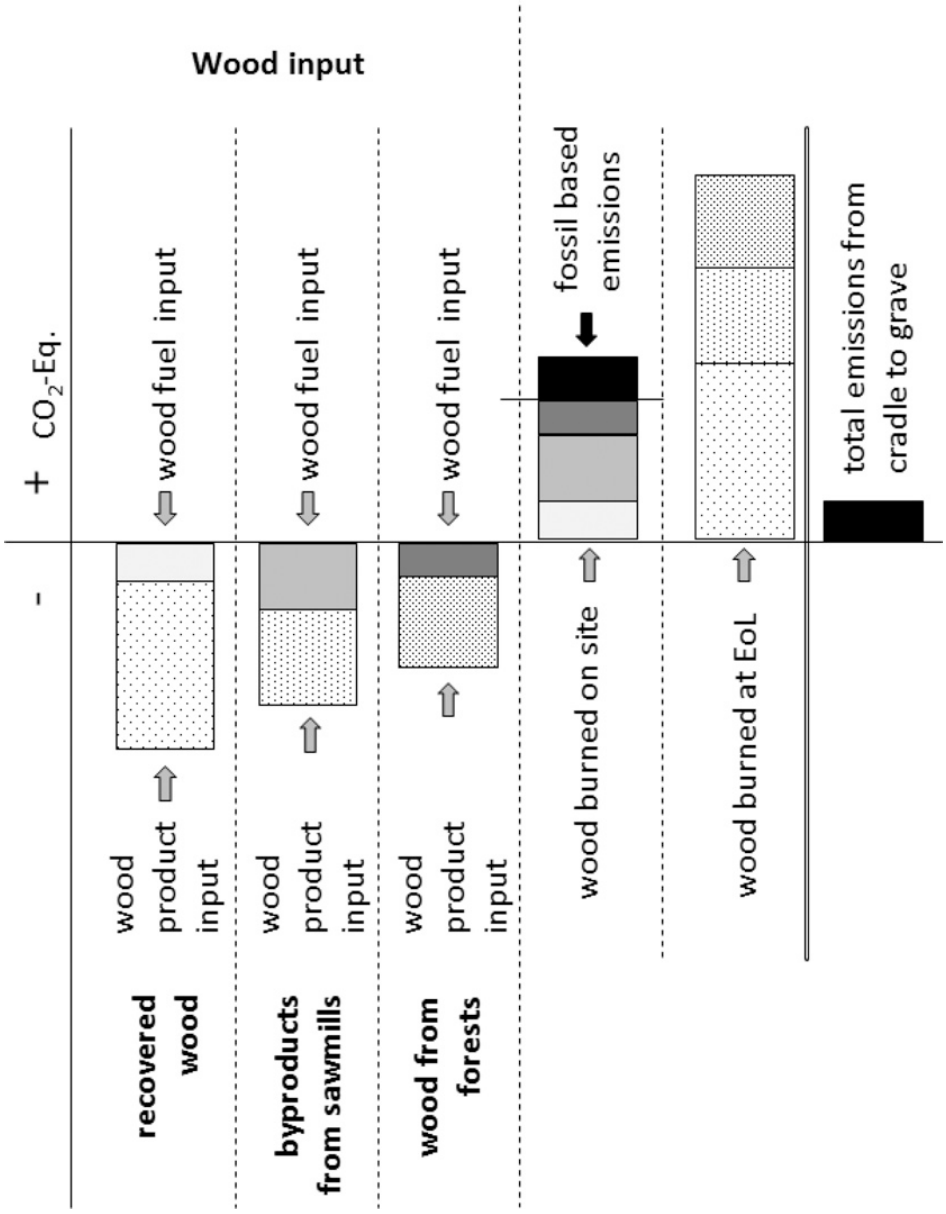


Figure 2. Typical carbon balance of wood-based panels. EoL, end of life.

Impact Assessment

The impact assessment covers six impact categories defined in EN (2012), which are global warming potential for 100 yr (GWP100), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), stratospheric ozone depletion potential (ODP), and abiotic resource depletion potential (ADP). For ADP, two subcategories exist. ADPe describes the depletion of elements of nonfossil resources, and ADPf describes the depletion of fossil fuels. Classification and characterizations of emissions are based on definitions published by Universiteit Leiden (2010). Carbon dioxide emissions evolving from oxidization of carbon contained in biomass and photosynthetic capture of carbon dioxide to carbon contained in biomass are not included in the GWP100 category for the reason previously described.

The impact assessment was conducted from cradle to gate, covering the complete system shown in Fig 1. Although the LCI from gate to gate was the main output of this study, the impact assessment was used to analyze the sensitivity of the

Table 3. Life-cycle inventory for functional units from cradle-to-gate, foreground system.[a]

Flow	Unit	PBr	PBm	OSB	MDF	HDF
Inputs						
Wood as material						
Stem wood	(kg)	86.9	84.8	708.0	414.0	254.1
Industrial residues	(kg)	404.7	402.4	—	398.6	614.4
Recovered wood	(kg)	125.8	135.0	—	—	—
Fuels						
Wood residues	(MJ)	465.1	746.5	1682.8	2,644.4	2030.1
Recovered wood	(MJ)	1152.5	598.6	—	3321.1	3838.8
Fuel oil	(MJ)	17.2	5.3	5.2	70.3	34.7
Gas	(MJ)	69.0	112.9	404.1	1.9	2.5
Diesel	(kg)	0.6	0.7	0.6	0.8	0.7
Electricity (from grid)						
Process	(kWh)	102.4	121.1	120.9	297.6	301.1
Equipment						
Lubricants and engine oil	(g)	55.6	61.4	55.6	260.4	260.4
Tools (steel)	(g)	63.3	69.2	13.9	133.7	133.7
Water	(kg)	202.7	317.4	499	1107.2	1107.2
Adhesive						
UF	(g)	49.0	44.8	—	95.6	113.3
MUF	(g)	5.0	8.7	9.7	—	—
PF	(g)	0.4	—	—	—	—
pMDI	(g)	0.9	—	21.1	—	—
Additives						
Wax	(kg)	2.7	2.0	11.3	4.7	5.6
Fire retardant	(g)	195.8	517.1	—	—	—
Lamination	(kg)	—	32.9	—	—	—
Wrapping						
Polymers	(g)	160.7	205.2	50.7	197.4	197.4
Wood	(kg)	5.2	5.2	2.0	21.6	21.6
Paper and cardboard	(g)	129.9	123.6	230.9	519.6	519.6
Steel	(g)	57.7	62.8	251.4	647.0	647.0
Outputs						
Product (wrapped)						
Product	(m^3)	1.0	1.0	1.0	1.0	1.0
Byproducts						
Residues	(kg)	79.8	91.2	177.1	222.2	199.2
Waste						
Waste	(kg)	0.1	0.1	0.1	0.4	0.4
Water	(kg)	202.7	317.4	499.0	1107.2	1107.2
Emissions (direct)						
CH_4	(g)	34.7	36.1	79.7	72.7	68.2
CO	(g)	66.0	63.2	68.9	219.1	212.3
CO_2 (from fossil fuels)	(kg)	8.3	9.9	26.9	6.6	3.7
N_2O	(mg)	456.0	426.4	705.6	1437.8	1369.6
NMVOC	(g)	126.6	128.4	103.5	224.1	238.6
SO_2	(g)	13.0	13.6	19.0	31.7	29.0
NO_x	(g)	164.6	161.3	180.3	520.9	502.2
Pb	(mg)	291.0	257.9	294.8	1085.2	1061.4
Cd	(mg)	0.7	0.6	0.7	2.4	2.4
Hg	(μg)	58.9	53.1	62.9	211.2	205.2
As	(mg)	13.6	12.1	13.8	50.8	49.7

Table 3. *Continued.*

Flow	Unit	PBr	PBm	OSB	MDF	HDF
Cr	(mg)	12.5	11.1	12.7	46.6	45.6
Cu	(mg)	140.6	124.6	142.4	524.4	512.9
Ni	(mg)	69.6	61.7	70.4	259.4	253.6
Zn	(mg)	0.3	0.3	0.3	0.9	0.9

[a] PBr, raw, nonfaced particleboard; PBm, particleboard with melamine face; OSB, oriented strandboard; MDF, medium-density fiberboard; HDF, high-density fiberboard; UF, urea–formaldehyde; MUF, melamine urea–formaldehyde; PF, phenol–formaldehyde; pMDI, polymethylenediisocyanate; NMVOC, nonmethane volatile organic compound.

evaluated impact categories toward variations in the LCI values caused by variations among companies and products and those caused by uncertainties in the data.

RESULTS

General

Table 3 shows all results of the LCI as average values weighted by production volume of all surveyed producers of a product. Table 4 shows the LCA results for each impact category from cradle to gate and the share of each subsystem defined in Fig 2.

In general, large shares of environmental impacts resulted from the gate-to-gate background system (supply of all products but wood) except for POCP. Here, on-site emissions were responsible for the greatest share. Regarding the wood supply alone, forestry and transport took the leading role for all indictors except ODP. Here, the share of impacts from sawmills played a major role. ODP shares were dominated by electricity consumption, which is naturally low for forestry and transport operations.

Environmental impact data were analyzed to better understand the environmental relevance of variations in LCI data. Hence, for every LCI category, a corresponding LCA background system was defined. Figure 3 shows impacts that can be connected to each category of the inventory of the cradle-to-gate impact assessment of PBr and FB. In Fig 3, the upper beam in each category indicates the PBr impact variation and the lower beam indicates variation in FB results. The dots indicate the absolute results based on the average values in the inventory for PBr (white upper dot), OSB (black upper dot), medium-density fiberboard (MDF) (white lower dot), and high-density fiberboard (HDF) (black lower dot). Gray-marked LCI categories (axis of ordinate) are identified to have variations causing high impact on the cradle-to-gate results. Those in particular are among the following description of variations. Indicator ADPf is not part of Fig 3 because its variations are very close to variations in GWP.

Wood as Material

Wood for material use is supplied to panel producers in the form of logs, industrial residues, or recovered wood. The latter is only used in the production of conventional PB representing an average of 20% of the wood material input (based on oven-dry mass). Residues are used for all panels based on particles and fibers except OSB. For OSB, logs are used exclusively. The corresponding LCA background system was defined to include the supply of wood, including all forestry, sawmilling, and transport operations necessary.

The supply of wood plays a significant role in the level of emissions classified to AP, EP, and GWP (compare total share of forest, transport, and sawmill in Table 4). Large variations within the impact factors of this LCA background system are influenced by variations in the amount of emissions. Sources of emissions are burning of diesel during forestry operations, road transport from forests to sawmill and from sawmill to panel production, and direct transport from forests to panel production. Panel density has a primary influence on the amount of emissions. Density variations between 600 and 730 kg/m^3 for PB and between 730 and 880 kg/m^3 for FB

Table 4. Life-cycle assessment results with share of each subsystem boundary to each impact category result (%).[a]

Flow	Unit	PBr	PBm	OSB	MDF	HDF
Foreground, gate to gate						
GWP	(%)	6	5	14	4	3
AP	(%)	21	14	11	29	26
EP	(%)	15	10	18	24	22
POCP	(%)	84	74	86	80	79
ODP	(%)	0	0	0	0	0
ADPe	(%)	0	0	0	0	0
ADPf	(%)	4	3	8	1	0
Background, gate to gate						
GWP	(%)	83	88	82	86	85
AP	(%)	57	70	82	49	49
EP	(%)	68	78	70	57	58
POCP	(%)	11	21	13	12	12
ODP	(%)	95	97	100	98	97
ADPe	(%)	99	99	100	99	99
ADPf	(%)	88	90	89	91	90
Sawmill						
GWP	(%)	1	1	0	1	1
AP	(%)	1	1	0	0	1
EP	(%)	0	0	0	0	0
POCP	(%)	0	0	0	0	0
ODP	(%)	3	2	0	2	2
ADPe	(%)	0	0	0	0	0
ADPf	(%)	1	1	0	1	1
Transport						
GWP	(%)	4	3	2	5	5
AP	(%)	7	5	2	12	13
EP	(%)	5	4	4	10	11
POCP	(%)	1	1	0	4	4
ODP	(%)	0	0	0	0	0
ADPe	(%)	0	0	0	0	0
ADPf	(%)	3	2	1	4	5
Forest						
GWP	(%)	6	4	3	4	5
AP	(%)	15	10	5	9	11
EP	(%)	11	7	9	8	9
POCP	(%)	4	4	1	4	4
ODP	(%)	1	1	0	1	1
ADPe	(%)	0	0	0	0	0
ADPf	(%)	5	3	2	4	4
Totals (cradle to gate)						
GWP	(kg)	217	328	318	406	429
AP	(kg)	0.50	0.72	1.06	1.10	1.15
EP	(g)	152	222	145	299	321
POCP	(g)	248	285	646	387	418
ODP	(mg)	24	43	22	58	59
ADPe	(mg)	215	246	989	280	315
ADPf	(MJ)	3665	5041	5817	6429	6897

[a] PBr, raw, nonfaced particleboard; PBm, particleboard with melamine face; OSB, oriented strandboard; MDF, medium-density fiberboard; HDF, high-density fiberboard; GWP, global warming potential; AP, acidification potential; EP, eutrophication potential; POCP, photochemical ozone creation potential; ODP, ozone depletion potential; ADPe, abiotic resource depletion potential elements of nonfossil resources; ADPf, abiotic resource depletion potential of fossil fuels.

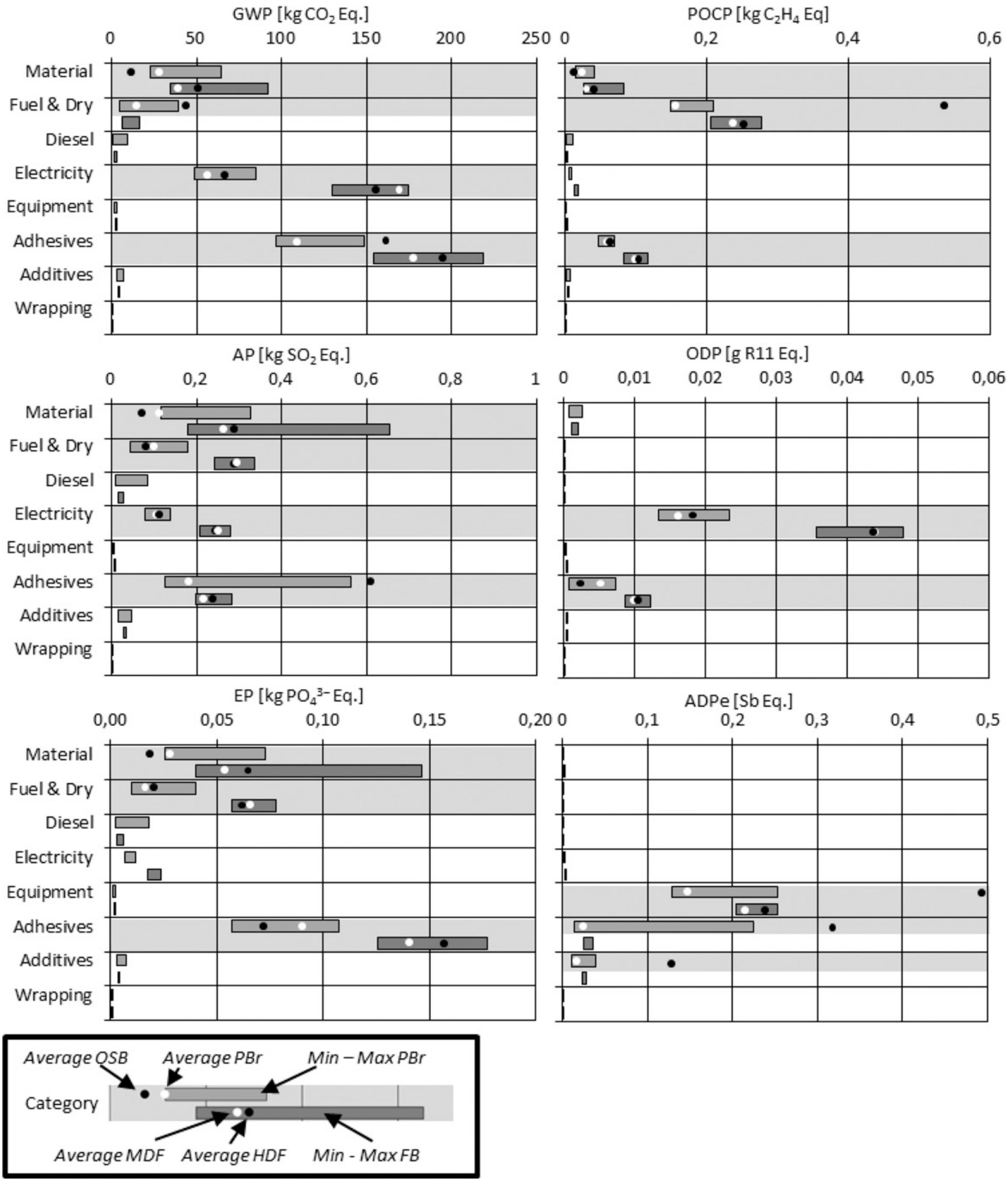


Figure 3. Sensitivity of impact categories to variations in life-cycle inventory amounts. GWP, global warming potential; POCP, photochemical ozone creation potential; AP, acidification potential; ODP, ozone depletion potential; EP, eutrophication potential; ADPe, abiotic resource depletion potential elements of nonfossil resources; OSB, oriented strandboard; PBr, raw, nonfaced particleboard; MDF, medium-density fiberboard; HDF, high-density fiberboard; FB, fiberboard.

result in quite linear variations in impact. Furthermore, variations in the material mix influence results. Panels with a high share of recovered wood have lower impacts than those that incorporate residues or logs. In the latter case, logs have lower impacts than residues. Variations in transport distances are low in the case of wood supply for PB production (80-120 km) and much higher for FB production (60-250 km). For the latter, transport distances may heavily eclipse the influence of density but play a minor role for variations in PB results.

Fuel and Drying

Thermal energy is predominantly generated by the combustion of wood fuels in the form of residues or recovered wood. The choice between residues and recovered wood is mainly influenced by the installed combustion technique and emissions threshold values, respectively. Fossil fuels are used only in exceptional circumstances or if thermal energy is not the driving force of production costs. The drying procedure, in which most of the generated heat is used, is responsible for most volatile organic compound (VOC) emissions on site. The corresponding LCA background system for fuel supply, combustion, and the drying process was defined to cover all emissions from supplying and burning of any fuel used to generate thermal energy as well as all direct emissions from drying.

Environmental impacts are primarily expressed as GWP, AP, EP, and POCP. Greenhouse gases mainly derive from combustion of fossil fuels. Nitrogen oxides and sulfur dioxide, dictating results for AP and EP, originate from combustion of wood fuels. Emissions of VOC from the drying procedure dictate the POCP indicator.

Naturally, variations in the pure amount of fuels burned have a large influence on variations in impacts. In the case of PB, between 872 and 2700 MJ/m^3 of energy input is needed, whereas 5100-6200 MJ/m^3 is needed for FB. The surveyed companies that produce PB used up to 5% fossil fuels, whereas surveyed FB production mills used wood fuels only. Therefore, variations in emissions of greenhouse gases were higher for PB than for FB.

VOC emissions were calculated on the basis of the total dried wood mass, which obviously resulted in good linearity between emissions and panel density. Only variation in yield after drying leads to disturbance of this linearity. Because little data for OSB production were available, it was assumed that all wood that entered the process was dried, indicating the worst case possible.

Electricity

On average, production of PBr consumes about 100 kWh/m^3 with variations from 80 to 140 kWh/m^3. For FB, electricity use of about 300 kWh/m^3 is average with variations from 230 to 310 kWh/m^3. The corresponding LCA background system was defined to include all emissions resulting from the production of electricity. Because a general electricity mix was used for the model, variations within the indicator results are linear to quantitative differences in electricity consumption of panel production. Global warming, resulting from electricity production, driven almost totally by carbon dioxide (95% of the impact) and acidification, sulfur dioxide (73% of the impact), and nitrogen oxides (27% of the impact), primarily influences the total cradle-to-gate impacts of panel production. Emissions leading to depletion of stratospheric ozone (ODP) result from use of chlorofluorocarbons in context with cooling during enrichment of uranium. Electricity consumption is the overall driving force of this latter indicator.

Adhesives

Generally, thermosetting adhesives are used in panel production. For PB, urea–formaldehyde adhesives are used predominantly. For FB production, the surveyed companies used urea–formaldehyde adhesives exclusively. OSB is typically produced by applying isocyanate-based adhesives. Average LCI data indicate that about 50 kg/m^3 are used for conventional PB, about 100 kg/m^3 are used for FB, and about 30 kg/m^3 are applied for OSB. The corresponding LCA background system comprises the production, supply, and curing of the adhesives used.

The panels analyzed in this study represent a weighted average of the surveyed production mix. Hence, the functional units describe average products with several types of adhesives, never being used in one product in reality. Therefore, the discussion about variations of environmental impacts caused by application of different adhesives focuses on the specific adhesive types rather than the functional units. Figure 3 indicates a distinctive sensitivity of impacts to variation in adhesive properties in every category. Particularly large variations are visible for GWP, AP, and EP.

