Quantification of chemical emissions from building materials in a circular economy perspective

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Preface

The Master thesis project at the master studies in Environmental Engineering was created in collaboration with University of Southern Denmark (SDU) Life Cycle Engineering and SDU Chemical Engineering to catalyse the interdisciplinary work between the research groups at the Faculty of Engineering at SDU. The project has been performed from September 1st, 2019 to June 1st, 2020 under the supervision of Professor WSR Morten Birkved, Professor WSR Xavier Fretté, and Assistant Professor, PhD Diane Bastien.

First, I would like to give a special thanks to my supervisor Professor Morten Birkved for allowing me to be a part of this specific project. It has been a delight to use my theoretical and practical knowledge both from my bachelor study in Biochemistry and Molecular Biology and my master study in Environmental Engineering. Thanks to both Professor Morten Birkved and Assistant Professor Diane Bastien for granting me the privilege to receive inspiration and guidance during the process of this project. A project that has opened for the opportunity to continue the work for half a year as a research and teaching assistant at SDU from August 2020 to January 2021. I am forever grateful for getting the opportunity to dive deeper into this project.

I would like to sincerely thank Professor Xavier Fretté for introducing me to the laboratory facilities at the Faculty of Engineering as well as for inspiring and supporting me both practically and theoretically in the laboratory. I hope to continue the great collaboration in the future work.

Finally, an enormous thank goes out to my boyfriend, my family, and my closest friends for the endless support they have given me during my educational journey and especially during the process of this project. Especially my closest friends, Mia de Laurent Clemmensen and Frederikke Juul Tidselholdt, for proofreading my thesis. An endless thank goes out to my boyfriend, Jacob, who has been unlimitedly supportive, kind, and patient with me, while also having to work on his bachelor project.

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Abstract

The change from a linear economy to a circular economy has become even more urgent in the last decades for the construction sector. The sector is one of the largest resource consumers, where the sectorial waste constitutes one-third of all waste products in Europe. However, reuse and recycling of construction materials also create an issue, since toxic chemicals can be emitted to the environment, which could lead to human health problems. The toxicity can be assessed as the direct/indirect exposure impact from a product or entity providing a service (embedded) or the direct/indirect toxicological impact throughout the whole value chain of a product (embodied).

The embedded toxicity in materials, such as concrete, wood, clay, straw, and wood fibreboard, is extracted with Solid Phase Micro Extraction before being analysed with gas chromatography-mass spectrometry (GC-MS). The emitted chemicals are identified and quantified as the ratio of chemicals present. The human toxicity impact of the chemicals is characterised and presented in Disability-Adjusted Life Years (DALY) per kg emitted substance. The sum of all chemical impacts gives the total embedded toxicity of each material. The embodied human toxicity is modelled in the software OpenLCA 1.10.2 for three levels of building material: 1 kg building material, 1 m^3 building component, and 1 m^3 complete external wall system. The calculated midpoint results for the human embodied toxicological impact is presented as DALY per level of building material assessed.

The embedded toxicity is highest for wood fibreboard and lowest for wood. However, the life cycle of 1 kg wood has the highest contribution to the embodied human toxicity impact. Six out of 30 identified chemicals could be characterised as having an impact on human toxicity, where the share of characterised chemicals varies between 4 % and 86 % out of 1 kg emitted substance. The embodied toxicity results for singular building materials show the highest toxicity belonging to 1 kg of wood and a negative embodied human toxicity impact for straw and wood fibreboard. The EcoCocon element and the complete external wall system has a higher impact than the concrete component and external wall. Recycling of wood in the EcoCocon element causes negative embodied human toxicity impact, due to avoided production of new materials. Recycling should always be the first choice even if the materials have a large embedded toxicity. Incineration should only be considered if the materials cannot be stripped of contaminants or properly recycled.

The embedded toxicity should logically be lower than embodied toxicity; however, the embodied toxicity can be negative, pointing towards the embedded and embodied toxicity are not relatable in the way they are assessed in this project. The embedded toxicity is a better method for assessing the consumer health-related toxicity of material compared to the embodied toxicity, that possibly accounts for emissions occurring far away from the consumer. Both methods can benefit in the design and production stage of future building materials as well as play a role in the choice of material used for construction to lower the polluting human toxicity across the value chain of materials.

Readers guide

The dissertation is divided into six major chapters: Introduction, Methodology, Results and Discussion, Future Perspective, Conclusion, and Appendices.

Chapter	Content
Introduction	The Introduction seeks to frame the problem by introducing toxicity in building materials in a circular economy perspective. The subchapter Scope and Limitations of the Work presents very shortly what I have performed during the thesis. It also covers the challenges that occurred, e.g. Lockdown of the university due to COVID-19 and the breakdown of an essential laboratory machine for three weeks in January. The literature on toxicity in building materials is presented along with the health effects caused by the toxicity released from building materials. A definition of embodied and embedded toxicity is given before presenting the theory behind the assessment of embedded and embodied toxicity. Lastly, hypothesis and research questions are presented.
Methodology	The Methodology is divided into two major subchapters: Embedded toxicity and Embodied toxicity. The chapters describe how I have performed the experiment and modelling in details.
Results and Discussion	The Results and Discussion presents, interprets, and discuss the embedded and embodied toxicity individually. Afterwards, the embedded and embodied toxicity is compared and discussed with a circular economy perspective.
Future Perspective	The Future Perspective contains research ideas for the upcoming project
Conclusion	The Conclusion seeks to answer the research questions while presenting the most relevant results.
Appendices	All toxicity results for each building materials from the experimental analysis of the embedded toxicity and the modelling of the embodied toxicity can be found in the Appendices.