Specific greenhouse gas emissions associated with formaldehyde-based adhesives ranged from 1.8 to 2.5 kg CO_2-Eq/kg. In the case of a melamine backing of the urea–formaldehyde-based adhesives (MUF), the melamine is responsible for about 0.5 kg CO_2-Eq/kg, depending on the amount added. In PB production, 46-66 kg/m^3 of formaldehyde-based resins are used, and for FB, 88-139 kg/m^3 are used. Specific greenhouse gas emissions as a result of pMDI application are about 4 kg CO_2-Eq/kg, mainly resulting from the production of aniline, one of the three base chemicals for production of pMDI, in addition to formaldehyde and phosgene. Typically, in the case of pMDI, less adhesive per cubic meter of panel is applied than for formaldehyde-based resins. About 35 kg/m^3 is applied in the manufacture of conventional PB, and 21 kg/m^3 is applied in the manufacture of OSB. Little amounts of MUF are typically used for the decking layer when pMDI is applied. Peak greenhouse gas emissions from OSB manufacture result from the worst case estimation for OSB production. This will be further discussed in the Uncertainties section.

Variation in emissions leading to AP is particularly great in PB production. The reasons are the high amounts of sulfur dioxide emissions from production of phenol used in phenol–formaldehyde-based adhesives and to an even larger extent from production of pMDI. Therefore, urea-based resins dominate at the lower part of the variation beam, phenol-based resins rank in the middle, and pMDI resides at the top.

This is inversely the case for emissions leading to EP. Urea-based resins reside at the top because of the high amount of emissions of ammonia to water during production of urea and melamine. Phenol-based resins are again in the middle, whereas production and use of pMDI result in the lowest EP compared with other adhesives.

Regarding ADPe, the phenol-based and pMDI adhesives are at the very top of the indicated range.

Others

Diesel consumption in forklifts and other machines is very similar for PB, OSB, and FB. The amounts do not result in relevant impacts in the LCA background system "Diesel," including fuel supply and emissions from combustion.

The total mass of energy-related emissions from equipment used during production of PB and OSB adds up to about 60 g/m^3, whereas fiber-based panels produce about 260 g/m^3. The production of fiber-based panels consumes about four times as much lubricants as the PB production process. With regard to the ADPe indicator, some panel producers use more steel for tools than others, a factor that influences variability in emission values.

Wax is used for panels that need to last in humid conditions. Therefore, large amounts are used for OSB. However, the amounts do not result in relevant impacts on the LCI background systems "Equipment" and "Additives."

About 160-200 g/m^3 of foil is used to wrap 1 m^3 of PB or FB. For PB, about 125 g of cardboard and 60 g of steel are needed as well. Packaging of fiber-based panels requires about 4 times the amount of cardboard and 10 times the amount of steel. For OSB, less foil but more cardboard and steel is used compared with PB. Also, the amounts do not result in relevant impacts on the

LCI background system "Wrapping," comprising supply and waste management of the wrapping material.

Melamine Lamination

Generally, PB and FB can both be surfaced with melamine paper. The analyzed process for PB can be transferred to melamine-coated FB. On-site, the process consumes about 11 kWh/m^3 of electricity and 100 MJ/m^3 of heat. The melamine lamination has an average mass of 32.9 kg/m^3, which results in 308 g/m^2 of laminated area or 616 g/m^2 if both sides are laminated.

In total, the lamination process (including lamination material) is responsible for about 24-33% of the cradle-to-gate results of PBm for GWP, AP, EP, ADPf, and ODP. POCP and ADPe make up 11-12% of the total cradle-to-gate results. Regarding the actual source of emissions from lamination, the production of the lamination material is responsible for at least 89% of all indicator results. For production of melamine lamination material, electricity consumption, production of basic paper, and production of the melamine-based prepolymer together are responsible for 89-96% of the total emissions.

DISCUSSION

Uncertainties

Regarding wood combustion, uncertainties may arise from the literature-based model for all products. There are data gaps and data ranges to deal with.

The reported data gaps do not interfere with the impact categories declared in this study, because none of the emissions has an impact in those categories. However, if other indicators, especially those focusing on toxicity, are evaluated based on this data set, uncertainties may arise from the documented data gaps.

However, the data ranges do interfere with the impact categories declared in this study. Regarding uncertainties listed by Rentz et al (2009) and their impact in terms of wood combustion emissions by the WBP industry, the indicators AP, EP, and POCP are affected by large uncertainty as to emissions of NO_x, SO_2, and nonmethane VOCs. Uncertainties relevant for POCP results also arise from poor knowledge of VOC emissions from drying. Table 5 summarizes the uncertainties in LCA results that derive from uncertainties in emissions data from combustion and drying. For the latter, the impact of a 10% uncertainty on the LCA results was analyzed.

Table 5. Uncertainty in life-cycle assessment impact indicators as a result of uncertainty in data (%).[a]

Uncertainty	Emission factors	VOC from drying
Alternation range	EEA[b]	10
GWP	0-1.2	0-0.2
EP	0-14	<0.1
AP	0-27	<0.1
ODP	<0.1	<0.1
POCP	0-95	0-6.0

[a] GWP, global warming potential; EP, eutrophication potential; AP, acidification potential; ODP, ozone depletion potential; POCP, photochemical ozone creation potential; VOC, volatile organic compound; EEA, European Environmental Agency.
[b] Rentz et al (2009).

For wood supply, it was assumed that sawmill residues used in the panel industry arise exclusively from milling. This assumption was used to simplify the complex model of byproduct supply to the panels. In reality, other residues (eg planing residues) might be used as well. Because allocation is based on the economic value of products, significant impact accounting gaps do not occur when the amount of byproducts decreases while the value of the main products increases along the process value chain of solid wood products.

In the case of OSB, further uncertainties arise as a result of missing process-specific data. VOC emissions from drying may be substantially overestimated because it was assumed that all wood entering a plant was dried, although it might have been sorted out for combustion before drying.

Representativeness

Table 6 shows the production amount analyzed in comparison with total national production. Differentiation between total production of HDF

Table 6. Products and representativeness (fraction) of the analyzed volumes 2011.

	Production (1000 m^3)	
Products[a]	National[b]	Survey
PB	5750	4705
OSB	1200	—
FB	3600	652

[a] PB, particleboard; OSB, oriented strandboard; FB, fiberboard.
[b] EPF (2012).

and MDF was not possible on the basis of available data. Because the LCI for OSB relied on a survey of one company only, representativeness cannot be given because of confidentiality reasons. However, representativeness can be assumed to be 33% for OSB because all three German OSB plants have similar capacities. In conclusion, the representativeness achieved is fairly high compared with comparable studies listed in the Introduction.

Other Studies

Table 7 shows specific aspects of LCI results compared with other studies. For OSB, lower fuel consumption was calculated compared with data from Frühwald et al (2000) and Kline (2005). For FB, lower electricity consumption was measured compared with data from Frühwald et al (2000), Rivela et al (2007), and Wilson (2010b). However, in most cases, impact values are similar to those of other studies indicating good plausibility of the results.

Applying Life-Cycle Inventory Data

The LCI presented in this study can be used as a source of background data for various applications in need of environmental information regarding the production of WBP. The documented variations can be used to either express uncertainty as to results or model worst and best case scenarios. Alternatively, LCA practitioners can gather more specific data on a panel to narrow the variations for a specific impact indicator.

For GWP and ADPf results, information on adhesives, density, specific electricity consumption, type of fuel used for generation of heat, and transport distances can be helpful. In most cases, information on the three latter aspects is rather unlikely to be available at the product use level. In contrast, information on product density and applied adhesives is available in most cases. These two aspects also help to decrease variations in AP and EP results drastically. If information on electricity consumption is available, ODP results can be narrowed.

For POCP results, more information on drying emissions is needed. Nevertheless, the influence of density can be used to narrow variations also for POCP. Because of large uncertainties in nonmethane VOC emissions from fuel combustion, POCP results remain vague for any type of panel.

For ADPe, information on adhesive type and the amount of steel used helps to narrow variations. The indicator is pushed markedly upward if pMDI or it is used in panel manufacture.

In the case of FB or PB with melamine paper coating, the mass per unit area primarily determines the additional environmental impact.

CONCLUSION

This study presents disaggregated gate-to-gate LCI data for typical products of the German

Table 7. Different life-cycle inventory results (gate to gate) for production of panels compared with other studies.[a]

	Mass (kg)		Electricity (kWh)		Fuel (MJ)		Diesel (MJ)	
Product[b]	This	Other	This	Other	This	Other	This	Other
PBr	596	636-746	102	105-158	1704	1655-3112	26	16-18
OSB	573	610-649	121	130-207	2092	3000-3865	26	15
FB	691	615-741	298	353-415	6038	4211-8568	34	37-51

[a] Based on Frühwald et al (2000), Kline (2005), Rivela et al (2006, 2007), and Wilson (2010b, 2010c).
[b] PBr, raw, nonfaced particleboard OSB, oriented strandboard; FB, fiberboard.

WBP industry, with high representativeness. The presented data were discussed in terms of their relevance for several environmental impact categories starting with a gate-to-gate view toward a more complete cradle-to-gate assessment. Furthermore, the data were analyzed in terms of the sensitivity of environmental impacts to the variations in LCI, which were reasoned by variations among companies, products, and processes.

The results supply good background information for any type of environmental impact assessment in connection with WBP. On one hand, the data can be used as an average or worst case scenario if WBP only plays a minor role in the analyzed production system. On the other hand, this study supplies information on how to narrow variations in results if more precise data are needed. LCA practitioners can gather specific information described in this study to narrow the variations in results with respect to the environmental impact category they are interested in.

Reliable data are presented for the environmental impact categories GWP, AP, EP, ADPe, ADPf, and ODP. In the case of POCP, the impacts of uncertainties in emissions from wood combustion outweigh the impacts based on reliable information. Hence, more data are needed if POCP results will be looked at in detail. Nevertheless, with the data presented, a reasoned estimation and worst case scenario can be formulated even for POCP results for each product. For assessment of toxicity impacts based on the presented data, attention has to be paid to data gaps concerning dioxins and several other emissions listed in this study.

ACKNOWLEDGMENTS

Thanks to all companies that supplied data via questionnaires and during on-site visits. Thanks also to "Verband der Deutschen Holzwerkstoffindustrie e.V." (wood-based panel association) for their invaluable assistance in organizing communication networks between science and the German wood-based panel industry. Financial assistance for this research was provided by the Fachagentur Nachwachsende Rohstoffe (22028808). Special thanks to Sebastian Rüter and Johannes Welling for making this research possible.

REFERENCES

AG Energiebilanzen e.V. (2010) Auswertungstabellen zur Energiebilanz Deutschland, Daten für die Jahre 1990 bis 2009. AGEB, Berlin, Germany. 13 pp.

Albrecht S, Rueter S, Welling J, Knauf M, Mantau U, Braune A, Baitz A, Weimar H, Sörgel S, Kreißig J, Deimling S, Hellwig S (2008) Ökologische Potentiale durch Holznutzung gezielt fördern. Johann Heinrich von Thünen Institut, Institut für Holztechnologie und Biologie, Hamburg, Germany. 298 pp.

Böhmer S, Gallauner T, Gössl M, Krutzler T, Moser G (2010) Biomassefeuerungsanlagen, Im Leistungsbereich von 400 kW bis 10 MW. Umweltbundesamt GmbH, Wien, Germany. 76 pp.

Borcherding M (2007) Rundholztransportlogistik in Deutschland–Eine transaktionskostenorientierte empirische analyse. PhD thesis, Universität Hamburg, Hamburg, Germany. 266 pp.

Diederichs SK (2014) 2010 status quo for life-cycle inventory and environmental impact assessment of the core sawmill products in Germany. Wood Fiber Sci 46(1):1-20.

EN (2012) EN 15804. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products. European Committee for Standardization, CEN/TC 350—Sustainability of Construction Works, Brussels, Belgium. 50 pp.

EPF (2007) Annual report 2006–2007. European Panel Federation, Brussels, Belgium.

EPF (2012) Annual report 2011–2012. European Panel Federation, Brussels, Belgium. 328 pp.

European Commission (2010a) ELCD core database version II. Joint Research Centre–Institute for Environment and Sustainability, Brussels, Belgium. http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm (1 October 2010).

European Commission (2010b) ILCD handbook, general guide for life cycle assessment—Detailed guidance. European Commission, Joint Reserach Centre, Institute for Environment and Sustainability, Ispra, Italy. 414 pp.

FAO (2013) Wood based panels, production quantity, 2011. The Statistics Division of the Food and Agricultural Organisation of the United Nations, Domain Forestry, Forestry Production and Trade. http://faostat3.fao.org/faostat-gateway/go/to/home/E (5 July 2013).

Frühwald A, Scharai-Rad M, Hasch J (2000) Ökologische Bewertung von Holzwerkstoffen Schlußbericht März 2000 Ergänzt in den Bereichen Spanplattenrecycling und OSB-Bilanzen, Hamburg, Germany.

ISO (2006) Environmental management—Life cycle assessment—Requirements and guidelines, ISO 14044:2006. International Organization for Standardization. TC 204/SC5.

Jungmeier G, Werner F, Jarnehammar A, Hohenthal C, Richter K (2002) Allocation in LCA of wood-based products experiences of cost action E9. Int J Life Cycle Assess 7(6):369-375. www.springerlink.com/content/w5h3070684802251/ (30 August 2010).

Kaltschmitt M, Hartmann H (2009) Energie aus biomasse. M. Kaltschmitt, H. Hartmann, and H. Hofbauer, eds. Springer, Dordrecht, The Netherlands, Heidelberg, Germany, London, UK, New York, NY. 1054 pp.

Kline DE (2005) Gate-to-gate life-cycle inventory of oriented strandboard production. Wood Fiber Sci 37(Corrim Special Issue):74-84.

Milota MR (2000) Emissions from wood drying. Forest Prod J 50(6):10-20.

NRW (2011) Holzpreise NRW. Landesbetrieb Wald und Holz NRW. www.wald-und-holz.nrw.de/45Wald_und_Holz/20_Holzmarkt/10_Holzpreise/index.php (1 October 2011).

PE International (2012) GaBi 4 Software and GaBi Professional Database Version 4.131. PE International. Leinfelden-Echterdingen, Germany (available at http://www.gabi-software.com).

Polley H, Kroiher F (2006) Struktur und regionale Verteilung des Holzvorrates und des potenziellen Rohholzaufkommens in Deutschland im Rahmen der Clusterstudie Forst- und Holzwirtschaft. Bundesforschungsanstalt für Forst- und Holzwirtschaft Hamburg, Institut für Waldökologie und Waldinventuren, Eberswalde, Germany. 128 pp.

Reitberger F, Huber S, Streit A, Schmoeckel G, Ebertsch G, Stöttner A, Zell B (2001) Energetische Nutzung nachwachsender Rohstoffe. Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen, München, Germany. 77 pp.

Rentz O, Oertel D, Woodfield M, Stewart R (2009) Manufacturing industries and construction (combustion). Chapter 1.A.2. *In* EMEP/EEA air pollutant emission inventory guidebook 2009. European Environmental Agency, Copenhagen, Denmark. pp 1-34

Rivela B, Hospido A, Moreira MT, Feijoo G (2006) Life cycle inventory of particleboard: A case study in the wood sector. Int J Life Cycle Ass 11(2):106-113.

Rivela B, Moreira MT, Feijoo G (2007) Life cycle inventory of medium density fibreboard. Int J Life Cycle Ass 12(3):143-150.

Rueter S, Diederichs S (2012) Ökobilanzbasisdaten für Bauprodukte aus Holz. Thünen Institut, Hamburg, Germany. 299 pp.

Schweinle J (1996) Analyse und bewertung der forstlichen produktion als grundlage für weiterführende forst- und holzwirtschaftliche produktlinien-Analysen. bundesforschungsanastalt für forst- und holzwirtschaft, Hamburg, Germany. 139 pp.

Silva DAL, Lahr FAR, Garcia RP, Freire FMCS, Ometto AR (2013) Life cycle assessment of medium density particleboard (MDP) produced in Brazil. Int J Life Cycle Ass 2013(18):1404-1411.

Speckels L (2001) Ökologische vergleich verschiedener verwertungs- und entsorgungswege für altholz, dissertation im fachbereich biologie, ordinariat für holztechnologie, Universität Hamburg. Ordinariat für Holztechnologie, Universität Hamburg, Hamburg, Germany. 403 pp.

StELF (2011) Der aktuelle rohholzmarkt in Bayern. Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten. www.stmelf.bayern.de/wald/holz/004816/index.php (1 June 2012).

Tsupari E, Monni S, Pipatti R (2005) Non-CO_2 greenhouse gas emissions from boilers and industrial processes. VTT, Espo, Finland. 110 pp.

UBA (2012) Entwicklung der spezifischen des deutschen Strommix 1990-2010 und erste Schätzungen 2011. Umweltbundesamt, Dessau-Rosslau, Germany. 5 pp.

Universiteit Leiden (2010) CML 2001, characterization and normalization data. Universiteit Leiden. Institute of Environmental Science, Faculty of Science, Leiden, The Netherlands. http://cml.leiden.edu/software/data-cmlia.html (19 November 2012).

Wilson JB (2008) Particleboard: A life-cycle inventory of manufacturing panels from resource through product, CORRIM Phase II, Final Report Module F. University of Washington, Seattle, WA. 57 pp.

Wilson JB (2009) Resins: A life-cycle inventory of manufacturing resins used in the wood composites industry, CORRIM: Phase II Final Report, Module H. University of Washington, Seattle, WA.

Wilson JB (2010a) Life-cycle inventory of formaldehyde-based resins used in wood composites in terms of resources, emissions, energy and carbon. Wood Fiber Sci 42(CORRIM Special Issue):125-143.

Wilson JB (2010b) Life-cycle inventory of medium density fiberboard in terms of resources, emissions, energy and carbon. Wood Fiber Sci 42(CORRIM Special Issue):107-124.

Wilson JB (2010c) Life-cycle inventory for particleboard in terms of resources, emissions, energy and carbon. Wood Fiber Sci 42(CORRIM Special Issue):90-106.

Zeppenfeld G, Grunwald D (2005) Klebstoffe in der holz- und möbelindustrie 2. überarb. DRW Verlag, Leipzig, Germany.

Zimmer B (2010) Ökobilanz waldhackschnitzel. Magazin der Bayerischen Landesanstalt für Wald und Forstwirtschaft und des Zentrums Wald und Forst Weihenstephan 74:22-25.

Eur. J. Wood Prod.
DOI 10.1007/s00107-015-0934-9

ORIGINAL

Monitoring energy efficiency and environmental impact of the woodworking industry in Germany

Stefan Klaus Diederichs[1]

Received: 25 September 2014

Abstract The forest wood chain is affected by the current policy framework in context with environmental and energy related issues in many ways. But since policy instruments interfere with certain parts of the forest-wood chain separately, there is no holistic monitoring installed which follows the development of the complete chain. Especially the development of environmental aspects of the production of wood products is a rather black spot. To include the environmental impact of the woodworking industry in long term evaluations of political decisions taken today, the monitoring of its changes is indispensable. The article presents a monitoring approach which combines comprehensive life cycle inventory data on product level with historical data on sector level. The approach is confirmed to be feasible for monitoring greenhouse gas emissions and the consumption of fossil fuels. The results show that from 2003 until 2012 the sawmill industry increased its average greenhouse gas emissions from 35 to 43 kg CO_2-eq./m^3 and the wood based panels industry decreased the emissions from 353 to 325 kg CO_2-eq./m^3. In both cases, a change in the product mix of the two sectors was identified to be responsible. However, the results also indicate that both sectors gravely reduced their greenhouse gas efficiency due to a decreasing capacity utilization, which means that the environmental impacts for a specific type of wood product have changed distinctly over time. A comparison of the findings with displacement factors for wood products substitution was conducted to understand the relevance of the results. It showed that the development of environmental aspects of the woodworking industry needs to be taken into account for long term evaluations of political decisions affecting the forest wood chain.

✉ Stefan Klaus Diederichs
stefan.diederichs@ti.bund.de

[1] Thuenen-Institute of Wood Research, Leuschnerstr. 91c, 21031 Hamburg, Germany

Abbreviations

CHP	Combined heat and power
EGHG	Energy related greenhouse gas
EPD	Environmental product declarations
FEC	Final energy consumption
GHG	Greenhouse gas
IOLCI	Input-output life cycle inventory
LCA	Life cycle assessment
LCI	Life cycle inventory
LULUCF	Land use, land use change and forestry
PEC	Primary energy consumption
PRODCOM	Production communautaire
SMI	Sawmill industry
WBPI	Wood based panels industry

1 Introduction

1.1 Embedment of the wood manufacturing industry in the international and national policy context

The forest wood chain is affected by the current policy frameworks in context with environmental and energy related issues in many ways. With decision (2/CMP. 7) (UNFCCC 2011) of the Kyoto Protocol, LULUCF activities are taken into account more comprehensively. Annex I Parties to the convention shall account for anthropogenic greenhouse gas emissions resulting from forest management (UNFCCC 2011, Article 3.4, paragraph 7) and the

Published online: 14 June 2015

change in carbon pools of harvested wood products (UNFCCC 2011, General, paragraph 26).

A major route for the conversion of forest resources to wood products is the processing of wood raw materials in the wood manufacturing industry. Its processes are affected by the policy framework as well. Three main factors can be distinguished:

Firstly, mandatory EU targets fix 27 % of renewable energy in the gross final energy consumption in 2030 and a share of 10 % in the transport sector for the EU in 2020 (European Comission 2009). In Germany, the fundamental national implementation to reach targets in context with renewable energies is the German Renewable Energy Act (EEG) which has been revised and passed the Upper House of the German Parliament in July 2014. Almost 56 % of all renewable energy (as final energy) consumed in the German industry in 2012 was consumed by the wood manufacturing industry [Destatis 2014, as defined by NACE 2.2 Code 16 (Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials), which means the SMI and WBPI, excluding the pulp and paper industry].