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List of Abbreviations

C	Carcinogenic
CAR	Carboxen®
CAS	Chemical Abstracts Service
CTUh	Comparative Toxic Unit for human
DALY	Disability-Adjusted Life Years
Danish EPA	Danish Environmental Protection Agency
DNPH	2,4-dinitrophenylhydrazine
DVB	Divinyl benzene
DVB/CAR/PDMS	Divinyl benzene/Carboxen® on Polydimethylsiloxane
EF	Effect Factor
EI	Electron Ionisation
FF	Fate Factor
FU	Functional Unit
GC	Gas Chromatography
GC-FID	Gas Chromatography-Flame Ionisation Detector
GC-MS	Gas Chromatography-Mass Spectrometry
He	Helium
HPD	High Population Density
IAQ	Indoor Air Quality
ILCD	International Reference Life Cycle Data System
IRINA	Innovative Room for Indoor Air studies
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LOAEL	Lowest Observed Adverse Exposure Level
LPD	Low Population Density
MS	Mass Spectrometry
MW	Molecular Weight
m/z	Mass-to-charge Ratio
NC	Non-carcinogenic
NIST	National Institute of Standards and Technology
NOAEL	No Observed Adverse Exposure Level
PAH	Polycyclic Aromatic Hydrocarbon

PCB	Polychlorinated Biphenyl
PDMS	Polydimethylsiloxane
RT	Retention Time
SETAC	Society for Environmental Toxicology and Chemistry
SD	Standard Deviation
SPME	Solid Phase Microextraction
TLV	Threshold Limit Value
UNEP	United Nations Environment Program
VOC	Volatile Organic Compound
WHO	World Health Organisation
XF	Exposure Factor

1. Introduction

The biggest challenge in the 21st century, affecting both humankind and every other life on Earth, is global warming and climate change [1]. Climate change, which is most likely caused by human activity, has led to a substantial increase in global atmospheric concentrations of greenhouse gas emissions since the industrial revolution began in the second half of the 18th century [2].

The construction sector has a substantial impact on the environment, including depletion of biological and fossil resources, increased greenhouse gas emissions from fossil fuels, the use of raw materials for construction, maintenance and renovation, and emissions of harmful chemicals used in modern construction [3][4]. Globally, approx. 50 % of all materials (both biological and fossil resources) extracted from Earth's crust are used in the construction sector, thereby being one of the most resource-consuming sectors. In Europe, construction and demolition waste constitutes one-third of all waste products and is therefore considered the largest waste stream from a single industrial sector [5].

1.1. Circular Economy in the Building Sector

The circular economy is a sustainable alternative to a linear economy and strives to minimise the use of resources and to eliminate waste by increasing the reuse and recycling of resources in a continuous cycle [6]. Changing from a linear economy approach to a circular economy approach has become more urgent for the building and construction sector. Rapid urbanisation and increasing population growth, causes an even greater expansion of the built environment and increases the need for more building materials [7][8].

The need for increased recycling of building materials is global, as, in many areas, we are close to having used up many of the resources that construction is dependent on [9]. In Denmark alone, we are close to having exhausted our readily available sources of sand and gravel, which is an essential raw material in the production of concrete [9]. Thus, a forecast from the Danish engineering consultancy company NIRAS predicts that the demand for gravel by the year 2040 will increase by more than 50 %, which according to the projections means that by the year 2027, the Capital Region is already hitting the "bottom" of their gravel pits [9] [10]. Furthermore, the Danish Ministry of the Environment and Food has chosen to phase out the extraction of the approximately 50,000 cubic meters of sand and gravel that is collected from the Sound every year, as this extraction of sand results in negative impacts on the marine environment in the Sound [9]. Dansk Byggeri also states that it is not a real alternative to gather gravel and sand abroad, as here too there is a shortage of sand and gravel, and long and heavy transport of gravel will be extremely stressful for the climate [9][10].

Thus, the only climate-friendly and realistic alternative to sand are to increase our recycling of (old crushed) concrete as aggregate instead of sand and gravel in new concrete. The increased recycling is supported by the EU Framework Directive for Waste 2008/98/EC, which states that 70 % of building and demolition waste must be recycled in the year 2020 [5].

The circular economy in construction is a hot topic these years. It is highlighted as one of the tools needed to reduce the contribution of the construction sector to global warming and the depletion of natural resources [11]. On the other hand, reuse and recycling of building materials can most likely cause an overlooked problem. Recycled materials can contain both environmental and health hazardous chemicals that can lead to an accidental release of chemicals with high biological activity to the environment as well as human health problems for the humans exposed to these chemicals. Some of the health problems for humans include asthma, allergy, reproduction impairment, congenital disabilities, and cancer [7][12].

1.2. Scope and Limitations of the Work

The thesis aims to analyse and quantify emitted pollutants from conventional recyclable building materials as well as "green" building materials to provide new information on embedded human toxicity in building materials. The experimental part of the project will consist of an accelerated release of the emitted pollutants (called "thermal stripping") into the gaseous phase. The gaseous phase will be at equilibrium and steady-state before is it captured and analysed by gas chromatography-mass spectrometry (GC-MS) using Solid Phase Micro Extraction (SPME). The purpose of the experiment is to analyse recycled materials such as wood and concrete accessed from the waste handling company RGS Nordic A/S and "green" building materials such as wood, straw, clay, and wood fibreboard accessed from Small Planet SMBA. The obtained GC-MS results of the substances emitted during thermal stripping will be qualitatively identified using the software Xcalibur and a chemical reference library. Each identified chemical will be quantified and characterised with human toxicity characterisation factors before the results are used to assess whether the analysed fraction of building material can be used and recycled without any health risk to present and future users. A life cycle assessment (LCA) will be made with the software OpenLCA to assess the human toxicity of incorporated pollutants in the analysed materials in different life cycle stages. The relationship between the emitted pollutants and incorporated toxicity will be compared for each specific building materials. Furthermore, incorporated toxicity in building components and complete external wall system is also assessed and compared to understand the toxicity, which is incorporated in the chosen building component or wall system.

In the beginning, the focus of the project was to study indoor emissions from building materials. However, since OpenLCA cannot assess the indoor environment, the focus changed to include an overall assessment of toxicity in building materials with perspective to materials used in the indoor environment and the circular economy approach. The emitted pollutants and incorporated toxicity are the closest to understanding the indoor environment. Exposure modelling of the chemicals could be an option to close the gaps between the assessment of toxicity in building materials and the reality, which will be conducted in the nearest future. Exposure modelling can be used to qualitatively understand how people would be exposed to chemicals being emitted both indoor and outdoor.

During the thesis work, a few challenges occurred, which influenced the final work. In January 2020, the GC-MS machine stopped working for three weeks due to malfunction, in which period it was not possible to perform laboratory work. Due to COVID-19, the university was on lockdown from March 12th, 2020. Luckily, the results for all sampled building materials were obtained and analysed in the laboratory a few days before the lockdown. Unfortunately, a small but essential part of the experiment was not able to be performed, namely the standard curve. The creation of a standard curve should have assisted the quantification of chemicals identified in each emitted substance of building materials. Without having a standard curve for the identified chemicals, it was only possible to quantify them relatively to the area under the peaks in the chromatograms by assuming equilibrium and steady-state of the sample and the gaseous phase. The result with characterisation factors is assessed as the human toxicity per kg emitted substance and not per kg sample or building material.

The goal, scope, and limitations of the thesis are described in further detail throughout chapter 1.3.

1.3. Indoor Air Quality and Emission from Building Materials

In the modern lifestyle, we spend on average 80-90 % of our time indoors, e.g. kindergartens, schools, workplaces, and homes [13]. New buildings have higher energy efficiency, which results in the reduction of unwanted air infiltration through the building fabric, which could compromise IAQ if an efficient and reliable mechanical ventilation system is not installed. In a report by [14], it has been indicated that more than 30 % of new or remodelled buildings worldwide may be the subject of excessive complaints regarding IAQ. Emission of pollutants will, under insufficient ventilation airflow rate, result in bad IAQ that contributes to the increasing human health risk [13]. It is, therefore, an essential factor to understand and provide new information on the toxicity of building materials and how it is related to sick building syndrome symptoms when facing short- and long-term exposure to bad IAQ.

1.3.1. Types of Indoor Emissions from Building Materials

The built environment can contain large amounts of chemical pollutants and heavy metals, some of which even comply with legal regulations at the construction time. The most frequently discussed pollutants of the indoor built environment can be categorised into three classes [15][16]:

1) Gasses and vapours
2) Non-viable particulate matter (e.g. asbestos)
3) Viable particulate matter (e.g. mould, spores, and other microbes)

The group of gasses and vapour includes organic compounds in indoor air such as volatile organic compounds (VOC) and irritants as well as formaldehyde, radon, polycyclic aromatic hydrocarbon (PAH) and biocides [15]. The focus of this project will be on the pollutants from group 1) and especially VOCs. It is essential to remember that there are so many more pollutants affecting the indoor built environment, causing different human health problems [16].

The past decades have substantially transformed the research on chemical emissions from materials. Most of the change has been due to advancements in analytical methods and technologies as well as the development of more accurate and precise sampling techniques [17]. Despite this, the mainstream building materials currently used are somewhat the same as those used 40 years ago [7].