Secondly, the EU set mandatory targets for the total consumption of energy. The energy efficiency directive (EED) sets an absolute maximum target of 62,090 Petajoule primary energy consumption in 2020 for the EU. On sub-national level, these targets are pushed further towards the different sectors of the economy. In Germany, an increase in energy efficiency in the industry was agreed upon between the German industry association and the government (BDI et al. 2012). Although not listed explicitly in the policy framework, ranking at position 9 of the biggest consumers of energy of all German industry sectors (Destatis 2014) the wood manufacturing industry is in charge of increasing its energy efficiency in line with other sectors of the industry.

Thirdly, a large application field for wood products construction—is increasingly influenced by environmental issues. On national and international level, assessment schemes for sustainability in construction have been introduced broadly. If decisions on building products are based on these schemes, the environmental impact as a consequence of producing wood products has a direct effect on the demand for these products.

1.2 Increasing pressure by policy development

During Kyoto's 1st commitment period, the EU over-accomplished its 2012 targets to reduce greenhouse gas emissions, but the implemented policy framework has to be improved in order to reach the targets for 2020 (European Comission 2013). While this deviation from the target path has been analysed for the fixed 2020 targets, the gap is likely to increase with regard to Barroso (2014), willing to push EU targets for 2030 down to minus 40 % and the German discussion towards a 40 % reduction target for 2020 (BMWi and BMU 2012a) (both targets are relative to emissions in 1990).

One of the reasons for the deviation from the target path are difficulties in increasing the overall energy efficiency. It is below target level in the EU (European Comission 2013) and also Germany is projected to shortfall in its 2020 targets, also because its industry has steadily worsened its energy efficiency since 2007 (Schlomann et al. 2012).

Further, the increase of the share of renewable energy of the total energy consumption is not on track. The progress report for renewable energies shows that although the EU hit the interim target of 10.7 % in 2010, further effort is needed to achieve the 2020 targets (European Comission 2013). Although not being the most evident failure in terms of compliance with EU targets, one reason for this gap is the negative trend for biomass energy utilization. It has a very large impact on the projected under-achievement of the EU and is assumed to be linked to the production cycles of the wood, pulp and paper industries (European Commission 2013).

The extensive use of wood fuel in the wood manufacturing industry and especially in the primary production of semi-finished wood products (the woodworking industry consisting of the SMI and WBPI) is well embedded within the national electricity mix. Since drying procedures (especially in sawmills) operate with low temperatures, CHP plants have been proven to be feasible additions on site: with a production of about 2 TWh of electricity in 2012 (Destatis 2012a), they produced approximately 6 % of the gross electricity production from biomass in Germany (BDEW 2013). Hence, the prosperity of the wood manufacturing industry is depending partly on the availability and price of the resource wood as well as the feasibility of benefiting from selling green energy in terms of remote heat or electricity from CHP plants.

With regard to Mantau et al. (2010) who projected the demand for woody biomass in Europe to very likely exceed its potential until 2030, prices for wood fuel are likely to rise. In addition, with the revision of the EEG, it also is still unpredictable how CHP plants or remote heat will contribute to the prosperity of the companies in the next years. As a consequence, the wood manufacturing industry is likely to face higher energy and material costs in the next years.

A possible reaction to higher resource costs, higher energy costs, a loss of indirect subsidies and the pressure to reduce the environmental impact could be a focus on resource efficiency and energy efficiency. One option to increase the resource efficiency is using less material for the same output, another is to use material with lower qualities or recycled material. Both bear interdependencies with other issues. Using less wood in the SMI or the WBPI either means to produce fewer by-products (in case of the SMI) or reduce the mass of wood in the products. The former will affect the WBPI as it relies on these by-products, the latter has an effect on the national greenhouse gas inventories in context with LULUCF accounting as described above.

Using more recycled wood is likely to change the specific environmental impact of the production, not just because the recycled material has different impacts (Höglmeier et al. 2014), but as today's processes rely on virgin material to a very large extent (recovered wood is used only for the middle layer of particle boards in Germany) they have to adapt to the characteristics of recycled material, which is likely to change their specific energy consumption.

1.3 Holistic approaches

The surveillance of the development of the aspects which influence the forest wood chain is performed on different aggregation levels. Forest management emissions and changes in wood product carbon pools can be assigned to the woodworking industry quite unambiguously since the interdependencies rely on the produced volumes which are available in national statistics.

In contrast to this, the development of the environmental implications of the production of the products is rather complex to assess since the available data is not directly referring to the woodworking industry. Today, the political target path is monitored on the basis of several indicators frequently published by the government (BMWi 2014). In this context, either the energy intensive industrial sectors are focused singularly, or the woodworking industry is aggregated within others (Fleiter et al. 2013; Lechtenböhme et al. 2014; Wünsch et al. 2012) and not part of the separate industry monitoring (Frondel et al. 2013).

Further on, the final energy consumption and direct CO_2 emissions are only one environmental aspect of the woodworking industry. The generation of energy (CHP plants) on site, emissions which occur in the supply chain (other than wood) and other important emissions like NMVOC, SO_2 and NO_x are not holistically available for the sector in general.

Theoretically, a comprehensive LCA approach could solve the problem, but as shown by Diederichs (2014a, b), the required data is not available for every product and every year.

Hence, it is not known how the sector changed nor is it expected to be known in the future if today's data availability remains. If the environmental impact of the wood manufacturing industry is to be included within long term evaluations of political decisions taken today, monitoring changes in the sector is indispensable. Further on, as LULUCF accounting differentiates between sawnwood and wood based panels, it is necessary to even go one level below the sector level and differentiate between the SMI and the WBPI.

1.4 Objective

It is the objective of this article to present a monitoring procedure for the woodworking industry sector which is able to answer the following question: How did the German sawmill industry and the wood based panels industry develop with regard to national targets on greenhouse gas emissions, energy efficiency and environmental issues in context with schemes for the assessment of sustainability of construction works?

The secondary objective of the article is to show the current data gaps which have an effect on the completeness and quality of such a monitoring procedure.

2 Methodology

2.1 General

The presented approach relies on two fundamental assumptions:

- A sector of industry can be defined holistically by the products or services it produces
- The energy consumption and environmental impacts which are caused by the production of those products and services can be quantified comprehensively by using the method of product LCA.

The logical conclusion from this is that multiplying the amount of the products and services supplied by the sector in a certain year by the product specific mean environmental impacts and energy consumption caused by the production of those products in the same specific year expresses the environmental impact and energy consumption of the sector of industry in the specific year.

Comparing the results of at least two different years then quantifies a development. This quantification is called monitoring.

In reality, the required comprehensive LCI information [i.e., all inputs and outputs of the production process of a certain product from all producers of a sector (see for example Diederichs 2014a, b; PE International 2012; Werner et al. 2007)], which is underlying every product LCA, is not available for every product and every year. The approach presented in this paper therefore combines comprehensive product specific LCI data for a product which is available in 1 year with sector specific data (e.g., annually surveyed electricity consumption data for a certain sector—see Sect. 2.5) which is available for other years.

To do this, firstly, the product specific LCI data is simplified by filtering the most relevant information which is needed to calculate an environmental impact or an energy consumption issue for this product. Secondly, this identified relevant share of the LCI is replaced by information on sector level if available for other years.

2.2 Indicators

The indicators which are disseminated in the monitoring are listed in Table 1. With regard to the aim of the monitoring approach, those indicators must be comparable to the indicators used to express political targets for 2020 and those used in context with the environmental assessment of building products in general.

To achieve comparability to indicators used for the environmental assessment of building products, the five impact categories disseminated in EPD based on EN 15804:2012-04 (2012) are included in the approach. To achieve comparability to the political targets on national level and EU level absolute values for the total FEC (European Parliament 2012), for the total PEC (European Parliament 2012) and the total emissions of greenhouse gases (United Nations 2012) are included. The comparability to sector level targets is gained by disseminating the above absolute values relative to the total production volume of a sector (Frondel et al. 2013) and relative to the net value added generated by the sector (BMWi and BMU 2012a; European Parliament 2012). The latter is also referred to as energy intensity or—reciprocal—energy productivity (carbon intensity respectively) but is not defined identically in every case. While BDI et al. (2012) uses the same term for targets which are related to the product value of the produced good, in this article the net value added (NVA) is used as it is promoted by the United Nations to be used for eco-efficiency indicators (Sturm et al. 2002) with

$$NVA = R - C - TA \text{ with} \quad (1)$$

R is the Revenue
C is the Cost of goods and services purchased
TA is the Depreciation on tangible assets

Table 1 Identified relevant indicators

Indicator (I)	Abbreviations
Absolute indicators	
Energy related indicators	
Final energy consumption	FEC
Primary energy consumption	PEC
Greenhouse gas emissions from energy consumption	EGHG
LCA related indicators	
Global warming potential 100yr.	GWP
Acidification potential of soil and water	AP
Eutrophication potential	EP
Depletion potential of the stratospheric ozone layer	ODP
Formation potential of tropospheric ozone	POCP
Abiotic depletion potential (ADP-elements) for non fossil resources	ADPe
Abiotic depletion potential (ADP-fossil fuels) for fossil resources	ADPf
Relative indicators	
All above indicators relative to production volume (per m^3)	P-(I)
All above indicators relative to net value added (per Euro)	V-(I)

2.3 Definition of the sector

The monitoring approach differentiates between the SMI sector and the WBPI sector analogously to the LULUCF accounting methodology, which differentiates between sawnwood and wood based panels (European Parliament and Council of the European Union 2013). Each sector is defined by its products listed in the *Statistics on the production of manufactured goods* supplied by the European Commission also known as PRODCOM. Hence, the SMI is defined by all products listed under PRODCOM Codes 16.1 (NACE Rev. 2) and 20.1 (NACE Rev. 1.1). The WBPI is defined by all products listed under PRODCOM Codes 16.21 (NACE Rev. 2) and 20.20.1 (NACE Rev. 1.1).

2.4 Life cycle inventory and impact data

2.4.1 *Functional units*

The monitoring approach is based on life cycle assessment methodology in accordance with EN ISO 14044:2006 (2006). Hence, the clearly measurable reference to which the LCI data refers is identical to the so called functional units used in LCA. The following functional units are applied:

In the simplifying approach (Sect. 2.4.4) a functional unit for the production of 1 m^3 of each core product of the sector (Sect. 2.4.3) is defined.

The monitoring approach on sector level uses three different functional units:

– the total production volume of all products in each sector per year

- 1 m^3 of an average (weighted by production volume) product of each sector
- 1 Euro of net added value in each sector.

2.4.2 System boundaries

Two types of system boundaries are applied to the monitoring approach (Fig. 1). In case of the energy related indicators (FEC, PEC, EGHG) the system boundaries comprise all energy inputs and outputs of a production site. They include electricity, fossil fuels and renewable fuels like biomass and remote heat. FEC is obviously measured at the gate to gate boundaries of a production site. It aggregates different energy types to one number, irrespective of their potential exergy level (1 MJ from electricity and 1 MJ from steam add up to 2 MJ of final energy). The PEC and EGHG are measured at the cradle to gate boundaries of the energy supply chain.

The second system boundary is defined for the LCA related indicators as defined in EN 15804:2012-04 (2012) with the exception that byproducts are not cut away by allocation procedures. Hence, the system boundaries comprise the production of the byproducts as well.

For energy outputs which occur due to utilisation of CHP plants, the respective inputs and emissions are allocated to the energy used on site based on exergy as described and reasoned by Diederichs (2014a, b) and Rueter and Diederichs (2012).

The wood resources used for material purposes are not included in the system boundaries. The reason for this is that the monitoring approach aims to show changes within the process of changing wood resources into wood products separately from the forest part and the product part of the forest wood chain.

This is in contrast to decision-oriented studies for wood products (e.g., Nabuurs et al. 2007; Osterburg et al. 2013; Sathre and O Connor 2010) which typically focus on the environmental benefit of different value-, process- or product-chains applicable to the same type of resource. In those cases all relevant aspects affected by the decision need to be included in the system boundary of the analysis.

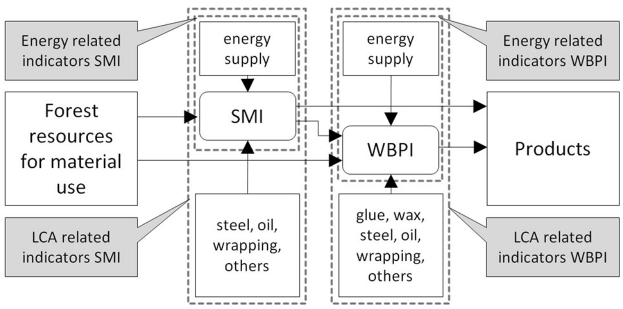


Fig. 1 System boundaries (*dashed lines*) for energy related indicators and LCA related indicators

However, retrospectively (monitoring) it is already known how much wood is used in the woodworking industry and how many products were produced. It is already known how the market reacted to the changing supply of wood products and the amount of recovered wood that entered the market. What is not known is how the environmental impact of processing the wood changed as a result of all those surrounding parameters.

The monitoring therefore does not take the complete life cycle of the wood products into consideration but only the processes between forestry and the semi-finished products of the SMI and the WBPI. In context of EN 15804:2012-04 (2012) this means that only modules A1 to A3 (Raw Materials, Transport and Production) are regarded without the wood used for material purposes. Wood used as fuel is considered in contrast as it is used or consumed on site and not only transformed to a different product.

2.4.3 Inventory data on product level

Data for the product specific environmental and energy related aspects of the woodworking industry is based on a survey of 43 German sawmills and 17 panel mills, supplying comprehensive LCI for their production. The survey was conducted over a period of 3 years and was complemented by several site visits including plausibility checks by comparing emission protocols and electricity bills. The reference year is 2010. Data was gathered for the core products of each sector.

Within the SMI, data for sawnwood green, sawnwood kiln dried and planed sawnwood was gathered (for coniferous and non-coniferous species). Within the WBPI, data was gathered for the production of particleboard raw and faced, oriented strand board, high density fiberboard and medium density fiberboard as well as plywood. Since the survey supplied data for plywood from two producers only, the plywood data was complemented by data from Wilson and Sakimoto (2005). The full LCI datasets for the core products and the relevant masses and contents of the functional units have been published prior to this paper (Diederichs 2014a, b).

The LCI datasets are assigned to the products listed under PRODCOM, whereas for the products of the SMI problems occur while differentiating between sawnwood which has been technically dried and sawnwood which has not. There is no comprehensive statistical data available that solves this issue. However, drying processes for sawnwood consume a lot of energy and differentiation between the products is necessary.

Therefore, it was assumed that all products which are declared to have been planed (in national statistics) were technically dried prior to the planing procedure. This means, that the minimum share of technically dried sawnwood is equal to the share which has been planed. Secondly, based on information from the German sawmill association (Deutsche Säge- und Holzindustrie Bundesverband e.V.) which made an internal (unpublished) survey in 2014, the share of technically dried wood of all sawnwood products currently (2013/2014) is between 50 and 70 %.

For the retrospective view, it needs to be considered that before 2005, green (not technically dried) wood was allowed for use in load bearing functions in construction applications (Schmidt and Schmidt 2005) and the production of engineered solid wood products that require technically dried sawnwood due to the utilisation of glues, has been increasing in the last years (UNECE and FAO 2012). For 2002 it is therefore assumed that the share of technically dried wood was much lower than in 2014, in fact between 23 % (the pure amount of sawnwood which has been reported to be planed) and 50 %. For the years in between, a linear trend is assumed. Consequently for 2010 the share is between 34 and 55 %. The model uses the average value for 2014 (60 %) and 23 % for 2002. The uncertainties connected to this are discussed in Sect. 3.2.

2.4.4 *Simplification of life cycle inventory data*

With regard to the complexity of LCI and LCA, simplification approaches [also called streamlining (Fleischer et al. 2001)] have been conducted by other authors before. Simplification in this context is neither referring to approaches which look at a few indicators only (e.g., Bouhaya et al. 2009) nor those that try to use few available indicators to explain missing indicators as this bears problems (Moberg et al. 2014). Simplifying here refers to completing an incomplete process LCI by using other data sources.

One of the most prominent approaches for this is hybrid LCI, a mixture between process-based LCI and IOLCI. The latter approach principally uses economic *supply-use* tables which supply information on the supply of goods and services from a sector (called activity) and the goods and services used by an activity. To isolate the goods and services that were needed in a sector to produce a certain product, all co-products which are produced by the sector as well are substituted by replacing them as negative input to the same activity (Weidema et al. 2009). The resulting tables are called *direct requirement* tables, and they offer a unique insight into the product requirements of a sector to produce a specific product.

Seppäläa et al. (2005), for example, presented a IOLCI-based method on how to measure and monitor the eco-efficiency of a region. The authors used economic input-output tables in combination with material flows according to NACE sector categories.

One of the advantages of this approach is its ability to produce rapid screening-level inventories (Wright et al. 2008) but high variations occur due to the necessary assumptions on prices (Moberg et al. 2014), and monetary input output tables may violate the underlying mass balance. Unless no detailed data on the difference in consumer prices is available, mass based information should be preferred before monetary input output tables are applied (Merciai and Heijungs 2014). Further on, calculation demands a lot of work and producing annual data is not possible. The material flow based analysis always implicitly assumes that each ton of material has the same environmental impact (Seppäläa et al. 2005).

In Germany, the economic *supply-use* tables are available in 4 year cycles, published 4 years after the reference year (data available from 2010, 2006 and 2002). As they are based on monetary units, the inherent assumption would be that every Euro of flow from a specific activity has the same environmental impact.

Hence, the hybrid approaches usually use process based LCI to cover the most relevant parts (in terms of their effect on an indicator) and IOLCI to complete the rest of the inventory (tiered hybrid analysis) or the cut offs of the process based LCI (integrated hybrid analysis) (Suh and Huppes 2005).

The approach presented in this article uses the sector level data for the most relevant parts which have effects on the indicators and the process based LCI data to complete the rest of the inventory of the sector instead. The left side of Fig. 2 shows the essential idea of the simplifying procedures that underly the monitoring approach in this paper. Process based LCI data for all product groups is analyzed in terms of the sensitivity of every inventory flow quantity towards an indicator following the concept of a perturbation analysis, which means that the sensitivity of the results for each input parameter is analyzed while neglecting the uncertainty in the parameter (Heijungs and Kleijn 2001).

Analogously to Collet et al. (2013), who used the approach to identify the sensitivity of temporal dynamics in the LCI in this paper, the approach is used to differentiate between inventory flows with high relevance (HiRel) for an indicator and those with low relevance (LoRel), based on the process based LCI of the reference year. The aim of this method is to cover at least 80 % of an impact category with as little information as possible, whereas 80 % is a freely chosen parameter to set a minimum limit.

From a mathematical point of view, the approach can be described with the following definition: For each inventory quantity A of an inventory flow k of product p, the factor f determines its importance for an indicator result. The factor f can be determined at the gate to gate system boundaries for every input and output flow of the inventory by

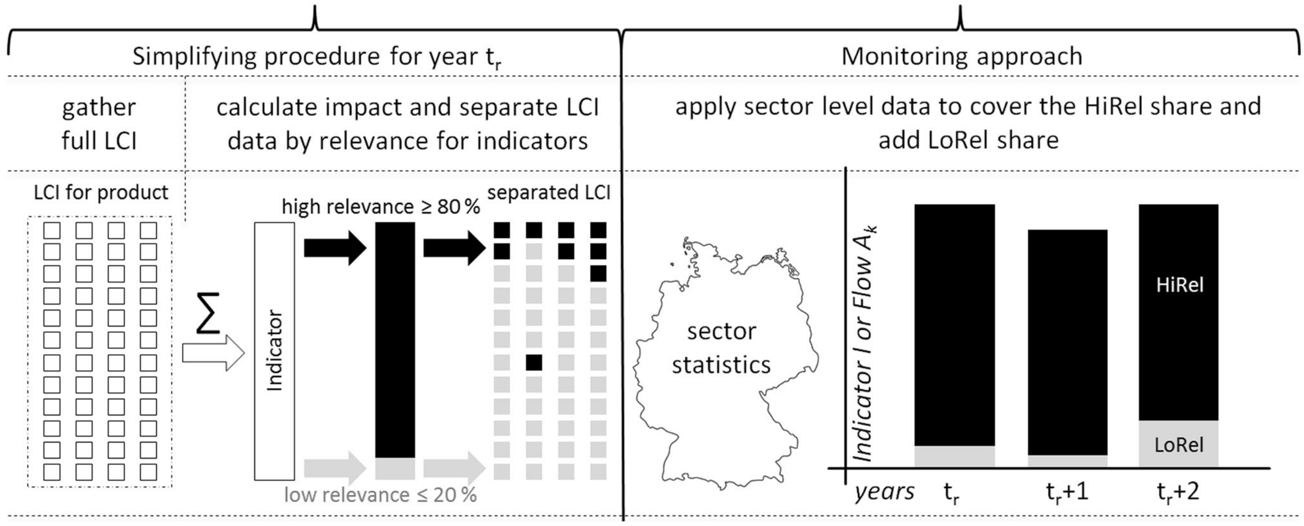


Fig. 2 Overview of the approach (*HiRel* high relevance, *LoRel* low relevance, t_r reference year)

calculating the specific impact of the flow. For the GWP indicator, for example, $f_{electricity}$ describes the CO_2-equivalent emissions emitted to supply 1 kWh of electricity from cradle to the production site, $f_{wrapping}$ describes the CO_2-equivalent emissions emitted to supply and dispose 1 kg of the average wrapping mix of a product. The sum of all A_k, f_k couples defines the total indicator result for the product (see Eq. 2).