In the literature, the analysed materials and products are grouped based upon their state of matter, e.g. either solid (dry) materials or liquid (wet) materials [17]. Wet materials include solvents such as paints and other adhesives. Dry materials include concrete, wood, plaster, textiles, and isolation material [18]. Researchers such as [19] also groups the materials and products either as "green" material or traditional, non-green material, where the "green" material is defined as non-toxic, low cost, and waste-, energy- and water-conserving materials. Water-based paint, wood, wood-fibreboard, clay, and straws are considered green building materials, while pressure-treated wood, solvent-based paint, and vinyl flooring are amongst the non-green material. Supposedly, "green" materials cause less harm than conventional materials to the environment as well as to the user and producers of the material [7].

[19] compared three groups of green materials with their counterpart non-green materials (Trex® decking wood vs pressure treated decking wood, ceramic floor tile vs vinyl flooring, and water-based paint vs oil-based paint and wood stain). The experiment was performed in small-scale chambers with controlled temperature, ventilation, and humidity, where the chamber air was collected and analysed by thermal desorption GC-Flame Ionisation Detector (GC-FID). All four non-green materials emitted far more hazardous VOCs than their green counterparts [19]. The non-green materials emitted

toluene, 3-carene, d-limonene, p-xylene, 2-butyl-1-octanol, and o-xylene, while the green materials only emitted 3-carene, camphene, and p-xylene.

It has been reported through past studies by [18] that wet materials are contributing largely to the total measured VOC levels (TVOC). [20] investigated emissions in a chamber test-house, which showed that the primary source of VOC emissions detected came from different sources of paints. Comparing the TVOC emissions from various paints showed a reduction in TVOC by a factor 100 when using water-based paints compared to solvent-based paints. The specific chemicals of concern regarding wet materials are xylene, 2-butanone oxime, formaldehyde, and acetaldehyde, which are associated with cancer and neurogenic and sensory effects [17].

For dry materials such as wood-based materials, e.g. particle boards and fibreboards, there is an essential concern of formaldehyde emission. Several standards have been developed to control the formaldehyde content in wood-based materials, which has led to the declination of the overall formaldehyde content in wood products [17]. Building materials made of natural "green" wood (untreated wood) have naturally occurring (biogenic) emissions, which are acetic acid, formaldehyde, formic acid, and many types of terpenes according to findings by [19]. Furthermore, preserved wood is of great concern, since the treatment can cause toxic emissions, that have damaging effects on the indoor and outdoor environment. Since 2006 specific impregnating agents based on arsenic, creosote, chromium, tributyltin naphthenate, and tributyltin oxide have been banned by law in Denmark [21]. Wood preserved with these impregnating agents could still be imported to Denmark, wherefore it is important to know how the wood has been preserved and, in most cases, find an alternative, e.g. naturally durable wood such as Western Red Cedar and Oak [22][23]. Likewise, wood treated with waterproofing agents approved for outdoor use contains chemical substances that are banned in wood used indoors, which on a circular economy approach leads to a problematic recycling process [24] [25].

To study new construction, [26] investigated the indoor VOC emissions from wood-based materials in an Innovative Room for Indoor Air studies (IRINA) by continuously monitoring in 3 weeks and analysis of the chamber air using Carbotrap cartridges with GC-MS and GC-FID. The study found that there was an unexpectedly high prevalence of VOCs such as α-pinene, limonene, hexaldehyde and especially formaldehyde. The results were correlated to the lower air renewal rate in new energy-efficient buildings along with increased use of wood-based materials in new construction [26].

In a study by [27] potentially harmful substances in crushed concrete, meant for recycling purposes in the construction sector, have been identified and assessed [27]. Three main groups of potentially harmful substances were identified: 1. Substances in mineral binders, aggregates, and lathing oils, 2. Additives used to improve the properties of concrete, and 3. Substances present in crushed concrete [27]. Concrete consists of water, mineral binder, and aggregates such as sand, gravel, and stone, which make up approx. 75 % of the concrete. The primary mineral binders in concrete used in Denmark consists of Portland cement, fly-ash concrete, micro silica, and pulverised blast furnace slag, where the share of mineral binders in the finished concrete is typically 5-20 % of the weight [27]. Some of the most harmful additives in concrete are aliphatic amines, dieldrin, epoxide, and different salts. The concrete can absorb secondary chemicals after production, e.g. polychlorinated biphenyl (PCB), bitumen, polycyclic aromatic hydrocarbons (PAH), phthalates, chlorinated paraffin, and heavy metal such as mercury [25][27][28]. Additives, along with secondary chemicals, can be present during use and in the crushed concrete, thereby resulting in unwanted effects on humans if recycled for construction purposes [29]. Extraction experiments of concrete by [27] showed the occurrence of substances such as benzene, toluene, xylene, ethylene, naphthalene, and different alkanes.

Sustainable green building materials have become more prevalent in new construction since they are composed of renewable resources and benefit by low cost and low waste while being energy- and water-conserving [19]. However, some green building materials have higher costs because of increased labour.