Since it is important to differentiate between data derived from product based LCI and the data available on sector level, *Prod* is used to describe an Indicator *I* or inventory flow *A* derived from product-LCI based data and *Sec* for an Indicator or flow derived from data available on sector level. Equation 2 shows the calculation of a single indicator for 1 m^3 of a product derived from product based LCI.

$$ProdI_p = \sum_{k=1}^{n} ProdI_{k_p} = \sum_{k=1}^{n} \left(A_{k_p} \times f_{k_p}\right) \tag{2}$$

The same indicator for the total production *V* of a product produced in year *t* is

$$ProdI_p(t) = V_p(t) \sum_{k=1}^{n} ProdI_{k_p} \tag{3}$$

and the indicator result for the total production *V* of all products produced in the sector *s* produced in year *t*, whereas the sector *s* is defined by its products $p = \{1, \ldots, n\}$ is

$$ProdI_s(t) = \sum_{p=1}^{n} ProdI_p(t) \tag{4}$$

Single inventory results based on product based LCI (*ProdA*), upscaled to sector level for the flow *k*, the year *t* and all products *p* of sector *s* can be calculated by

$$ProdA_{k_s}(t_1) = \sum_{p=1}^{n} \left(V_p(t_1) \times \left(A_{k_p}\right)\right) \tag{5}$$

To introduce the product based LCI *LoRel* share (Eq. 7) named *ProdLoRel* and the *HiRel* share named *ProdHiRel*, the couples ($ProdI_{k_p}$) are sorted by value in descending order and an $x \in k$ is introduced which defines the border (20, 80 %) between flows of high relevance $k = \{1, \ldots, x\}$ and those of low relevance $k = \{x+1, \ldots, n\}$ (Eq. 6). Hence, $x + 1$ defines the greatest pair included in the *ProdLoRel* share of a certain product and consequently *x* the smallest couple in the *ProdHiRel* share (Eq. 8).

$$ProdI_{1_p} > ProdI_{2_p} > \cdots > ProdI_{x_p} > ProdI_{(x+1)_p} > \cdots > ProdI_{n_p} \tag{6}$$

$$ProdLoRel_p \leq ProdI_p \times 0.2 = \sum_{k=(x+1)}^{n} \left(A_{k_p} \times f_{k_p}\right) \tag{7}$$

$$ProdHiRel_p = ProdI_p - ProdLoRel_p \tag{8}$$

2.5 Data available on sector level

2.5.1 General

The right side of Fig. 2 shows the application of the simplified data and sector data for the monitoring. In contrast to typical hybrid approaches, the most important part of the LCI is covered by data not derived from product based LCI. In the approach, available (retrospective) data on sector level is applied to cover the *HiRel* share which was identified in the perturbation analysis. Instead of using monetary flow information from input-output tables, statistics on energy consumption and emissions on sector level are used based on their physical units.

Hence the *HiRel* share based on sector data named *SecHiRel* in the specific year t_1 for sector s is defined by Eq. 9.

$$SecHiRel_s(t_1) = \sum_{k=1}^{x} \left(A(t_1)_{k_s} \times f_{k_s} \right) \quad (9)$$

The LoRel share on sector level (named *SecLoRel*) in the specific year builds upon the information in the LCI from the reference year t_r and the production quantities V produced in the specific year t_1, whereas the sector s again is defined by its products $p = \{1, \ldots, n\}$ (Eq. 10).

$$SecLoRel_s(t_1) = \sum_{p=1}^{n} \left(V_p(t_1) \sum_{k=(x+1)}^{n} \left(A_{k_p}(t_r) \times f_{k_p} \right) \right) \quad (10)$$

The result of adding the shares (Eq. 11) is the final indicator I including a complete LCI of a specific year of a sector, combining sector level data with product specific LCI data.

$$I(t_1)_s = SecHiRel(t_1)_s + SecLoRel(t_1)_s \quad (11)$$

The absolute development from year t_1 to t_2 is defined by Eq. 12, the relative development is defined by Eq. 13, whereas t_3 typically is equal to t_1 since the change from 1 year to another is typically described as the change relative to the first year. If an index is used (for example 100 % = 2003) the change from 2010 to 2011 is expressed in relation to the year 2003.

$$\Delta I(t_1 \rightarrow t_2)_s = I_s(t_2) - I_s(t_1) \quad (12)$$

$$\Delta I \left(\frac{t_1 \rightarrow t_2}{t_3} \right)_s = \frac{I_s(t_2) - I_s(t_1)}{I_s(t_3)} \quad (13)$$

2.5.2 *Production quantities*

Since PRODCOM data is used to define the sector, information on annual production volumes for the core products are based on Destatis (2012b) et seqq. and Destatis (2010) et seqq. The latter publications supply useful aggregated production data for the woodworking industry which is needed to avoid data gaps due to confidentiality reasons in the former publications. Data is available from 2002 until 2012.

2.5.3 *Energy consumption*

The FEC is surveyed by the German statistical office on a yearly basis (Destatis 2012a) and publicly available for each sector. Responding to the survey is obligatory for all companies. The survey includes the consumption of all final energy types except diesel for trucks and forklifts used on site. Further on, the generated electricity is surveyed. Data is available from 2003 until 2012. PEC and EGHG can be based on PEC when differentiated by energy types and adding background information on energy transformation and supply technologies (Energiebilanzen e.V. 2010, et seqq.). The electricity produced in the sector is allocated in the same manner as described in Sect. 2.4.

2.5.4 *Emissions*

On national and European level, emission data is available from the European Pollutant Emission Register (EPER) based on Directive 96/61/EC from 2003 until 2005 and from the Pollutant Release and Transfer Register (PRTR) based on Regulation 166/2006/EC from 2007 onwards (see EEA 2014 and UBA 2014, for complete data).

The reporting allows insights into several emissions into air from the wood based panels industry but none from the sawmill industry. The PRTR forces the WBPI to report their emissions if they exceed the thresholds defined in the regulation. In case of CO_2, the typical size of a WBPI member is too small to exceed the threshold values, although biogenic carbon dioxide is part of the PRTR reporting. For several companies, emissions of NO_x and non-methane volatile organic compounds (NMVOC) are reported. Allocation procedures in terms of additional emissions due to CHP plants are executed as described above.

2.5.5 *Economic value added*

Information on NAV of different industry sectors is calculated and reported by the German statistical office and published annually (Destatis 2012c, et seqq.).

2.6 Plausibility check

Before the data on sector level is used to calculate results for other years, a plausibility check is done for 2010, comparing up-scaled LCI results $ProdA_{k_s}(t_r)$ (Eq. 5) for electricity, fuels and emissions of NMVOC and NO_x with the available data on sector level $SecA_{k_s}(t_r)$. The relative difference of the two datasets is defined as

$$\Delta A_k(Prod \rightarrow Sec, t = 2010) = SecA_{k_s}(2010) - ProdA_{k_s}(2010) \quad (14)$$

3 Results and discussion

3.1 Simplification of the LCI

Figures 3 and 4 show the information required to cover the HiRel share of all LCA based indicators for all sawmill products and panel products.

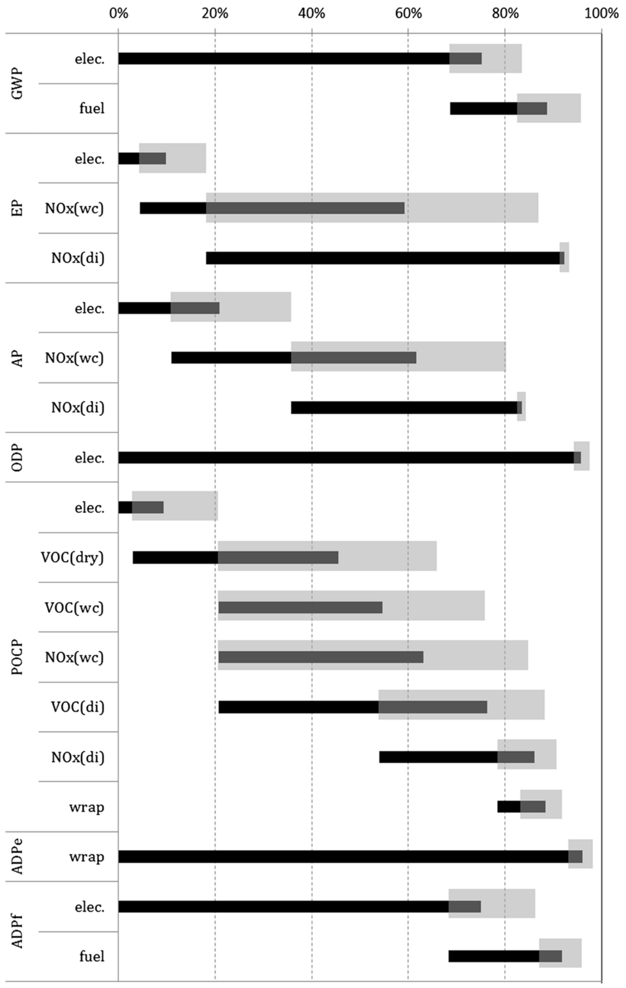


Fig. 3 Information requirement to cover the HiRel share for a cradle to gate LCA excluding wood supply for the core products of the SMI. For each piece of information, the *black beam* shows the average cover of the cradle to gate result of the indicator. The *gray beam* indicates the possible deviation for each product. The next *lower beam* shows, how much information is added to the first piece of information. The HiRel share is complete if the *left border* of the *gray beam* reaches 80 % or more

With regard to the sawmill products (Fig. 3), the knowledge of electricity consumption covers large parts of the GWP, ODP and ADPf indicators, for green or air dried sawnwood; it even covers more than 80 % of the total GWP results. If information on the total consumption of fossil fuel and diesel is added, the HiRel share of GWP, ODP and ADPf is covered for all sawmill products. For the evaluation of the EP and AP indicator, knowledge of the total emissions of NO_x from wood combustion and diesel combustion is needed. For POCP, knowledge of NMVOC emissions from the drying process and the combustion of wood and diesel as well as information on the steel used for wrapping is needed to cover the HiRel share. The ADPe indicator is sufficiently described by the steel used for wrapping singularly.

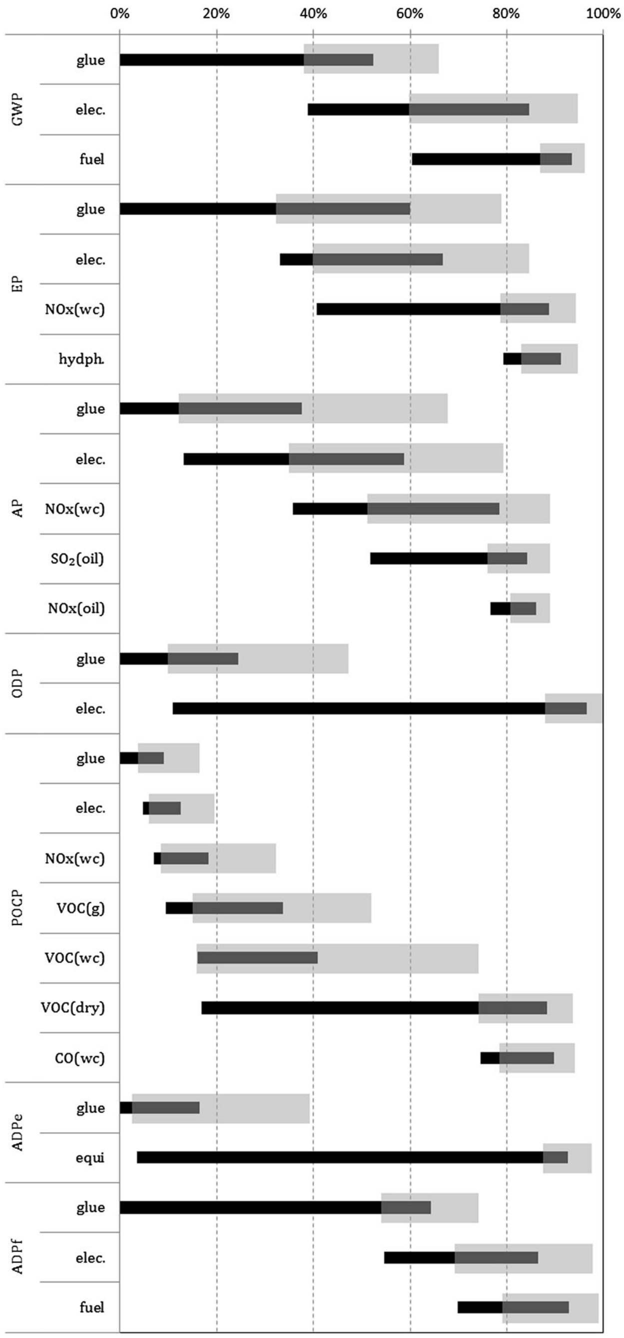


Fig. 4 Information requirement to cover the HiRel share for a cradle to gate LCA excluding wood supply for the core products of the WBPI. See also caption of Fig. 3

The cradle to gate indicators for the panel products (Fig. 4) are essentially described by the same type of information. Additively, information on the amount and type of applied glue and wax are important. Due to a different mix in fuels used to generate thermal energy, information on NO_x and SO_2 emissions due to use of fuel oil are part of the HiRel share. Further on, emissions of CO from wood combustion and the total amount of steel used as equipment are required

Table 2 Difference of LCI up-scaled data to available data on national level, *Prod* Results derived from bottom up approach by using product specific LCI, *Sec* Data from national statistics, $\frac{\Delta A}{Prod}$ Deviation of data from statistics to data derived from LCI

Inventory for t = 2010	s = SMI			s = WBPI		
Flow *k* (Unit)	*Prod*	*Sec*	$\frac{\Delta Prod \rightarrow Sec}{Prod}$ (%)	*Prod*	*Sec*	$\frac{\Delta Prod \rightarrow Sec}{Prod}$ (%)
Electricity (GWh/year)	1018	1050	3	2519	2605	3
Fuels (PJ/year)	30	20	−32	42	33	−21
NO_x (t/year)		n.a.		3981	>4551	>14
her/year)		n.a.		2234	>4477	>100

information. The first three purely energy related indicators in Table 1 (FEC, PEC and EGHG) are influenced by the consumed electricity, fuel for thermal heat generation, sold electricity and heat as well as consumption of diesel. None of these aspects has been proven to have (singularly) less than 20 % influence. Hence, all aspects need to be included to cover the HiRel share.

3.2 Plausibility check

Table 2 shows the difference between results from up-scaled LCI data and data available on sector level. In terms of electricity consumption only small differences exist between data reported on sector level and those derived from upscaling LCI data. Larger differences are visible for data on fuel consumption and emissions. PRTR data on sector level is higher in case of NMVOC and NO_x.

With regard to uncertainties in context with the amount of kiln dried sawnwood, a variation of the values for green sawnwood from 50 to 70 % in 2014 and 23 to 50 % in 2002 was applied. The difference $\frac{\Delta Prod \rightarrow Sec}{Prod}$ for electricity alternated between 0.5 and 7 % and between 45 and 30 % for the consumption of fuel.

3.3 Discussion and relevance for the monitoring approach

The simplification procedure showed that only little data is necessary to cover at least 80 % of each indicator for every product. For the energy related indicators and GWP from cradle to gate, mainly data on energy consumption is needed.

To evaluate the results of the plausibility check in terms of their significance, the underlying calculation and survey methods have to be compared in each case:

Strictly speaking, the comparison of results in context with energy consumption is a comparison between the results of two different surveys with similar goals. The product based LCI are based on information from companies and—with a few exceptions where data was controlled by comparing it to invoices—the responsibility of correctness of the data lies with the company. While doing plausibility checks on the mass balance of the wood inputs, outputs and wood that had been used to generate energy, several problems became apparent which are closely related to the inherent characteristics of wood. First of all, the units used for logs, sawnwood, byproducts and wood fuel are different. While logs and products are typically sold based on their solid volume, byproducts and fuel are mainly traded in mass or bulk volumes. Since the raw density of wood can deviate greatly even for one species, and the water content of the wood is either hard to measure or just not available continuously, a conversion from volume to mass bears some strong uncertainties. Secondly, logs sold to sawmills are usually sold by their solid volume without the bark. Hence, the amount of bark is assumed while its specific volume depends on the average diameter of the logs which can be very different depending on the type of sawmill technology. For the WBPI the problem is less severe. Since the quality of the panel products strongly relies on the quality of the chips, strands or fibers including their humidity, the relevant parameters are typically controlled continuously. However, quantities and heating value of the wood fuel used in the WBPI struggle with the same uncertainties as described for the SMI. Finally, there are no harmonized and accepted conversion factors for bulk volumes to solid volumes. The survey showed that a large variety of conversion factors were used by the companies.

For this reason, the conducted survey focused on the volume of wood inputs and outputs. As those were subject to trade and pricing, it was assumed, that their quantities were well known. The difference of the mass balance of the wood input and output was assumed to be the mass of wood which was used for generation of energy on site. For each wood species, one specific density and heating value was chosen. The share of bark was averaged and assumed to be the same for each species. If conversion factors were needed, they were used consistently within the survey, irrespective of information from the companies. All relevant conversion factors and characteristic values for the wood species are documented in prior publications (Diederichs 2014a, b; Rueter and Diederichs 2012).

In contrast, the statistical office conducts surveys on energy consumption by directly asking for the amount of energy used (Destatis 2013). This approach seems to be less suitable since the energy used on site is typically estimated by using individual conversion factors as described above. This was also an experience made during the survey conducted by the author.

On the other hand, it is a complete inventory account, not vulnerable to deviation of specific energy consumption issues like the product specific LCI data is. One would therefore expect information on energy inputs which are uniquely countable like electricity consumption, to be a good indicator for the comparability of the two datasets. For the wood fuel one would expect the LCI data to generally declare higher consumption while the difference is expected to be smaller for the WBPI, since their share of additionally bought fuel (and therefore subject of trading and better knowledge) is higher.

The plausibility check for 2010 (Table 2) showed that especially results on electricity consumption based on data from LCI are consistent with data on sector level. Data for the fuel consumption on sector level are much lower than the data derived from the process LCI. For the WBPI this difference is smaller than for the SMI. The results therefore comply with the expected results.

With regard to comparison of emissions of NO_x and NMVOC, two conclusions can be drawn:

Firstly, since not all companies report their emissions via PRTR, but the sum of the reported emissions is already higher than the sum of NO_x emissions or NMVOC emissions which are derived from the process based LCI, the latter is likely to underestimate these emissions gravely. Also, the emissions reported via PRTR were measured in most cases (75 % for NMVOC and 60 % for NO_x in 2010) and LCI data for NO_x emissions and NMVOC emissions were based on continuously conducted measurements for two companies only, but primarily derived from literature (emission quantities were modeled for different combustion sizes, filter technologies and fuel wood types as described in Diederichs (2014a, b) and Rueter and Diederichs (2012).

Hence, for NO_x and NMVOC emissions this means that they quantitatively rank at the higher border of uncertainties described by Rentz et al. (2009), and additionally for NMVOC emissions that other processes like drying and pressing may also be gravely underestimated by the LCI data.

Secondly, the results strengthen the hypotheses that energy statistics on sector level underestimate the amount of biomass used for energy since the quantity of emissions is closely connected to the amount of fuels used.

However, the results stay uncertain. As shown by Rueter and Diederichs (2012), the emissions can deviate heavily for different combustion sizes, filtering technologies and fuel types. Official data on uncertainties published by Rentz et al. (2009) and sensitivity analysis for wood products done by Diederichs (2014a, b) based on those uncertainties confirm this.

With regard to the monitoring approach, this implies that the HiRel share for a retrospective view back to 2003 can be thoroughly covered for all energy related indicators by data on sector level. The GWP indicator lacks data on sector level concerning glue types and amounts for the WBPI. Hence, only 50 % can be covered by data on sector level for the WBPI sector. For the SMI, the HiRel share of the GWP indicator can be covered completely. For the AP and POCP indicators, a minimum value for the WBPI can be derived when using PRTR data. For all other indicators, no robust retrospective view can be derived from the available data.

3.4 Selected results of the monitoring

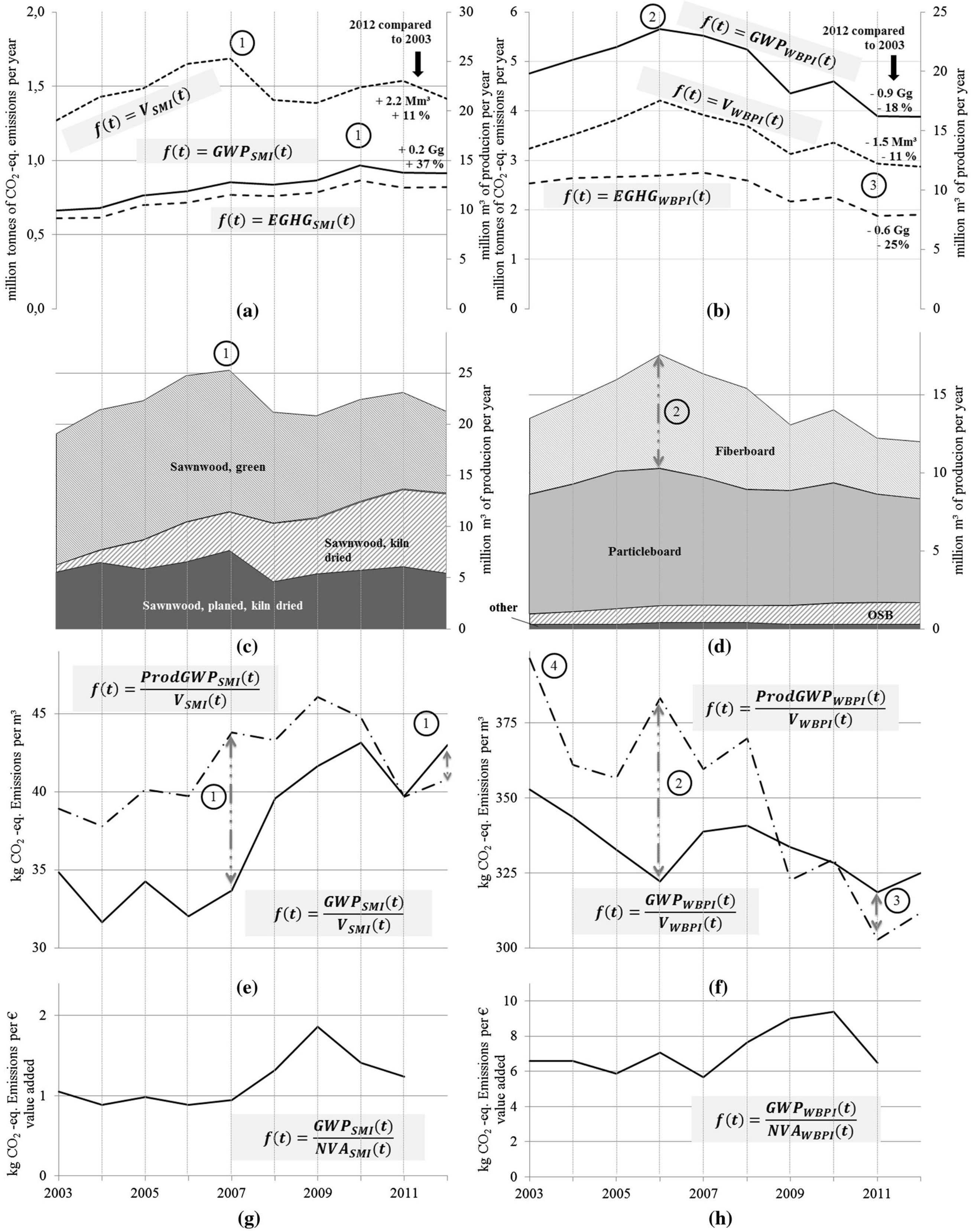
3.4.1 *General*

The monitoring approach delivers reliable results especially for the consumption of energy from non renewable resources and the cradle to gate GHG emissions. Only a possible development in the specific emissions of glue production cannot be monitored today.

Figure 5a–h shows the development of the GHG emissions from the SMI and the WBPI from 2003 until 2012. Figure 5a, c, e, g show the development of the SMI, whereas Fig. 5a shows the development of the total GHG emissions and the EGHG emissions (dashed line) from cradle to gate (without forestry) compared to the total production volume of the SMI (finely dashed line). Figure 5c shows the total production of the SMI differentiated by product types within the portfolio. Figure 5e shows the average volume specific GHG emissions from cradle to gate (without forestry) calculated according to the monitoring approach and based on the LCI data only (dashed line) and Fig. 5g shows the GHG emissions per value added. Figure 5b, d, f, h show the same context for the WBPI.

3.4.2 *The sawmill industry*

In absolute quantities, the sawmill industry increased its GHG emissions from 664 kt CO_2-eq. in 2003 up to 912 kt CO_2-eq. in 2012 (+37 %). In the same time the total production increased by only 11 % (Fig. 5a). The specific GHG emissions to produce 1 m^3 of an average product from this sector increased from 35 up to 43 kg CO_2-



million tonnes of CO_2-eq. emissions per year
million m³ of producion per year
2012 compared to 2003
$f(t) = V_{SMI}(t)$
$f(t) = GWP_{SMI}(t)$
$f(t) = EGHG_{SMI}(t)$
+ 2.2 Mm³
+ 11 %
+ 0.2 Gg
+ 37 %
(a)
$f(t) = GWP_{WBPI}(t)$
$f(t) = V_{WBPI}(t)$
$f(t) = EGHG_{WBPI}(t)$
- 0.9 Gg
- 18 %
- 1.5 Mm³
- 11 %
- 0.6 Gg
- 25%
(b)
Sawnwood, green
Sawnwood, kiln dried
Sawnwood, planed, kiln dried
(c)
Fiberboard
Particleboard
other
OSB
(d)
kg CO_2-eq. Emissions per m³
$f(t) = \frac{ProdGWP_{SMI}(t)}{V_{SMI}(t)}$
$f(t) = \frac{GWP_{SMI}(t)}{V_{SMI}(t)}$
(e)
$f(t) = \frac{ProdGWP_{WBPI}(t)}{V_{WBPI}(t)}$
$f(t) = \frac{GWP_{WBPI}(t)}{V_{WBPI}(t)}$
(f)
kg CO_2-eq. Emissions per € value added
$f(t) = \frac{GWP_{SMI}(t)}{NVA_{SMI}(t)}$
(g)
$f(t) = \frac{GWP_{WBPI}(t)}{NVA_{WBPI}(t)}$
(h)

◀**Fig. 5** Development of GHG emissions from the SMI and the WBPI, **a** Total GHG emissions (cradle to gate and energy related only) and total production volume in the SMI and **b** in the WBPI, **c** Total production volume of product portfolio in the SMI and **d** in the WBPI, **e** Average product specific GHG emissions calculated by the monitoring approach and by using LCI data only of the SMI and **f** of the WBPI, **g** GHG emissions per value added in the SMI and **h** in the WBPI, numbers *1* to *4* are referred to in the text

eq. (Fig. 5e). The main reason for this was the increased production of kiln dried sawnwood at the burden of green sawnwood in the product portfolio (Fig. 5c).

From an economical point of view, the emitted GHG per value added (Fig. 5g) increased from 1.05 to 1.24 kg CO_2-eq./Euro (+18 %) between 2003 and 2011 (no figures available for 2012 at the time of calculation). This means the sawmill industry was not able to demand higher prices on the market in the same magnitude as CO_2 emission was increased.

Single years should be highlighted in the context of specific emissions. In 2007, the total production of the SMI was at its highest level (see Aspect 1 in Fig. 5). A reasonable amount of the production increase before 2007 was due to the extra production of kiln dried sawnwood (a product with high GHG compared to the green sawnwood). From an LCA modeling perspective, the GHG emissions therefore should have increased accordingly. But they did not. The highest GHG emissions were reported in 2010 instead.

The LCI based development in Fig. 5e (dashed line) shows the product specific emissions without the efficiency change. The LCI based development uses the efficiency in 2010 and retraces the average product emissions back to 2003. This means, if in 2007 the efficiency of the SMI had been on the same level as in 2010 (which is known from the LCI data), the production of an average product from the SMI would have caused 44 kg CO_2-eq. instead of 34 kg CO_2-eq. as it actually did. This calculation already includes the change in the product portfolio, which means that the increase in the total amount of dried wood is not the cause here.

This indicates that the GHG emissions efficiency to produce a specific product (not the average product of the sector but, e.g., particle board or fiberboard) decreased. A reason for this could be the decrease in capacity utilization: in 2007 the production volume was about 20 % higher than in 2012. Since several infrastructural processes in the sawmill industry (lighting, transport chains etc.) consume the same amount of energy no matter if the capacity of the mill is fully utilized or not, the energy efficiency of a sawmill is likely to increase with an increased utilization of its capacity.

The distance between the lines in Fig. 5e therefore indicates the point of highest efficiency (2007) and the lowest (2012). This means that from 2007 until 2012 the GHG efficiency (CO_2-eq per m^3) decreased by 35 %.

There is a reasonable amount of uncertainty in these figures due to the described data quality for the biomass quantities in the surveys from the statistical offices (see Sect. 3.3). The LCI based development (dashed line in Fig. 5e) is based on the energy mix used to generate thermal energy in the SMI which is based on the share of fuels reported by the statistical office. If the amount of biomass used for the generation of thermal energy was actually higher than reported, the actual share of fossil fuels (relevant for GHG emission) would have been lower (and therefore closer to the other line, which means that the efficiency loss was actually less than 35 %). However, the gravity of these uncertainties cannot be quantified in this context.

3.4.3 *The wood based panel industry*

The wood based panels industry decreased its total GHG emissions from 4751 kt CO_2-eq. in 2003 down to 3885 kt CO_2-eq. in 2012 (–18 %, Fig. 5b). In the same time, the total production volume decreased by only 11 %. In addition, the product specific emissions of GHG (for the specific product mix) decreased from 353 to 325 kg CO_2-eq./m^3 (–8 %) (Fig. 5f). The emitted GHG per value added decreased as well, from 6.6 to 6.5 kg CO_2-eq./Euro (–1.5 %) between 2003 and 2011 (Fig. 5h).

The production maximum in 2006 (see Aspect 2 in Fig. 5) leads to total GHG emissions of about 5658 kt CO_2-eq. in that year, the highest value between 2003 and 2012. But as shown in 5b, the EGHG emissions did not increase much between 2004 and 2007.

This is caused by the high GHG efficiency for the specific product (e.g., 1 m^3 fiberboard) in 2006 which is also visible in Fig. 5f: in 2006 the actual GHG emissions per m^3 were much lower than they would have been if the efficiency level of 2010 was assumed (which is known from the LCI data).

The lowest efficiency level was in 2011 (see Aspect 3 in Fig. 5). This means between 2006 and 2011 the GHG efficiency (for the specific product like fiberboard, not for the mix) of the WBPI decreased by about 21 %. Again, the change in the product portfolio is not the reason here as this is already taken into account.

Analogously to the SMI, the point of highest efficiency was calculated for the year with the highest capacity utilization. The uncertainties connected with the biomass fuel quantities also apply to the WBPI. Especially in the first year of the survey (2003), the amount of reported biomass used to generate thermal energy was very low. Hence, the share of fossil fuels in the energy mix (the LCI data is based on this) probably overestimates the GHG emissions in that year (see Aspect 4 in Fig. 5)

4 Conclusion and recommendation

In this article, a monitoring procedure for the woodworking industry is presented. The approach includes the relevant indicators used to express political targets and the relevant LCA indicators used in the context of schemes for the assessment of ecological sustainability of construction works.

The data needed for the calculation is publicly available and updated frequently (see EEA 2014 and Destatis 2014) which is in accordance with publicly accepted requirements for indicators (BMWi and BMU 2012b). With the simplification of LCI data in terms of focusing on flows with high importance for an environmental indicator, it was shown that relevant LCA results can be derived from much smaller amounts of data than the usual complexity of LCA studies would suggest.

The approach is confirmed to be feasible for some indicators and yet to need further development for others. Besides some essential conclusions which can be drawn from the available results of the monitoring, the data quality of available data and the circumstance that more data is needed to complete the approach need to be discussed:

So far, reliable results are available for the global warming potential of the average product of the sawmill industry and the wood based panels industry.

The sawmill industry increased its average greenhouse gas emissions from 35 to 43 kg CO_2-eq./m^3 between 2003 and 2012. One aspect which leads to this increase was the increased production of kiln dried products. However, with a reduction of the total production volume since 2007 and the resulting overcapacity of many sawmills, a GHG efficiency loss starting in 2007 may have added a reasonable share to this total increase of product specific GHG emissions.

With regard to economic values, the sawmill industry was not able to compensate higher greenhouse gas emissions with an increased net value added. From 2003 to 2011, the emitted greenhouse gases per value added increased from 1.05 to 1.24 kg CO_2-eq./Euro.

The wood based panels industry decreased its average greenhouse gas emission from 353 to 325 kg CO_2-eq./m^3 from 2003 until 2012. This decrease was mainly reasoned by a change in the product portfolio. In fact, the share of fiberboard (very energy intensive production process and high glue content) has decreased from 2006 until today.

In contrast, the GHG efficiency of a specific product (not the mix of the sector) (CO_2-eq per m^3) decreased as the capacity utilization of the production sites decreased. This efficiency loss was estimated to be approximately 20 % which means that a panel, which caused 200 kg CO_2-eq. in 2006, was responsible for approximately 240 CO_2-eq. in 2012.

Unfortunately the efficiency loss cannot be allocated to a specific product, neither for the sawmill industry nor for the wood based panels industry. However, from the perspective of capacity utilization, the efficiency loss is probably located at the processes before the kiln drying process in the case of sawmills. In the case of wood based panels, the production of fiberboard decreased more than the production of other panels. Hence the efficiency loss is estimated to have happened especially here.

This obviously means that although the overall efficiency decreased, single products, like OSB whose production volume increased steadily since 2003 may not have suffered a decrease of their specific GHG efficiency.

Results on final and primary energy consumption include the use of biomass fuel. For this type of fuel it was shown that its quantity is probably gravely underestimated by the data available from the statistical office. Since the surveys on sector level started in 2003 and a learning curve of the companies and the statistical office can be assumed, an index of the final energy demand starting in 2003 is likely to gravely overestimate the increase of the use of biomass.

For the wood manufacturing industry this means that official data likely show a severe divergence between the behavior of the sector and the intended national final energy efficiency increase to reach 2020 targets. The results also indicate that the wood manufacturing industry is most likely responsible for a larger share of the increase of renewable fuels in the final energy mix than shown by official data.

Results in terms of acidification potential, eutrophication potential and photochemical ozone creation potential rely heavily on information on emissions of NO_x and NMVOC. On sector level, the relevant data is not readily available to be used for monitoring as it lacks completeness. However, the available data already shows that both types of emissions are underestimated by available LCI data. For NMOVC, the underestimation is severe.

For other impact categories (ODP, ADPe and toxicity indicators) no relevant results could be derived, since the relevant data on sector level is missing.

With regard to the political and social pressure of reducing environmental impacts and increasing energy efficiency, the results should urge the wood manufacturing industry to improve the quality of the available data especially in terms of the quantities of bio-fuels. The data should also be supplied to the relevant databases.

In this context it seems to be reasonable to define a harmonized approach for the sector. With regard to data quality of emissions of NMVOC and NO_x, such an approach would seem productive as well.

In general, the presented approach can also be applied to other sectors. Especially for sectors with a high energy intensity (e.g., pulp and paper), the approach can be transfered provided that representative LCI data are available for the typical products.

Lastly, the presented monitoring approach not only offers a way to monitor a sector, but the results from the simplifying procedure allow companies to focus on some single numbers to quantify the improvements they achieved individually. Results on company level need to be taken with caution though, since the wood used for material was left outside the system boundary.

To understand the relevance of the development of process based emissions and energy consumption in the wood manufacturing industry, the values can be compared to displacement factors for wood-product substitution, summarized by Sathre and O Connor (2010). Assuming a deliberate displacement factor of 0.8 t carbon emissions per 1 t of wood product, the monitored change from 2003 to 2012 in the wood manufacturing industry equals 12.6 % of the substitution effect in the case of panels and 1.2 % in the case of sawmill products. For panel products with lower displacement factors of about 0.5, the change in the wood manufacturing industry already equals the displacement factor. For sawmill products a displacement factor of 0.3 leads to equal results. Sathre and O Connor (2010) also found several studies which calculated factors below 0.3. Hence, the monitored development plays an essential role within decision oriented studies aiming to environmentally optimize the use of wood.

Acknowledgments Thanks to all companies that supplied data via questionnaires and during on-site visits. Thanks also to Norbert Buddendick and Norbert Burkart *Deutsche Säge- und Holzindustrie Bundesverband e.V.* (sawmill association) and to *Verband der Deutschen Holzwerkstoffindustrie e.V.* (wood based panel association) for their invaluable assistance in organizing communication networks between science and the German wood industry. Financial assistance for this research was provided by the Fachagentur Nachwachsende Rohstoffe (22028808) and Intelligent Energy Europe (IEE/11/946/SI2). The author would also like to thank Anne Rödl and Sebastian Rüter for their thoughtful comments.

References

Barroso JMDA (2014) Statement by President Barroso on the 2030 energy and climate framework

BDEW (2013) Brutto-Stromerzeugung 2012 nach Energieträgern in Deutschland. English title: gross electricity production 2012 by energy carrier in Germany. http://www.bdew.de

BDI, BDEW, BMWI, BMU, BMF (2012) Vereinbarung zwischen der Regierung der Bundesrepublik Deutschland und der deutschen Wirtschaft zur Steigerung der Energieeffizienz vom 1. August 2012. English title: agreement between the government of the Federal Republic of Germany and the German industry to increase the energy efficiency from 1st August 2012

BMWi (2014) Zweiter Monitoring-Bericht Energie der Zukunft. English title: second monitoring report "energy of the future". Bundesministerium für Wirtschaft und Energie (BMWi), Berlin

BMWi, BMU (2012a) Erster Monitoring-Bericht Energie der Zukunft. English title: first monitoring report "energy of the future". Bundesministerium für Wirtschaft und Technologie (BMWi), Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU), Berlin

BMWi, BMU (2012b) Monitoring Energie der Zukunft. Vorbereitung des ersten Berichtes 2012 für das Berichtsjahr 2011—Indikatoren zur öffentlichen Diskussion. English title: monitoring energy of the future, preparation of the first report (2012) for the reporting year 2011—indicators for public consultation. Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen

Bouhaya L, Le Roy R, Feraille-Fresnet A (2009) Simplified environmental study on innovative bridge structure. Environ Sci Technol 43(6):2066–71

Collet P, Lardon L, Steyer JP, Hélias A (2013) How to take time into account in the inventory step: a selective introduction based on sensitivity analysis. Int J Life Cycle Assess 19(2):320–330

Destatis (2010) Rohholz und Holzhalbwaren, Arbeitsunterlage. English title: raw wood and semi finished wood products, procedure documentation. Statistische Bundesamt, Wiesbaden

Destatis (2012a) Erhebung über die Energieverwendung. Survey of energy use. Statistische Bundesamt, Wiesbaden. directly available at publisher, English title

Destatis (2012b) Fachserie 4 Reihe 3.1, Produzierendes Gewerbe, Produktion des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden 2011. English title: Series 4, Tier 3.1, Industry, Production of the manufacturing sector and mining and quarrying. Statistische Bundesamt, Wiesbaden

Destatis (2012c) Fachserie 4 Reihe 4.3 Produzierendes Gewerbe - Kostenstruktur der Unternehmen des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden, 2010. English title: Series 4, Tier 4.1, Industry, Cost structure of the manufacturing sector and mining and quarrying. Statistisches Bundesamt, Wiesbaden

Destatis (2013) Erhebung über die Energieverwendung der Betriebe des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden—Qualitätsbericht. English title: survey of the energy use of companies in the manufacturing sector and mining and quarrying—quality report. Statistisches Bundesamt, Wiesbaden

Destatis (2014) Energy use in the industry 2012. http://www.destatis.de/EN/FactsFigures/EconomicSectors/Energy/Use/Tables/EconomicBranch12.html. Accessed March 6. 2014

Diederichs S (2014a) 2010 Status quo for life-cycle inventory and environmental impact assessment of the core sawmill products in Germany. Wood Fiber Sci 46(1):65–84

Diederichs S (2014b) 2010 Status quo for life cycle inventory and environmental impact assessment of wood-based panel products in Germany. Wood Fiber Sci 46(3):1–16

EEA (2014) European PRTR and EPER Database. http://www.prtr.ec.europa.eu

EN 15804:2012–04 (2012) Sustainability of construction works. Environmental product declarations, Core rules for the product category of construction products

Energiebilanzen e.V. AG (2010) Auswertungstabellen zur Energiebilanz Deutschland. Daten für die Jahre 1990 bis 2009. English title: calculation tabels for energy balances Germany. Data for the years 1990–2009. http://www.ag-energiebilanzen.de

EN ISO 14044:2006 (2006) Environmental management—Life cycle assessment—Requirements and guidelines

European Commission (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

European Commission (2013) Progress towards achieving the Kyoto and EU 2020 objectives, COM (2013) 698

European Parliament (2012) Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC

European Parliament, Council of the European Union (2013) Decision No 529/2013/EU of the European Parliament and of the Council of 21 May 2013 on accounting rules on greenhouse gas emissions and removals resulting from activities relating to land use, land-use change and forestry and… April 2002, Brussels

Fleischer G, Gerner K, Kunst H, Rebitzer G (2001) LCA methodology a semi-quantitative method for the impact assessment of emissions within a simplified life cycle assessment. Int J Life Cycle Assess 6(3):149–156

Fleiter T, Schlomann B, Eichhammer W (2013) Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien—Einsparpotenziale, Hemmnisse und Instrumente. English title: energy consumption and CO2 emissions from industrial process technologies - reduction potentials, constraints and instruments. Fraunhofer Institut für System- und Innovationsforschung ISO, Karlsruhe

Frondel M, Janssen Timmen R, Ritter N (2013) Statusbericht 2011 und 2012 zur Umsetzung der Vereinbarung zwischen der Bundesrepublik Deutschland und der deutschen Wirtschaft zur Klimavorsorge vom 9. November 2000. English title: status report of the implementation of the agreement between the government of the Federal Republic of Germany and the German industry in the context of climate protection from 9th November 2000. November 2000, Rheinisch-Westfälisches Institut für Wirtschaftsforschung, Essen

Heijungs R, Kleijn R (2001) Numerical approaches towards life cycle interpretation, five examples. Int J Life Cycle Assess 6(3):141–148

Höglmeier K, Weber-Blaschke G, Richter K (2014) Utilization of recovered wood in cascades versus utilization of primary wood - a comparison with life cycle assessment using system expansion. Int J Life Cycle Assess. doi:10.1007/s11367-014-0774-6

Lechtenböhme S, Knopf B, Bauer N, Durand A, Hanke T, Luhmann HJ, Samadi S, Schmid E, Schneider C (2014) Kosten- und Modellvergleich langfristiger Klimaschutzpfade bis 2050. English title: cost- and model comparison of long term climate protection-pathways unti 2050. Umweltbundesamt, Dessau-Rosslau, Germany

Mantau U, Saal U, Steierer F, Verkerk H, Lindner M, Anttila P, Asikainen A, Oldenburger J, Leek NKP (2010) Real potential for changes in growth and use of EU forests. Final Report, Hamburg, Germany

Merciai S, Heijungs R (2014) Balance issues in monetary input-output tables. Ecol Econ 102:69–74