In 2019 the Danish architecture firm Henning Larsen Architects drew an annexe for the existing free school in Feldballe, Denmark, which had the focus on lowering the climate burden [30]. The school will amongst other things be built with EcoCocon walls from Small Planet SMBA composed of pressed straw (89 %) and wood (10 %), which internally is covered with STEICO wooden fibreboard and a series of clay plaster layers [30][31]. Like concrete, studies of clay showed it is also able to absorb chemicals, which during use can be emitted through the porous clay plastered wall to the indoor air [32]. Clay plaster consists of clay as a binder, water, and additives such as sand or gravel [33]. Straw can contain pesticides, mould, and other harmful substances, depending on how the straw has been farmed. The declaration for EcoCocon straw shows that the straw is sprayed with urea and ammonium nitrate soak (KAS-32), and Fertileader Tonic, while ammonium nitrate (N-34), granulated limestone and NPK 15-15-15 is spread on the field [34]. Biogenic substances in cereal straw includes ketones and alkanes. All substances in straw could potentially be emitted and cause effects on human health when installed as the walls in a building.

A study by [35] of wood fibreboards (MDF and particleboards) showed findings of VOCs such as hexanal, toluene, benzene, benzaldehyde, and different alkanes. In the production of wood fibreboards, glue and other additives are added for improvement of the boards. The amount of harmful

VOC in wood fibreboards is higher for boards that are glued compared to ones bonded together by lignin, which is a substance naturally found in the wood [35].

1.3.2. Health Effects of Exposure to VOCs

As mentioned in chapter 1.1, the exposure of emissions from building materials can lead to several health-damaging problems for humans. The health effect of being exposed to indoor emissions differs and should, according to [15], be categorised as follows:

1) Immune effects and other hypersensitivities
2) Respiratory effects
3) Cellular effects
4) Neurogenic and sensory effects
5) Cardiovascular effects

The immune effects include asthma, allergy, and non-specific hypersensitivity, while cellular effects include cancer and reproductive disruption. The cardiovascular effects include odour, irritation, and neurotoxic symptoms [15].

The toxic pollution, also known as toxicants, enter the body by one of the following routes: ingestion, inhalation, injection, or dermal absorption, and is absorbed to the bloodstream where it is transported to organs, which can either eliminate and excrete the toxicant or be damaged by the toxicant [36][37]. The diseases mentioned above are said to occur more often when a certain level of accumulated chemical pollutants in the body is exceeded, which can either be caused by a short duration of exposure or repeated exposure [38]. Furthermore, it is believed, that accumulated pollutants are concentrated between generations, thereby a new-born child can have accumulated pollutants already at birth. For instance, an increasing number of people are suffering from allergies (some even from birth) because of accumulated pollutants, which makes them more sensitive to chemicals around them [36][38].

As mentioned above, there are several intake routes of chemical pollutants from the indoor environment, where the most considerable amount, nearly 60 % of the total amount of substances, is taken in through respiration. The percentage intake can be higher for some chemicals than others, e.g. 95-99 % of benzene exposure is through respiration [39]. Unlike dirty water and rotten food, air pollution often cannot be seen. Therefore, people are not as worried about worsening the air quality, which mentioned before contributes to the increase of the human health damage of pollutants from indoor building materials [38].

A way to assess the health risk of chemical substances emitted to the air is by using the "Dose versus response"-relationship, which is created by toxicological studies on biological organisms either for acute toxicity or chronic toxicity [37]. A curve is created with the fraction of individuals experiencing a certain response (low/average/high) to the dose, and it usually is represented by normal distribution [36]. The curve gives a "No observed adverse effect level" (NOAEL), which is the highest exposure level or dose at which no adverse effects are detected. Lowest observed adverse exposure level (LOAEL) is the lowest dose at which there is a statistically significant change, and thereby an effect is detected [37]. The threshold dose is the lowest value in the dose-response curve, and below this dose, toxicants can be detoxified and eliminated by the body without adverse effects. The "Threshold Limit Value" (TLV) gives an estimate of how much chemical substance a worker can be exposed to every day during a working lifetime without experiencing adverse effects [36]. The TLV is defined as the acceptable average concentration of a chemical substance in the air which one is exposed to via dermal or respiratory routes [37]. For gases and vapours, like VOCs, the TLV is given in ppm. The lower the TLV, the higher the concern is for the specific chemical substance, since it only requires exposure to small amounts of the chemical to cause adverse effects [36].

The World Health Organisation (WHO) have guidelines covering recommended concentration limits of harmful air pollutants for both the indoor and outdoor environment [39]. Most recommendations are created using the NOAEL/LOAEL as a threshold combined with safety factors to minimise the health risks of the chemical exposure [37]. As an example, the recommended annual mean limit concentration of benzene is 5 µg/m^3 [39]. A project called "AIRMEX" have examined the relationship between indoor air pollution and human exposure to pollutants during different activities such as working, commuting, and rest time [40]. The project was created to understand the impacts of indoor air pollution in the built environment on human health. Pollution was measured using passive samplers such as Radiello® at public buildings, schools, and kindergartens in Athens, Arnhem, Brussels, and Milan. Personal exposure was conducted on employers at the same place where the pollution was measured [40]. The results showed benzene concentrations in the indoor environment varying between 2.9 and 63.7 µg/m^3, while benzene concentration in the outdoor environment varied from 1.9 to 15.2 µg/m^3. The annual limit concentration of benzene (5 µg/m^3) was exceeded both in the indoor and outdoor environment, as well as for the personal exposure, which was ranging from 5.3 to 9.1 µg/m^3 [40]. It is of high importance to lower the concentration of benzene to lower the health-risk; therefore, it is crucial to know where the chemical emission arises.

1.4. Embedded and Embodied Toxicity

Conventional life cycle assessment of buildings materials is typically used to assess the environmental impact of buildings from cradle-to-grave, so that materials can be selected, e.g. based on their carbon footprint [41]. In this context, the toxicological impacts are typically overseen, along with the toxic chemicals that can have contaminated the building materials through use. Human health challenges due to toxicity of building materials can be addressed as an embedded or embodied toxicity.

The embedded toxicity seeks to quantify the direct impacts related to an entity providing a service (i.e. thus fulfilling a functional unit (FU)) [42], contrary to the embodied toxicity which also includes the indirect impacts occurring in relation, e.g. production and disposal of an entity providing a service [41]. The embodied toxicity hence addresses the direct and indirect impact, which is not to be confused with the embedded toxicity that addresses the indirect and direct exposure solely [42].

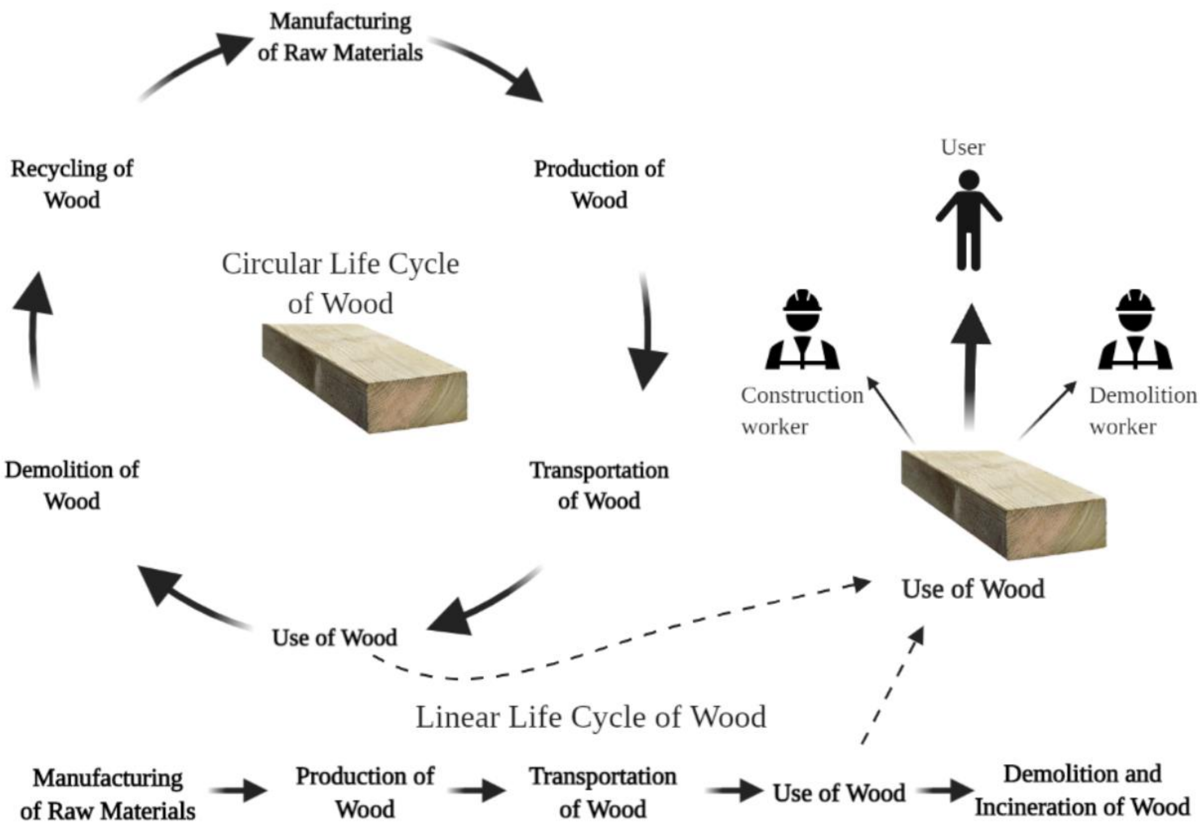

Figure 1 Circular and linear life cycle of a wooden beam regarding embedded and embodied toxicity
The toxicity of a wooden beam can be addressed as an embedded or embodied toxicity, where the embodied toxicity addresses direct and indirect impact throughout the value chain (either circular or linear), while the embedded toxicity addresses solely indirect and direct exposure. The embodied toxicity is the life cycle aggregated toxicological impact of the wooden beam. The toxicity represents the holistic toxicological footprint aggregated from cradle-to-grave, where all emissions that take place in the value chain (either circular or linear) are taken into account including the effects induced by emissions as a result of, e.g. the production of fuel for the machines used in the extraction of raw materials needed to produce the wooden beam. The embedded toxicity is the toxicity that is embedded within the wooden beam. Embedded toxicity only affects those, who are in direct or indirect contact with the wooden beam from once it has been created until it is being disposed of, thereby involving construction workers, users, and demolition workers. In principle, the users are most in contact with the material, why they are also at higher risk of exposure.