Moberg A, Borggren C, Ambell C, Finnveden G, Guldbrandsson F, Bondesson A, Malmodin J, Bergmark P (2014) Simplifying a life cycle assessment of a mobile phone. Int J Life Cycle Assess. doi:10.1007/s11367-014-0721-6

Nabuurs G, Masera O, Andrasko K, Benitez-Ponce P, Boer R, Dutschke M, Elsiddig E, Ford-Robertson J, Frumhoff P, Karjalainen T, Krankina O, Kurz W, Matsumoto M, Oyhantcabal W, Ravindranath N, Sanchez MS, Zhang X (2007) Forestry. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds.),Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge

Osterburg B, Rüter S, Freibauer A, De Witte T, Elsasser P, Kätsch S, Leischner B, Paulsen HM, Rock J, Röder N, Sanders J, Schweinle J, Steuk J, Stichnote H, Stürmer W, Welling J, Wolff A (2013) Handlungsoptionen für den Klimaschutz in der deutschen Agrar- und Forstwirtschaft. English title: fields of action for climate protection in the German agricultural and forestry economy. Johann Heinrich von Thünen-Institut, Braunschweig. doi:10.3220/REP10.3220/REP

PE International (2012) GaBi 4 Software and GaBi Professional Database Version 4.131, Leinfelden-Echterdingen. http://www.gabi-software.com

Rentz O, Oertel D, Woodfield M, Stewart R, (2009) Manufacturing industries and construction (combustion). Chapter 1.A.2. In: EMEP, EEA air pollutant emission inventory guidebook (2009) European Environmental Agency. Denmark, Copenhagen, p 34

Rueter S, Diederichs S (2012) Ökobilanz-Basisdaten für Bauprodukte aus Holz. English title: life cyle assessment base data for wood contruction products. Johann Heinrich von Thünen Institut, Institut für Holztechnologie und Holzbiologie, Hamburg

Sathre R, Connor OJ (2010) Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environ Sci Policy 13(2):104–114

Schlomann B, Eichhammer W, Fritzen P, Reuter M, Schrader T (2012) Energy Efficiency Policies and Measures in Germany, Odyssee Mure 2011. Monitoring of EU and national energy efficiency targets, Fraunhofer Institut für System- und Innovationsforschung ISO, Karlsruhe

Schmidt H, Schmidt D (2005) Bauen mit trockenem Holz—Neue Normen sprechen eine klare Sprache. English title: contruction with wood—new standards speak a clear language. Holzbau 1:45–49

Seppäläa J, Melanen M, Mäenpää I, Koskela S, Tenhunen J, Hiltunen MR (2005) How can the eco-efficiency of a region be measured and monitored? J Ind Ecol 9(4):117–130

Sturm A, Mueller K, Upasena S (2002) A manual for preparers and users of eco-efficiency Indicators: conceptual framework and guidelines. United Nations conference on trade and development, Geneva

Suh S, Huppes G (2005) Methods for life cycle inventory of a product. J Clean Prod 13(7):687–697

UBA (2014) German PRTR and EPER Database. http://www.thru.de

UNECE, FAO (2012) Forest Products Annual Market Review, 2011–2012, ece/tim/sp edn. United Nations Economic Commission for Europe and Food and Agriculture Organization of the United Nations, Geneva

UNFCCC (2011) Land use, land-use change and forestry (Decision 2/CMP.7). March, United Nations Framwork Convention on Climate Change

United Nations (2012) Doha amendment to the Kyoto Protocol

Weidema BP, Ekvall T, Heijungs R (2009) Guidelines for application of deepened and broadened LCA. 037075, ENEA, The Italian National Agency on new Technologies, Energy and the Environment Project

Werner F, Althaus HJ, Künniger T, Richter K, Jungbluth N (2007) Life cycle inventories of wood as fuel and construction material, ecoinvent report No.9. EMPA, ESU, Dübendorf

Wilson JB, Sakimoto ET (2005) Gate-to-gate life-cycle inventory of softwood plywood production. Wood Fiber Sci 37:58–73

Wright HE, Zhang Q, Mihelcic JR (2008) Integrating economic input-output life cycle assessment with risk assessment for a screening-level analysis. Int J Life Cycle Assess 13(5):412–420

Wünsch M, Seefeld F, Schlomann B, Fleiter T, Gerspacher A, Rohde C, Geiger B, Kleeberger H,(2012) Datenbasis zur Bewertung von Energieeffizienzmaßnahmen, (2008) English title: database for the evaluation of energy efficiency measures 2008. Umweltbundesamt, Dessau-Rosslau, Germany

Hindawi Publishing Corporation
International Journal of Polymer Science
Volume 2015, Article ID 383279, 14 pages
http://dx.doi.org/10.1155/2015/383279

Research Article

Potential Environmental Benefits of Ultralight Particleboards with Biobased Foam Cores

Christelle Ganne-Chédeville[1] and Stefan Diederichs[2]

[1] *Bern University of Applied Sciences, Institute for Materials and Wood Technology, Solothurnstrasse 102, 2500 Biel-Bienne, Switzerland*
[2] *Thünen Institute of Wood Research, Leuschnerstr. 91c, 21031 Hamburg, Germany*

Correspondence should be addressed to Christelle Ganne-Chédeville; gnc1@bfh.ch

Received 20 December 2014; Accepted 5 March 2015

Academic Editor: Nicole Stark

A new generation of ultralight particleboards (ULPB) with an expanded foam core layer produced in an in-line foaming step is under development. The environmental impacts of three types of ULPB containing foam based on 100% polylactic acid (PLA), 100% expanded polystyrene, and 50% PLA/50% polymethyl methacrylate, as well as a conventional particleboard (PB), have been compared in an LCA. Two approaches were chosen for the assessment: first, the "EPD-approach" in accordance with EN 15804 for EPD of building materials and second, a holistic-approach which allows an expansion of the system boundaries in order to forecast the consequences of a broader replacement of PB with ULPB. The results show that most of the environmental impacts are related to raw materials and end-of-life stages. Both approaches show that the exchange of PB with ULPB with a foam core based on PLA leads to a reduction of greenhouse gas emissions. On the other hand, the PLA is responsible for higher ecotoxicity results in comparison to non-bio-based polymers mainly due to agricultural processes. Both approaches allowed the drafting of complementary advisories for environmental impact reduction addressed to the developers.

1. Introduction

Particleboards (PB) are pressed panels made out of wood particles and adhesives. They typically consist of a lower density core layer of coarse particles and high density surface layers made with finer particles. They typically have a density of 600–700 kg/m^3 and are used in very diverse applications like home and office furniture, cabinets, kitchens, flooring, load bearing applications in construction and diverse interior design elements. They show an improved homogeneity and stability in comparison to solid timber.

Initially, PBs were developed to valorize the large amount of particles produced in sawmills. Today, with the ambition of reducing production costs, the wood based panel industry aims to use less or cheaper materials and to reduce energy consumption while maintaining the properties in accordance with the relevant product standards.

The sandwich-like construction of PBs is advantageous for a high specific bending strength. To maintain this, developments started in the 1940s with the substitution of the core layer with honeycomb or similar hollow structure [1–3], and until today other strategies are being developed to reduce the density of the core layer: extrusion with hollow tubes, using low density wood species particles, or substituting the core layer with foam material in a sandwich construction. The latter strategy led to sandwich panels with a foam core made out of polyurethane or polystyrene which are established in the market today (density: 100–350 kg/m^3).

From a process perspective, these "ultralight" PBs (ULPB) can either be produced by producing the core layer and external layer separately and merging them in a separate pressing process, or by an in-line foaming step (patented by Luedtke et al. [4]) on continuous presses which are typically used in today's PB production.

Environmental impacts associated with conventional PBs arise mainly during the production of the adhesives, the combustion of fuel on site and the generation of electricity for the production steps at the panel manufacturers, whereby the particle preparation and finishing process take the leading positions [5–10]. But with regard to the complete life cycle of PBs and recognition that wood has a heating value of 15–20 MJ/kg, the end-of-life processes may dictate the results depending on the assumptions made for the scenarios (i.e., incineration, landfilling, and thermal energy recovery).

ULPBs typically use less adhesive, fewer particles need to be prepared and dried, and as they are lighter, transport emissions may be reduced. On the other hand, the heating value per volume will be different from PBs and, depending on whether biobased or fossil-based foams are utilized, the supply chain of these materials and the end-of-life assumptions may be connected to impacts which differ greatly from those of PBs.

Hence, especially the end-of-life, the adapted continuous pressing process, the particle drying, the reduced supply of wood and adhesives, as well as the supply of foam materials needs to be the focus of LCA for ULPBs. Recognizing that wood used in PBs is typically a byproduct of the sawmill industry, LCA should also include the assessment of other routes for those byproducts. This surely includes the assessment of other routes if the foam material is based on byproducts.

A respective comparison of ULPBs (polyurethane foams) with PBs was conducted by Feifel et al. [11]. The authors concluded that the impacts were 2 to 3 times higher for the UPLBs. Unfortunately the results only consider cradle-to-gate effects and no inventory was published which would offer the possibility of a comparison to real ULPBs. A cradle-to-grave assessment for ULPBs, substituting PBs, was further conducted by Feifel et al. [12] but focused only on honeycomb core layers and excluded the supply of wood.

From a resource perspective, an LCA conducted by Silva et al. [13] gives insight to results of PBs produced in Brazil, where 50% of the chips had been replaced with sugarcane bagasse. Results were compared to results from standard particle boards showing beneficial aspects in some impact categories and quite equal results in others. However, the end-of-life was not considered in this study and the alternative byproduct routes of bagasse were not included. As Brazilian producers primarily use wood resources, no results could be derived for the alternative routes of sawmill byproducts typically used by European producers of PBs.

The primary target of the study is to analyze the environmental benefits or drawbacks of using ULPB with a foam core processed on a continuous press, for applications where conventional PBs are commonly used. In addition, as the described ULPBs are still in development, the secondary target is to identify the parameters with the largest influence on environmental impacts, helping the developers to understand which decision in design might lead to better or worse results in the overall environmental impact of the new product.

2. Methodology

2.1. Two-Pronged Strategy. Principally, LCA can be used for improvements by identification of key issues. Products can be benchmarked by comparing them to the LCA results of an average or another product. LCA can help to communicate environmental issues and on policy level the tool is used to supply strategic decision support.

In this context it is important to understand which question is addressed in the goal of the study. One would ask "*what is?*" to identify environmental key issues of the product life cycle or to benchmark one product against others. But to understand the consequences of a decision, the relevant question would be "*what if ?*".

The two modelling approaches behind these questions are referred to as attributional (ALCA) and consequential life cycle assessment (CLCA) and their capabilities have been discussed extensively. It is generally understood that both approaches yield valuable insights [14–16] and some aspects are evident in one method and are overlooked in the other [17]. Therefore, this paper follows a two-pronged strategy.

2.2. The Harmonized Approach for Building Products. In Europe, the underlying LCA methodology for building products is defined in EN 15804 [18], which builds upon ISO 14044 [19] but clarifies open methodological choices where ISO 14044 [19] offers them. EN 15804 [18] defines the core product category rules for Environmental Product Declaration (EPD) built upon ISO 14025 [20].

In the context of this paper, the utilization of this methodology is intended to supply information on how the new products would compare to PB, following the comparison principles of building products. It will be referred to in the text as the *EPD-approach*.

2.3. Expanding the Scope. The *EPD-approach* is based on an ALCA model. On the resource side it disregards the fact that the production of byproducts of a process is typically driven by the demand for the primary product and not for the byproducts. Hence the approach excludes the impacts of alternative routes for those byproducts. As the amount of these byproducts (wood or biobased foams) differs heavily between PB and ULPB, the EPD approach disregards a potentially crucial impact.

Further on, EN 15804 [18] and, respectively, its utilisation on building level, separate the benefits of the energy recovery at the end-of-life from the impact assessment. As this might be a reasonable approach at the building level, a direct comparison of products with different densities and heating values, which is the case for PB and ULPB, may be driven especially by those aspects of the product life cycle.

Therefore, the second approach in this paper includes aspects which are outside the system boundaries regarded in the EN 15804 [18], with the aim of including all processes and services which are likely to be affected by a replacement of PB with ULPB. This approach will be referred to in the text as *holistic approach*.

Both approaches will also give valuable insights for beneficial product development strategies.

2.4. Standards, Software and Databases. The LCA was done in accordance with the ISO 14040/14044 [19, 21], EN 15804 [18] and EN 16485 [22] standards using the Aveny LCA Software [23]. If not specified otherwise, the database Ecoinvent v2.2 was used for standard datasets [24].

2.5. Description of the System under Study

2.5.1. Manufacturing of Conventional PB (Cradle-to-Gate). The PB considered in this study is based on wood residues from sawmills, urea-formaldehyde (UF) resin as adhesive and produced in a continuous-press. Hydrochloric acid or liquid ammonia is used as hardener and paraffin is added for water-repellence.

The production of PB begins with the preparation of the wood particles for the surface and core layers including chipping, classifying, screening, and drying. The particles are then blended with UF resin and hardener in a continuous flow mixer cooled with water. The mat is formed by deposition of the surface and core layer particles on a conveyer belt and goes to a roller press heated at 220°C. After the pressing, the PB are sawn and cooled down by storage. The final density is 680 kg/m^3.

2.5.2. Forecasted Manufacturing of ULPB (Cradle-to-Gate). Based on the laboratory development we assume, that the ULPBs considered in this study are composed of surface layers made of wood particles, prepared in an identical manner as for the PB production, and a core layer of expanded polymers. Three ULPB core layer types are simulated in the study:

(1) A core layer made of EPS, which corresponds to the state of the art of the in-line foaming technology [25].

(2) A core layer made of a mix of PLA and polymethyl methacrylate (PMMA) (50/50%), which corresponds to the current development formulation in the project [26].

(3) A core layer made of PLA (100%) which corresponds to the aimed formulation.

EPS is directly available as granulate, preimpregnated with pentane as blowing agent. The mix of PLA and PMMA has to first be coextruded with a small quantity of talc in order to provide nucleation sites for the foaming and then it has to be granulated. Granulates of PLA or PLA/PMMA mix are then impregnated with liquid CO_2 (blowing agent) in a batch reactor and stored for a short-time in a chiller at 10°C before they can be used in the production. The current ULPB laboratory developments allow the possible manufacturing process to be forecasted: the production of the considered ULPBs should be identical to the production of the PB, except for the mat forming and pressing phases. During the mat forming the technology stays the same as for PB but the coarse particles of the core layer are substituted by polymer granulate of EPS, PLA or the mix of PLA/PMMA preimpregnated with blowing agent. As the ULPB should have the same mechanical properties as the PB, the bending stiffness is increased by surface layers of higher density. This means that the amount of surface layer particles in ULPB is increased in comparison to PB. Pressing occurs in 3 successive steps: surface layer compaction and consolidation step, expansion step and stabilization step (Figure 1). The first step occurs at a pressing temperature of 100°C whereas the last step (stabilisation) occurs at 20°C which implies the utilisation of a cooling system. After pressing, the last manufacturing steps of the ULPB are identical to those of the PB. The final density of the ULPB is 315 kg/m^3.

2.5.3. Use Phase and End-of-Life Scenario (Gate-to-Grave). A scenario was considered for the gate-to-grave part of the life cycle of the panel: the panels are transported to a furniture manufacturer where they are modified to be part of a piece of furniture (shelf) and then transported to the final user. During the use phase the furniture is stored in a house. At its end-of-life it is picked up at the place of use by the municipal waste collection and burned in the municipal incineration plant.

2.6. Functional Unit. The functional unit is 1 m^3 of panel (thickness 19 mm), fulfilling the requirements of the EN 312 [27] and utilized as furniture shelf board. The different panel formulations are compared for the same life span. The units and quantities of the different raw materials used for the manufacturing of the functional unit are presented in Table 1. Because no detailed data was available on the internal waste flows of the production, all inputs of adhesives and additives were assumed to leave the manufacturer as content of the respective product analogous to Diederichs [28]. All products were regarded in the *EPD-approach*. The *holistic approach* only takes the PB and ULPB with a 100% PLA core into account.

2.7. System Boundaries

2.7.1. EPD Approach. The EN 15804 [29] standard defines the categorization of life-cycle phases of building materials into stages from A (manufacturing) to C (disposal). Benefit or burdens out of the system boundaries can be presented as additional information in the D stage. The attribution of the life-cycle stages of the ULPB and PB following EN 15804 [29] is given in Figure 2.

All phases from cradle-to-grave are considered except the use phase of the product (shelf board in a furniture part), as it is considered equal for all products.

2.7.2. Holistic Approach. EPD and also the EN 15804 [29] are not specifically intended to declare the impact of the consequences of producing more of one product and less of another, but can be regarded as doing so, if the production of a unit of material or energy has the same environmental impact as producing an extra unit of it [30].

In other words, if a constraint in the market leads to the fact that an extra unit does not equal the average of all units produced so far, the *EPD approach* will not be able to answer the question: what would happen if a certain amount of conventional PB was replaced by ULPB with 100% PLA core layer?

In the EPD approach, the supply chain of the corn used for PLA includes every flow, starting with the planting and fertilizing to the harvesting and transporting of the corn. But if more corn is produced to be used for the PLA, it requires more agricultural area, possibly replacing the production of other crops. If no additional corn is produced, but the corn available on the market is used, those processes which

Table 1: Units and quantities of the raw materials used in the production of a 1 m^3 panel. The bold data refer to functional units regarded in the holistic approach.

Raw material input	Unit	PB	ULPB (EPS)	ULPB (PLA/PMMA)	ULPB (PLA)
Residual wood	m^3	**1.38**	0.59	0.59	**0.59**
PMMA	kg	—	—	12.38	—
PLA	kg	—	—	12.38	**24.75**
EPS	kg	—	25.00	—	—
Hardener	kg	**2.00**	0.94	0.94	**0.94**
UF	kg	**51.00**	23.87	23.87	**23.87**
Talc	kg	—	1.00	1.00	**1.00**
CO_2 liquid	kg	—	—	0.81	**0.81**
Organic additives	kg	**11.00**	5.15	5.40	**5.40**

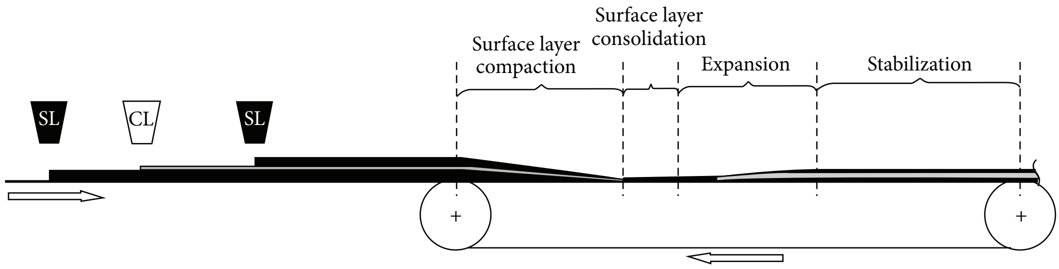


Figure 1: Description of the in-line foaming process for production of ultralight particle-board with a foam-core layer on a continuous press (SL = surface layer; CL = core layer) (adaptation of Luedtke et al. [4]).

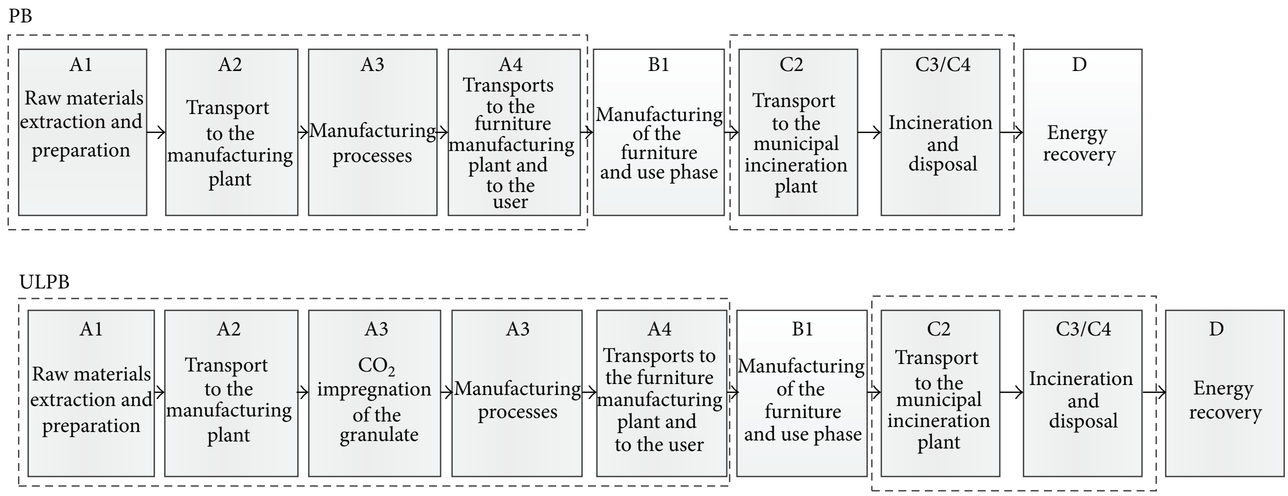


Figure 2: System boundaries following EN 15804 for the LCA of PB and all ULPBs.

would have used the corn instead need to switch to another feedstock.

In case of the wood residues used for the PB, the model used in the *EPD-approach* includes all environmental impacts from the forest to the sawmill, whereas the impacts of the sawmill are allocated partially to the byproducts. This means, if the wood content of a panel is reduced, the LCA model reduces the impact from the sawmills as well. But the demand for sawmill byproducts does not necessarily lead to a reduced demand for the primary products of sawmills, which is sawn wood. Hence the same emissions arise from the sawmill industry and the same amount of byproducts are available on the market. But instead of the panel producers, probably others will use the byproducts.