The embedded toxicity is the toxicity that is embedded (contained) within a product such as a concrete slab, a wooden beam, or a window, that can be emitted and induce toxicological impacts in operators or users of the product under the right circumstances [14][17]. The embedded toxicity is what is contained within a product or the entity providing a service defined by the FU. The embedded toxicity can only be induced if the FU is being provided, such as a 1 m^2 window surface. Embedded toxicity only affects those, who are in direct or indirect (e.g. via inhalation of air contaminated by the product) contact with the product from once it has been created until it is being disposed of [42][43]. Thereby value chain wise, the embedded toxicity covers the last parts of the construction stage, the whole use stage, and the initial part of the demolition/disposal stage of the product. It therefore involves the people creating the product, builders, users, and people dismantling the product. The people most at risk of embedded toxicity are the users, since they are the ones that spend the most time in direct or indirect contact with the product during its use stage [14][17]. The builders and the demolition people are only in "brief" contact with the product during construction, maintenance, and demolition, which are all minuscule timeframes compared to the actual use stage. The embedded toxicity is a fraction of the entire value chain since it does not account for the direct and indirect toxicological impacts induced during raw material extraction or production of the materials needed for producing the product [41]. Evidently, by representing only a fraction of the value chain, the embedded toxicity of product should logically be smaller than the embodied toxicity.

The embodied toxicity is the life cycle aggregated toxicological impact (also referred to as the toxicological footprint) of a service or a product [41][42]. The toxicity represents the holistic toxicological footprint aggregated from cradle-to-grave, where all emissions that take place in the value chain are taken into account, e.g. including the effects induced by emissions as a result of the production of fuel for the machines used in the extraction of raw materials [41]. The toxicological footprint is not user-oriented since the toxicological footprint of the use phase does not distinguish between user exposure to a chemical present in the product and exposure of people during the production of fuel for the mining machinery, which could take place on a different continent [41].

Seen from a sustainability point of view, the embodied toxicity is the most representative. However, the embodied toxicity is quantified across several modelling steps and is hence associated with considerable uncertainty. Also, since the embodied toxicity covers a large geographical and temporal scopes, it is impossible to validate [41]. The embedded toxicity, on the contrary, can easily be validated by quantification of the potential toxicological impacts that can be induced by the chemicals emitted from a product or an entity using standard analytical equipment [43][44].

The embedded toxicity can be used as a reference point for the quantification of the embodied toxicity since the embedded toxicity should be smaller than the embodied toxicity (thus providing a pseudo mean of validation for the embodied toxicity) [42]. It is therefore essential to test whether toxic substances can be released and in what quantities, mainly from building materials that are desired to be recycled, but also from new materials.

RGS Nordic A/S is a Danish company that bases its business on receiving and reselling construction waste for recycling in the construction sector [45]. Before reselling, it is crucial to ensure that the materials are not contaminated with toxic substances. Concerning screening for toxic substances in building materials, heavy metals, asbestos, PAH, chlorinated paraffins, PCBs, and VOCs are often tested [44]. Some types of toxic substances are challenging to analyse, including PCBs, due to its affinity of glass and quartz substances [46]. Eurofins is one of the companies that screen for a large part of the toxic substances available in building materials. The test used by Eurofins is carried out in a ventilated chamber with an air change rate of 0.5 times per hour and lasts approx. 28 days, after which air is collected using passive samplers with Tenax® and 2,4-dinitrophenylhydrazine (DNPH) tubes, which are analysed in their laboratories [47].

The analysis performed by Eurofins is a standardised and International Organisation for Standardisation (ISO) certified method, which determines the total level of VOCs, total PAH/PCB content and selected heavy metals emitted by the material [44]. The method is similar to the one commonly used and described in the literature, where in many cases test chambers are used where ventilation, temperature and humidity can be controlled to simulate the degassing process under approximate realistic conditions for the individual building materials [19][26][40][47]. Passive samplers are a preferred choice for analysing indoor air quality among these toxic emissions from building materials. Several different passive samplers exist, as the individual sampler is often made to screen for specific emitted components [40][47].

A newer type of passive sampler is the Solid Phase Micro Extraction (SPME) fiber that can be used to extract VOCs from a sample, which afterwards can be identified and quantified [48][49][50]. The SPME sampler has explicitly been used to analyse a variety of VOC components as potential biomarkers in various types of cancers both in vivo and in vitro. In these studies, VOCs was shown to be related to cancer; thus, there may be a relationship between indoor evaporation of VOC from materials and some instances of cancer [12].

Chapter 1.4.1 and 1.4.2 goes into detail with the theory regarding the assessment of embedded and embodied toxicity.