The *EPD-approach* neglects the market constraints especially with regard to these two aspects. Other inputs and outputs of the PB and ULPB production with high impact, energy demand, or mass are the supply of electricity and the glue which is primarily made of the base chemicals formaldehyde and urea. Since these substances are mainly derived

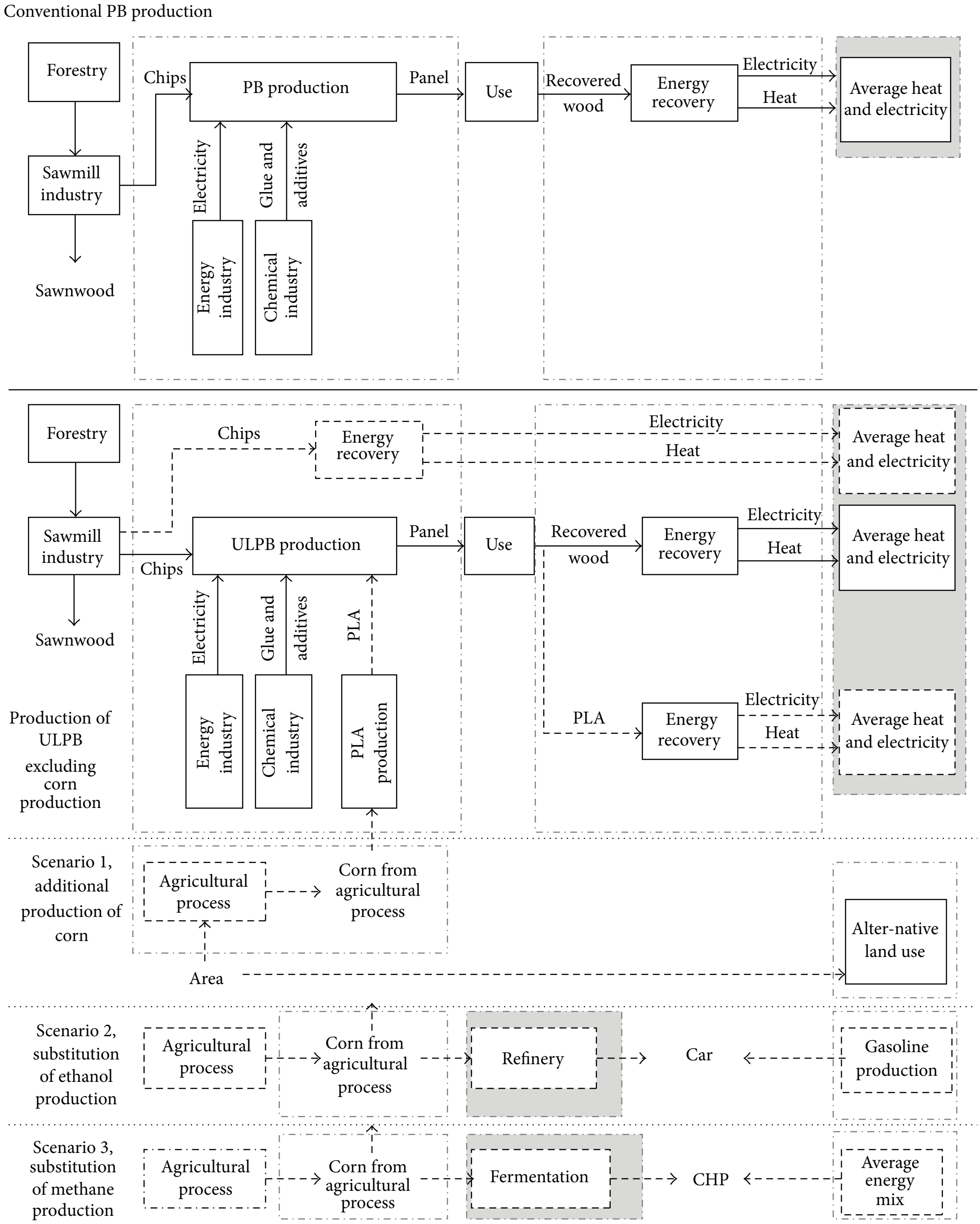


Figure 3: System boundaries of the holistic approach. Dashed processes and lines represent the affected processes of an increased production of ULPB (100% PLA core).

from nonrenewable resources and are not typical byproducts of other processes, market constraints are assumed to be negligible.

Figure 3 shows the model which underlies the *holistic approach*. On the top, the production of the conventional PB is shown. It is the same model as used for the *EPD approach* including transports to the user and also to the disposal but it excludes the sawmill supply chain and includes the energy recovery at the end-of-Life. The grey system boundaries describe a system expansion. In the case of PB, the energy generated during disposal is assumed to replace energy from the average generation processes of heat and electricity. Hence the impact has to be subtracted from the model.

Just below, the production of the ULPB with 100% PLA is shown without the production of the corn for PLA. The dashed lines mark all flows and processes which need to be added or changed if the PB production is replaced by the production of the ULPB.

The production of sawmill byproducts is independent from the change in production within the panel industry. Therefore, the chips which were used for the core layer and those which were used to generate the energy for drying the core layer are assumed to be burned directly without being used for material purposes. The PLA core is burned in context with the disposal of the panel; energy is recovered (system expansion, grey field). The process of producing PLA from corn is included but (initially) without the corn.

Some processes used for PB production are also used for ULPB production, but the flow quantity changed: less electricity, glue, and additives are needed.

As it is not clear if additional corn is produced or if not which feedstock is replaced, three scenarios for the corn production/displacement are analysed:

(i) Scenario 1 (S1) describes the impact if additional corn has to be grown, including impacts of agricultural processes and the impact of land use change triggered by this extra production.

(ii) Scenario 2 (S2) describes the impact if available corn is used for PLA which would have been used for the production of bioethanol to replace gasoline. This is a relevant question for the US, where bioethanol is produced from corn.

(iii) Scenario 3 (S3) describes a typical German case. Available corn which would have been used for the production of biogas (methane) is used for PLA instead. Hence the energy derived from the methane (biogas) has to be substituted.

2.8. Inventory. Data for the production of $1\,m^3$ of conventional PB ($680\,kg/m^3$) from cradle-to-gate correspond to the Ecoinvent v2.2 process "Particleboard Indoor use" [8].

Data regarding the formulation of the ULPB arise from the last available laboratory developments of the NRP 66 project. In order to forecast the situation of an industrial production, the inventory was based on the available dataset from Ecoinvent for LCA of particleboard production [8]. The first step was to disaggregate the energy consumption of the manufacturing step of the Ecoinvent dataset following the proportions given in the literature [10] in order to spread it into single manufacturing stages (Table 2). As the stage "mat forming" is not described in the publication of Frühwald et al. [10], this data is based on assumptions made by the authors. The repartition of the total gas consumption of the Ecoinvent data between the stages *Drying* and *Others* is also an assumption.

Based on the laboratory data, the ratio between the amount of wood used in PB and used in ULPB is 0.422. This ratio was applied to calculate the ULPB flows linked to wood flows (wood transport to the plant, electricity for particle preparation, waste water treatment from particle preparation, drying thermal and electrical energy, VOC and particulate emissions during drying, and wood chips volume as byproduct). Also based on laboratory data, the ratio between the amount of UF glue used in PB and used in ULPB is 0.468. This ratio was applied to calculate the flows of ULPB linked to the glue flows (Hardener, Transport glue and additives to the plant, electricity and cooling water for gluing, and formaldehyde emissions). The gate-to-gate inventories (Modules A3) based on the functional unit of the four types of panels is presented in Table 4. Flows which are already included in Table 1 are not listed here. Further detailed data sources used and assumptions made for the Life Cycle Inventory of PB and ULPB from cradle-to-grave are in Appendix 1 in Supplementary Material available online at http://dx.doi.org/10.1155/2015/383279.

Some additional data and assumptions were necessary for the holistic approach (Table 3). The agricultural process to produce the corn is based on data from Searchinger et al. [31] and PE International [32]. The land use change effects are modelled according to results summarized by Wicke et al. [33]. These refer to land use change models based on market equilibrium models which consider effects called "indirect land use changes," including land use change in one geographical context which triggers land use elsewhere to continue to meet demands and also the change of crop prices, which results in more land taken elsewhere for the production.

Data for corn-to-wheel production are taken from Searchinger et al. [31] in combination with conversion factors from Shapouri et al. [34]. Gasoline production and combustion emissions are derived from PE International [32]. Emissions for the fermentation from corn to the methane and utilization in a CHP plant are taken from Vogt [35] for a 500 kWel plant. Supply of electricity and heat is derived from PE International [32].

2.9. Impact Categories. For an EPD following the standard EN 15804 [29], three categories (environment, resources, and wastes) of indicators are disseminated. In this study we show only the EN 15804 [29] environment category indicators following CLM2001 [36]: Global Warming Potential 100 years with biogenic carbon accounting following EN 16485 (GWP), Global Warming Potential without biogenic carbon (GWP^*), Ozone Depletion Potential steady state (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP); Abiotic Depletion Potential Elements (ADPE), Abiotic Depletion Potential Fossil (ADPF). We also present the results of two additional multi-criteria Life Cycle Impact Assessment (LCIA) methods of interest in Switzerland: Ecological Scarcity 2006 [37] expressed in Eco-factors-in German: *Umweltbelastungspunkte* (UBP) and USETox fate and freshwater ecotoxicity [38], expressed in Comparative Toxic Unit ecotoxicity (CTUe). For the holistic approach only GWP^* will be reported.

2.10. Sensitivity Analysis. A sensitivity analysis was carried out for the EPD approach in order to evaluate the uncertainties of the LCIA results. The parameters, which were identified as relevant or uncertain (because of assumptions), were perturbed marginally in order to observe their effect on the final result. The effect of 10% decrease of several relevant

Table 2: Disaggregation of the energy consumption for each manufacturing stage (A3 modules) of a 1 m^3 conventional PB (Ecoinvent v2.2 dataset) using literature information and assumptions.

Manufacturing stage	Particle preparation	Drying	Gluing	Mat forming	Pressing	Others	Total
Electricity (%)	31	21	5	4	21	18	100
Electricity (kWh/m^3)	32	22	5	4	22	19	104
Electricity (MJ/m^3)	116	79	19	15	79	67	374
Wood (%)		83			17		100
Wood (MJ/m^3)		913			187		1,100
Fossil (%)		41			13	46	100
Heavy oil (MJ/m^3)		17			21	48	86
Light oil (MJ/m^3)		17			21	48	86
Natural gas (MJ/m^3)		100				54	154
Total fossil (MJ/m^3)		134				150	326
Total energy (MJ/m^3)	116	1,125	19	15	266	217	1758
Total energy (%)	7	64	1	1	15	12	100
Total energy (kWh/m^3)	32	313	5	4	74	60	488

Table 3: CO_2 emissions from the additional processes of the model. Ranges are analyzed in terms of their impact on the totals.

Process	kg CO_2-eq/kg corn
Agricultural process	0.19–0.61
Alternative land use	0.05–0.86
Refinery (corn-to-wheel)	0.38–0.40
Gasoline production (cradle to wheel)	0.75
Fermentation (corn to CHP)	0.03–0.30
Supply of electricity and heat	0.18–0.31

resources (wood and fossil fuels), energy consumption during manufacturing (electricity and heat), transport distances (A2, A4, and C2 modules), and the density of the panels as well as the effect of the substitution of 10% PMMA with PLA in the ULPB with PLA/PMMA core were calculated for the impact category GWP* and Ecological Scarcity 2006.

For the holistic approach the maximum and minimum values of the additional data and assumptions were included in the scenarios. Therefore minimum and maximum results exist for each scenario.

For land use change calculations, maximum values are based on Searchinger at al. [31], and minimum values are based on Laborde [39]. Three scenarios on methane leakages [35] were applied for the fermentation from corn to methane, and different carbon intensities were used for electricity generation in the model (Table 3).

3. Results

3.1. EPD Approach

3.1.1. Comparing Life Cycle Stages. The relative impacts of the different ULPB life cycle stages for each indicator are presented in Figure 4. Detailed results are available in Appendix 2. For all indicators considered, except the Ecological Scarcity, the raw materials stage (A1 module) has the highest impacts. Thereafter the disposal (C4 module) followed by the manufacturing processes (A3 processes) are relevant. Considering that the disposal is mainly influenced by the quantity of material to be disposed of, both stages A1 and C4 will have the tendency to progress proportionally (reducing the amount of raw material will reduce the environmental impact due to the disposal). But the core layer composition could affect this proportionality. Ecological Scarcity results heavily weigh on the environmental effects of the disposal. The transport stages (A2, A4, and C2) have the lowest environmental impact for all considered indicators.

3.1.2. Raw Materials. As the raw material stage (A1 module) seems to be the most critical stage, the GWP* of this stage was analysed first. The obtained results show that the polymer composition of the core layer influences the global result of GWP*. The PMMA, which is used at the moment in the formulation in order to enhance the foaming process, represents 41% of the GWP* of the Module A1. The production of PMMA requires several intermediate products [40], all derive from fossil resources (crude oil and natural gas), which explains this high GWP* score. The UF resin (32% of the GWP* of Module A1) is also a problematic raw material because of the intensive fossil resources use for manufacturing. As has already been observed by other authors, UF resin has the greatest impact in GWP* of PB [5, 6, 9]. Finally the PLA, representing 18% of the Module A1 GWP* score, needs an important amount of fossil energy for production and agricultural processes even if produced from renewable resources. Detailed scores for Ecological Scarcity show that PLA, PMMA, and UF represent 29%, 30%, and 27%, respectively, of the A1 module. In this model the emissions to air (CO_2 emissions of fossil fuels for energy purpose) and to water (emissions of nitrate and phosphorus from fertilizers for corn grown as PLA raw material) during manufacturing of the polymers are predominant impacts. When looking at the ecotoxicity results using USETox PLA represent 45%, UF 32%, and PMMA 12% of the A1 module. Biocides (mostly atrazine and chlorpyrifos) used for the corn

Table 4: Detail inventory for 1 m^3 panel from gate-to-gate (Module A3).

Flow	Unit	PB	ULPB (EPS)	ULPB (PLA/PMMA)	ULPB (PLA)
		Input			
Resources					
Water for cooling	m^3	0.30	0.14	0.14	0.14
Equipment					
Plant	Count	3.33E − 08	3.33E − 08	3.33E − 08	3.33E − 08
Batch reactor	Count			3.33E − 08	3.33E − 08
Absorption chiller	Count			5.88E − 06	5.88E − 06
Liquid storage tank	Count			1.31E − 09	1.31E − 09
Energy					
Electricity	kWh	104.00	69.98	72.00	72.00
Heat	MJ	1426.00	821.05	821.05	821.05
. . .thereof Biomass	MJ	1100.00	572.29	572.29	572.29
. . .thereof Gas	MJ	154.00	96.22	96.22	96.22
. . .thereof Oil	MJ	172.00	152.54	152.54	152.54
		Output			
Product	m^3	1	1	1	1
Byproducts: wood chips	m^3	0.35	0.15	0.15	0.15
Waste water	m^3	0.04	0.02	0.02	0.02
Heat	MJ	375.00	158.25	158.25	158.25
Emissions					
CO_2 fossil	kg	22.34	17.54	18.35	18.35
CO_2 biogenic	kg	106.37	55.34	55.34	55.34
NO_x	kg	0.13	0.07	0.07	0.07
SO_x	kg	0.04	0.04	0.04	0.04
NMVOC	kg	0.17	0.07	0.07	0.07
Particulates	kg	0.08	0.03	0.03	0.03
Formaldehyde	kg	3.00E − 03	1.40E − 03	1.40E − 03	1.40E − 03
Pentane	kg		2.00		

agricultural production are mostly responsible for high soil emissions of the PLA in USETox. Metal emissions to air (vanadium and nickel) and to water (chromium) during the manufacturing stages of UF and PMMA explain the score of these polymers in USETox.

3.1.3. Manufacturing Process. The manufacturing steps with high GWP* impacts are the finishing (due to high electricity demand for sanding and sawing, etc.), the pressing, and drying (due to electricity and heat from fossil fuels), and the particle preparation (due to high electricity demand for particle sieving and screening) (Figure 5). The high GWP* observed for all processes involving electricity point out that the type of the electricity mix used in the plant might be a relevant factor influencing the results of the A3 modules. For the Ecological Scarcity the drying stage has the highest score, due to the emissions of particulates. Pressing, finishing and particle preparation stages are, likewise for GWP*, relevant stages in this model due to the consumption of electricity. USETox results of the manufacturing stages are in the same order of relevance than GWP* results mainly due to the emissions to air produced during the combustion of fossil fuels and the generation of the consumed electricity.

3.1.4. Transport. Environmental impacts due to transports are related to the means of transportation used, the distance driven and the weight of the material transported. Based on the chosen scenario the transport to the user (A4 module) has the highest impact, because it is the less optimized transport (a small quantity of panel on a relatively long distance).

3.1.5. Disposal. In the incineration process all polymer based on fossil resources (UF, PMMA, and paraffin) release fossil CO_2, which is directly accounted in the GWP* score. Biobased materials (wood and PLA) have less influence on the GWP* score of the incineration module. Considering the Ecological Scarcity method, the emissions into air (dioxins) and water (total organic carbon) during incineration of wood are highly weighted. The compounds manufactured from fossil fuels contribute to a lesser extent to the score, mainly due to their fossil CO_2 emissions. Finally in USETox, the disposal of UF has the highest score in the incineration (about 60% of the C4 module CTUe) due to emissions into water (heavy metals).

3.1.6. Effect of Production Capacity Reduction on GWP. Lüdtke [41] showed that an in-line foaming process needs a reduction

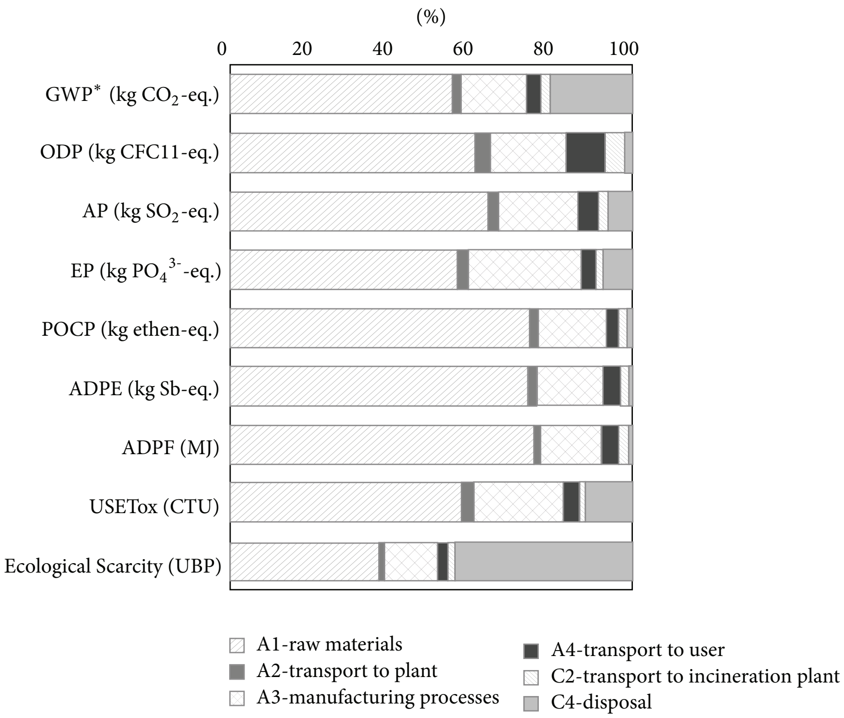


Figure 4: Relative environmental impact assessment of the ULPB for each life cycle stage corresponding to EN 15804 modules for the 9 indicators considered.

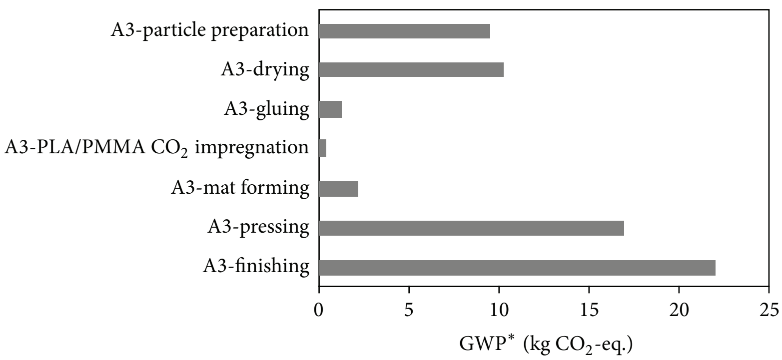


Figure 5: GWP* of all manufacturing stages (A3 modules) for the ULPB with PLA/PMMA core.

of the speed of production. Indeed the foam needs to be expanded and the panel has to cool down before it can be cut or sanded. This could represent a decrease of the production capacity of about 50%. The effect of the reduction of speed on the GWP* of accumulated process A1 to C4 has been simulated. The results of the calculation show that a decrease of the production capacity from 600 000 m^3/yr to 300 000 m^3/yr would increase the GWP* of the overall ULPB LCA of 15%.

3.1.7. Effect of Core Layer Substitution. The impacts of the four core layer cases for the GWP*, Ecological Scarcity, and USETox are presented in Figures 6, 7, and 8. For both GWP* and the Ecological Scarcity method, the cumulative impacts of the Stages A1 to C4 are higher for the wood core layer than all other ULPB cores simulated. This is, for the GWP*, mainly due to a higher amount of particles to prepare in the manufacturing process as well as the increase of transport emission due to the higher density of the panel. For the ecological Scarcity, the wood core shows a significant drawback due to process-specific burdens of the incineration (see Section 3.1.5).

Regarding the different ULPB core types, the core containing PMMA shows the highest impact for the GWP* and the Ecological Scarcity methods. This is mainly due to the high fossil energy consumption during manufacturing of PMMA. The substitution of PMMA with PLA shows benefits in the GWP* and the Ecological Scarcity method. Concerning GWP*, the substitution of 1 kg PMMA with PLA will allow a decrease of 6 kg CO_2-eq. for Stages A1 to C4.

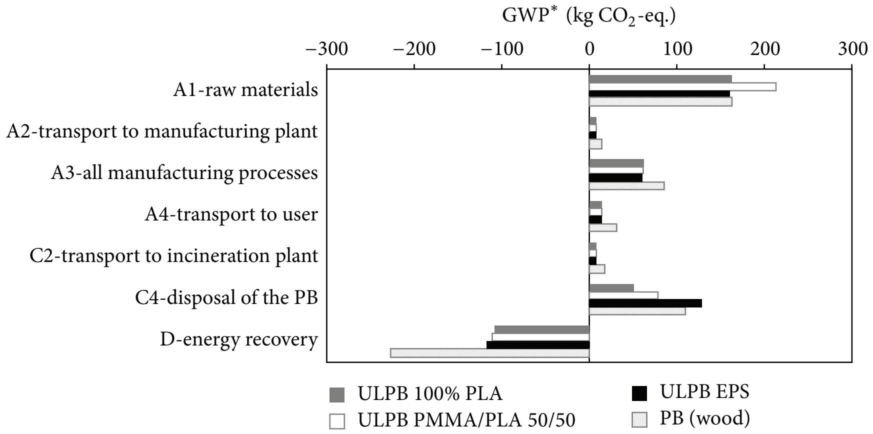


FIGURE 6: LCA impact category GWP* results of 1 m^3 panel with different core layer compositions.

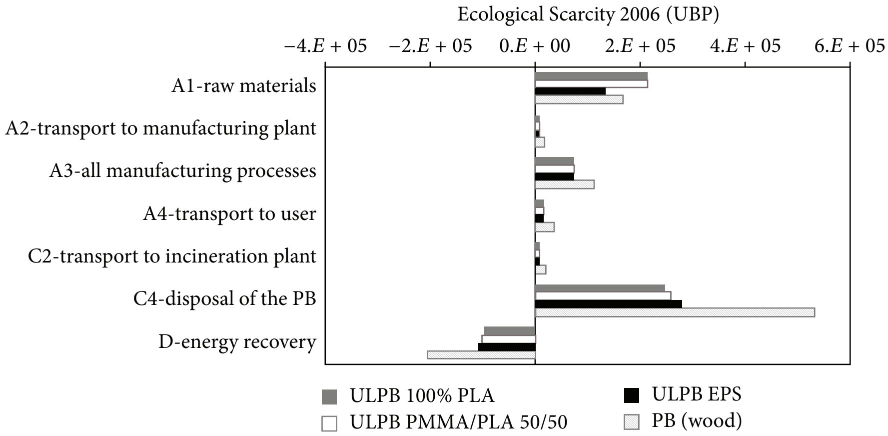


FIGURE 7: LCA impact category Ecological Scarcity results of 1 m^3 panel with different core layer compositions.

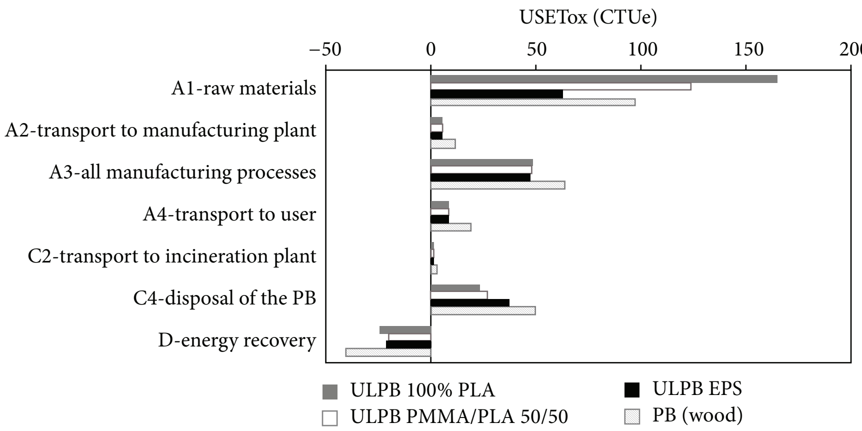


FIGURE 8: LCA impact category USETox results of 1 m^3 panel with different core layer compositions.

EPS causes slightly more fossil CO_2 than PMMA during stage C4 due to the higher carbon content of this polymer. Core layers containing PLA have a higher influence for the stage A1 on the ecological Scarcity method. Analogously, the USETox results show that the panel containing PLA has a considerable drawback on the ecotoxicity, mainly in Module A1. Reasons are the same as explained in Section 3.1.2. PMMA is also problematic in terms of USETox as the manufacturing of this polymer causes relevant emissions to water (see Section 3.1.2). The ULPB with EPS foam core has less ecotoxic effect in Module A1 than the PB, this is directly linked to the reduced amount of UF.

3.1.8. Sensitivity Analysis. The results are very sensitive to the density of the panels (10% change leads to 7.5%–9.2% impact change). It has a direct influence on the raw material module (A1), on the transport modules (A2, A4, and C2), on the disposal module (C4), and on some of the manufacturing processes (A3 modules), especially the particle preparation process. This confirms that the amount of raw material used has a high significance on the model. The reduction of 10% PMMA (replaced by 10% PLA) in the core layer had a moderate effect on the models GWP* (−2.2%) and USETox (1.7%) whereas it has a nonsignificant effect on Ecological Scarcity (−0.3%). The scenario of 10% reduction of electricity consumption, heat production, and fossil fuels in heat generation mix in production processes allow us to evaluate the uncertainties due to the assumption made on the energy flows during production of the panels. For all three impact categories observed, the perturbations did not significantly change the overall results (less than 1.3% of the original scenario). This means that the assumption made for these processes (A3 modules) does not influence the model to a relevant extent. Calculated scenarios for 10% reduction of transport distances of the main components and products are also not perturbing the system noticeably (less than 1.2%). This confirms the low contribution of transport processes to the entire system.

3.2. Holistic Approach. Figure 9 shows the results of the holistic approach. The first (white) beam on the left shows the total difference between the *conventional PB production* and the *production of ULPB excluding corn production* as defined in Figure 3 (86.8 kg CO_2-eq. per m^3 of panel). To complete the calculation, the three scenarios are added to the beam with their minimum and maximum values. If it is assumed that extra corn has to be produced (Scenario 1), the maximum impact of the extra corn production, including indirect land use change, is 55 kg CO_2-eq. per m^3 of panel, leaving a remaining benefit of 32 kg CO_2-eq. per m^3 of panel for the ULPB.

If available corn is used for the production of PLA and the bioethanol which would have been produced from that corn needs to be replaced by conventional gasoline (Scenario 2), the remaining benefit will be between 73 and 74 kg CO_2-eq. per m^3 of panel. If corn is used which would have been used in a biogas fermentation process (Scenario 3), the remaining benefit will be at least 76 kg CO_2-eq. per m^3 of panel. In the case of high methane leaks in the fermentation process, the benefit is even 91 kg CO_2-eq. per m^3 of panel.

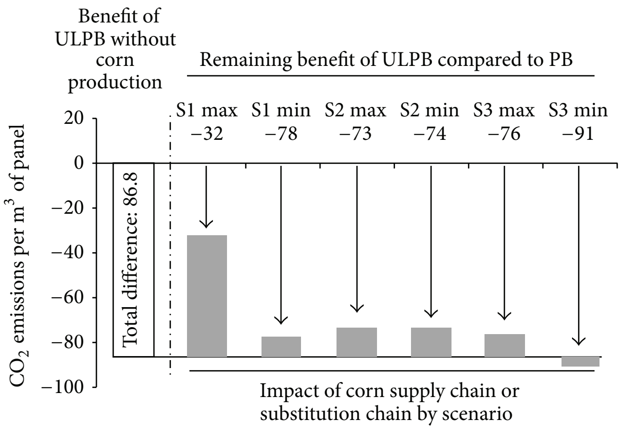


Figure 9: Results of scenarios used in the holistic approach.

4. Discussion

4.1. The Global Warming Potential. The two approaches produce similar results, which lead to the same conclusion in terms of greenhouse gas reduction potentials by exchanging PB with ULPB based on 100% PLA cores. However, the dependencies of the models on circumstances are different, and therefore recommendations to developers can be broadened by considering both models.

The differences between the panels observed with the EPD approach result from a reduction in the consumed electrical energy for the processes and exchanging UF with core material.

The holistic approach, on the other hand, takes more effects into account than the two described above. First of all, the amount of biomass which has to be burned to dry the extra amount of chips in the PB is recognized as not available for other applications. In contrast, the EPD approach only recognizes them in terms of their supply chain (in the case of recovered wood, only the transport is taken into account), since the carbon within the biomass is considered carbon neutral. This also means that reducing the amount of energy from biomass needed for the process has a much greater effect in the holistic approach than in the EPD approach.

Secondly, the characteristics of the recovered wood at the end-of-life are not taken into account in the EPD approach, but are in the holistic approach. Since the holistic approach assumes that the byproducts from sawmills are used elsewhere if not used within the panel, the model theoretically takes into account whether the incineration process of the pure sawmill byproducts would have been different from the process of burning the panels at their end-of-life. As we assumed these processes to be the same, no difference can be derived here, but in cases where the panels are burned at their end-of-life less efficiently due to mixed waste fractions, this would be taken into account by the holistic model.

Further on, the holistic model takes into account that PLA has to be produced from corn, which is a limited resource. If other routes for the corn exist, where the environmental benefit is higher than it is in the core layer of the ULPB, this is recognized by the holistic model. The EPD model does not take this into account.

With regard to the differences between PB and ULPB with PLA, the maximum PMMA content in the core layer of PMMA/PLA panels can be determined. The maximum here is defined as the point where the PLA/PMMA mixture core panels have no benefits compared to a conventional PB. In the worst case (maximum land use change) only 20% (5 kg) of PMMA and in the best case (minimum biogas) 56% (14 kg) of PMMA can be included in the core layer. In the other cases, 45% to 48% define the threshold.

4.2. USETox and Ecological Scarcity 2006. Although not analyzed specifically in the *holistic model*, some general aspects in addition to the results of the *EPD approach* can also be derived for USETox and Ecological Scarcity.

In case of the UBP indicator, the incineration of wood has a very high impact. As the holistic model assumes that the sawmill byproducts will be burned at some point in time anyway, no matter whether they are used in the panel or not, the importance of the incineration of wood of the different panels will diminish drastically.

The USETox indicator for the PLA core panels is driven by the pesticides used during production of corn. This is included in the holistic model as well, but only if the production of an extra amount of corn is taken into account (Scenario 1). If available corn is used (Scenarios 2 and 3), the use of pesticides has a much lower impact.

5. Recommendations

The following recommendation can be made for the developers of ULPB with foam cores:

(i) The biopolymers used as foam precursor should have low energy demand or/and use renewable energies for their production. If possible, the chosen biopolymer should be produced out of biomass issued from organic agriculture (no pesticides or fertilizer) or sustainable managed forests. Their production should not be based on sugar derived from primary resources like corn but from waste flows (sugar, starch, and celluloses) which are not used elsewhere or only in a very inefficient way. This would exclude the land use change scenario from the model and would also avoid concurrency with the production of food.

(ii) The amount of UF resin should be reduced or better substituted by a renewable resource-based adhesive or recycled polymer adhesive with low energy consumption or/and use of renewable energies for manufacturing.

(iii) If PMMA is still necessary for enhancing the foaming and the foam properties, the portion of PMMA should be reduced as much as possible. If possible, PMMA should be substituted by a recycled polymer or a biopolymer with the same properties.

(iv) The technology should be developed in order to maintain the same production capacity, and if possible, to increase it.

(v) Besides the fact that the ULPB is already very light, decreasing the density even more could contribute to a reduction of the environmental burdens.

(vi) Solution for reducing the energy consumption of the particle preparation processes as well as the finishing processes (mainly the sanding) should be elaborated.

(vii) The materials should be separable at their end-of-life. The efficiency of the waste treatment for the mixed fractions like PB should be as close to the efficiency of the incineration of the pure sawmill byproducts or the end-of-life treatment of products made of them other than panels.

(viii) The panel should be recyclable or able to be reused at the end-of-life instead of being incinerated.

6. Conclusions

With the aim of developing a product with a better environmental profile with respect to greenhouse gas emissions, the comparison done in this study shows that exchanging PB with 100% PLA core ULPB is beneficial. Exchanging conventional PB with ULPB based on EPS or PMMA/PLA cores is beneficial as well. However, the benefits of reducing the amount of adhesives in the ULPB compared to PB is almost made up for by the production of the foam core material if based on fossil resources. On the other hand, the use of conventional PLA induces specific agricultural issues mainly due to use of pesticides and fertilizers, land reconversion, land use, and agricultural process energy consumption.

This study shows that both EPD and holistic approaches were useful in order to forecast the environmental issues of in-development ultralight panels based on wood and biopolymers. Both approaches provided relevant recommendation for further development of these products.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors gratefully acknowledge the Swiss National Foundation Program NFP66 (Project 406640_136678) and the COST Action PF1303 of the EU RTD Framework Program for financial support of this study.

References

[1] A. May-Pat, F. Aviles, and J. Aguilar, "Mechanical properties of sandwich panels with perforated foam cores," *Journal of Sandwich Structures and Materials*, vol. 13, no. 4, pp. 427–444, 2011.

[2] L. J. Gibson and M. F. Ashby, *Cellular Solids: Structure and Properties*, Cambridge University Press, Cambridge, UK, 2nd edition, 1997.

[3] D. Zenkert, *Handbook of Sandwich Construction*, Engineering Materials Advisory Services, Worcester, UK, 2008.

[4] J. Luedtke, J. Welling, H. Thoemen, and M. C. Barbu, "Lightweight wood-based board and process for producing it," WO 2008/071617 A2, 2008.

[5] M. F. N. Dos Santos, R. A. G. Battistelle, B. S. Bezerra, and H. S. A. Varum, "Comparative study of the life cycle assessment of particleboards made of residues from sugarcane bagasse

(*Saccharum* spp.) and pine wood shavings (*Pinus elliottii*)," *Journal of Cleaner Production*, vol. 64, pp. 345–355, 2014.

[6] S. Rueter and S. Diederichs, *Ökobilanz-Basisdaten für Bauprodukte aus Holz*, Thünen Institut, Hamburg, Germany, 2012.

[7] J. B. Wilson, "Life-cycle inventory of particleboard in terms of resources, emissions, energy and carbon," *Wood and Fiber Science*, vol. 42, no. 1, pp. 90–106, 2010.

[8] F. Werner and K. Richter, "Wooden building products in comparative LCA," *The International Journal of Life Cycle Assessment*, vol. 12, no. 7, pp. 470–479, 2007.

[9] B. Rivela, A. Hospido, M. T. Moreira, and G. Feijoo, "Life cycle inventory of particleboard: a case study in the wood sector," *International Journal of Life Cycle Assessment*, vol. 11, no. 2, pp. 106–113, 2006.

[10] A. Frühwald, M. Scharai-Rad, and J. Hasch, *Ökologische Bewertung von Holzwerkstoffen Schlußbericht März 2000 Ergänzt in den Bereichen Spanplattenrecycling und OSB-Bilanzen*, Universität Hamburg, Hamburg, Germany, 2000.

[11] S. Feifel, A. Faul, and L. Schebek, "Vergleichende ökologische Analyse leichter Holzwerkstoffplatten mit unterschiedlichem Aufbau," *Holztechnologie*, vol. 52, pp. 22–27, 2011.

[12] S. Feifel, W.-R. Poganietz, and L. Schebek, "The utilization of light weight boards for reducing air emissions by the German wood industry—a perspective?" *Environmental Sciences Europe*, vol. 25, no. 1, article 5, 2013.

[13] D. A. L. Silva, F. A. R. Lahr, A. L. R. Pavan et al., "Do wood-based panels made with agro-industrial residues provide environmentally benign alternatives? An LCA case study of sugarcane bagasse addition to particle board manufacturing," *The International Journal of Life Cycle Assessment*, vol. 19, no. 10, pp. 1767–1778, 2014.

[14] R. J. Plevin, M. A. Delucchi, and F. Creutzig, "Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers," *Journal of Industrial Ecology*, vol. 18, no. 1, pp. 73–83, 2014.

[15] S. Suh and Y. Yang, "On the uncanny capabilities of consequential LCA," *The International Journal of Life Cycle Assessment*, vol. 19, no. 6, pp. 1179–1184, 2014.

[16] M. Brandão, R. Clift, A. Cowie, and S. Greenhalgh, "The use of life cycle assessment in the support of robust (climate) policy making: comment on "Using attributional life cycle assessment to estimate climate-change mitigation . . ."," *Journal of Industrial Ecology*, vol. 18, no. 3, pp. 461–463, 2014.

[17] J. M. Earles and A. Halog, "Consequential life cycle assessment: a review," *The International Journal of Life Cycle Assessment*, vol. 16, no. 5, pp. 445–453, 2011.

[18] EN 15804:2013. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products; German version EN 15804:2012+A12013. Brussels: European Committee for Standardization, CEN/TC 350—Sustainability of con- struction works, 2013.

[19] ISO, "Environmental management—life cycle assessment—requirements and guidelines," ISO 14044:2006, 2006.

[20] *ISO 14025:2006, Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures*, vol. 3, 2006.

[21] ISO, *DIN EN ISO 14040:2006. Umweltmanagement—Ökobilanz—Grundsätze und Rahmenbedingungen*, ISO, 2006.

[22] British Standards, "Round and sawn timber—environmental product declarations—product category rules for wood and wood-based products for use in construction," BS EN 16485: 2014, 2014.

[23] Aveny GmbH, Aveny LCA, 2012.

[24] R. Frischknecht, N. Jungbluth, H.-J. Althaus et al., "The ecoinvent database: overview and methodological framework," *International Journal of Life Cycle Assessment*, vol. 10, no. 1, pp. 3–9, 2005.

[25] A. Shalbafan, J. Luedtke, J. Welling, and H. Thoemen, "Comparison of foam core materials in innovative lightweight wood-based panels," *European Journal of Wood and Wood Products*, vol. 70, no. 1–3, pp. 287–292, 2012.

[26] H. Thoemen, "Ultra-light bio-based particleboard with a foam core—NRP 66 'Resource Wood'," 2012, http://www.nfp66.ch/E/projects/wood-material-for-components/ultra-light-bio-based-particleboard/Pages/default.aspx.

[27] BSI, "Particleboards—specifications," Tech. Rep. EN 312:2010, British Standards Institution, 2010.

[28] S. K. Diederichs, "2010 Status quo for life-cycle inventory and environmental impact assessment of the core sawmill products in germany," *Wood and Fiber Science*, vol. 46, no. 1, pp. 65–84, 2014.

[29] EN 15804: Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products, 2014.

[30] B. Weidema, "Market information in life cycle assessment," Environmental Project 863, Danish Environmental Protection Agency, 2003.

[31] T. Searchinger, R. Heimlich, R. A. Houghton et al., "Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change," *Science*, vol. 319, no. 5867, pp. 1238–1240, 2008.

[32] PE International, *Gabi 4 Software and Gabi Professional Database*, PE International, Stuttgart, Germany, 2012.

[33] B. Wicke, P. Verweij, H. van Meijl, D. P. van Vuuren, and A. P. C. Faaij, "Indirect land use change: review of existing models and strategies for mitigation," *Biofuels*, vol. 3, no. 1, pp. 87–100, 2012.

[34] H. Shapouri, J. A. Duffield, and M. Wang, "The energy balance of corn ethanol: an update," Agricultural Economic Report 813, US Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses, 2002.

[35] R. Vogt, *Basisdaten zu THG-Bilanzen für Biogas-Prozessketten und Erstellung neuer THG-Bilanzen*, Insitut für Energie und Umweltforschung, Heidelberg, Germany, 2008.

[36] J. B. Guinée, R. Heijungs, G. Huppes et al., *Life Cycle Assessment: An Operational Guide to the ISO Standards*, Leiden University, Leiden, The Netherlands, 2001.

[37] R. Frischknecht, R. Steiner, and N. Jungbluth, *The Ecological Scarcity Method—Eco-Factors 2006. A Method for Impact Assessment in LCA*, Federal Office for the Environment (FOEN), Geneva, Switzerland, 2009.

[38] A. D. Henderson, M. Z. Hauschild, D. van de Meent et al., "USEtox fate and ecotoxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties," *The International Journal of Life Cycle Assessment*, vol. 16, no. 8, pp. 701–709, 2011.

[39] D. Laborde, "Assessing the land use change consequences of European biofuel policies," Specific Contract SI2.580403, International Food Policy Research Institute, 2011.

[40] I. Boustead, *Eco-Profiles of the European Plastics Industry—Polymethyl Methacrylate (PMMA)*, PlasticsEurope, Brussels, Belgium, 2005.

[41] J. Lüdtke, *Entwicklung und Evaluierung eines Konzepts für die kontinuierliche Herstellung von Leichtbauplatten mit polymerbasiertem Kern und Holzwerkstoffdecklagen*, Hamburg University, 2011.

Eidesstattliche Versicherung nach §7(d)

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift mit dem Titel *EMPOWERING WOODWORKING INDUSTRY STAKEHOLDERS TO REDUCE ENVIRONMENTAL IMPACTS* selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Hamburg, 21.05.2015

Ort, Datum

Unterschrift (Stefan Diederichs)