1.4.1. Embedded Toxicity

SPME together with the combined analytical technique of GC-MS, is used to analyse the embedded toxicity in construction materials such as concrete, wood, wood fibreboard, straw, and clay. The following chapters include separate descriptions of the different techniques used in this project.

1.4.1.1. Solid Phase Microextraction

SPME is a sample extraction technique, which most commonly uses a fiber coated with a liquid or solvent extraction phase to extract volatile or non-volatile analytes from different samples in either a liquid or gaseous phase [50]. SPME is a non-exhaustive microextraction technique, which has the advantages not to alter either the chemical components or the concentration of analytes in a sample since only a minimal amount of target analytes is removed from the samples [50]. Compared to other extraction techniques, the microextraction technique gives more representative information, which leads to a more accurate characterisation of the samples being analysed [50]. For the extraction of analytes, the distribution of analytes must reach an equilibrium between the sample and the headspace/gaseous phase above the sample. When the equilibrium is reached, the quantity of the extracted analytes will be proportional to the concentration in the sample [49]. Equilibrium extraction is most often conducted in the SPME procedure, where the analytes are selectively extracted according to their affinity to interact with the coating of the SPME fiber [51]. It is therefore vital to choose a proper coating of the SPME fiber since the properties of the chosen coating greatly determine the selectivity, sensitivity, and reproducibility of the extraction technique [51].

There are two different types of SPME coatings; 1) polymeric films for the absorption of analytes and 2) particles embedded in polymeric films for adsorption of analytes. Types of film absorption include fibers coated with polydimethylsiloxane (PDMS). In contrast, the particle adsorption includes fibers containing porous particles such as Carboxen® (CAR), divinylbenzene (DVB), or the combination of both, where usually PDMS is the polymeric binding film [49]. Particle fibers are more suitable for trace analysis methods in lower concentrations since the adsorption on a particle is a more robust and a more efficient extraction mechanism compared to the absorption on film fibers [51].

The criteria for selecting the proper fiber coating include the size and molecular weight (MW) of the analytes, polarity of the target analytes, the sample complexity, and the concentration of analytes [51]. Table 1 gives information for the selection of the SPME fiber for different analyte types based on their MW, polarity, and volatility.

Table 1 The recommended SPME fiber coating in comparison to analyte types.
The recommended SPME fiber coating is based on the properties of the analytes, including molecular weight (MW), size and polarity. The recommended fibers includes variations of SPME fiber coating with Carboxen® (CAR), polydimethylsiloxane (PDMS), and divinylbenzene (DVB) [51]

Analyte types	**Recommended fiber**
Gases and low MW compounds (MW 30-225)	75 µm/85 µm CAR/PDMS
Nonpolar and volatile compounds (MW 60–275)	100 µm PDMS
Volatile, amino, and nitroaromatic compounds (MW 50–300)	65 µm PDMS/DVB
Nonpolar and semi-volatile compounds (MW 80–500)	30 µm PDMS
Nonpolar and high MW compounds (MW 125–600)	7 µm PDMS
Volatiles and semi-volatiles C_3-C_{20} (MW 40-275)	50/30 µm DVB/CAR/PDMS

The recommended SPME fiber, for extraction of the emitted VOCs from different building materials, is the 50 µm/30 µm divinylbenzene/Carboxen® on polydimethylsiloxane (DVB/CAR/PDMS) on an adsorbent StableFlex™ fiber [51]. The extraction of the target analytes is performed manually and therefore also includes a manual SPME holder, wherein the fiber is inserted.

After manual extraction of the target analytes, the DVB/CAR/PDMS SPME fiber is desorbed, also known as thermally cleaned, into the GC injector port at a high temperature (approx. 230-270 °C) for a minimum of 1.5 minutes [51]. Figure 2 gives an overview of the combined GC-MS system used for the experiment, which is further described in the following chapters.

1.4.1.2. Gas Chromatography

Gas chromatography is a technique for the separation of volatile substances of a sample by distributing the analytes between the carrier gas phase (mobile phase) and the internal coating (stationary phase) in the column [52]. The analytes extracted from a sample using the SPME fibers are injected into the GC injector port, where the extracted analytes are being vaporised and volatilised in a heated chamber before it enters the column [53][54]. Most typically, the analytes of a sample are being mixed with helium (He) (see Figure 2) that acts as a carrier gas for transportation of the sample to the column. However, other inert gases, such as argon or nitrogen, are also used [55]. Helium is unable to react with the sample analytes, wherefore the analytical technique yields reliable and robust results[56]. The GC system can be set manually to ensure the most optimal GC run and resolution, regarding different parameters such as injector port temperature, run time, initial and final temperature of the GC oven, and temperature increase per minute during the run, also referred to as ramp [55]. As the analytes are carried through the column, they interact with the stationary phase, causing the analytes to elute from the column at different time points, also known as the retention time (RT) [52][54]. The most volatile analytes are favouring the carrier gas, which leads to faster elution, thereby giving the specific analytes shorter RT. In the combined GC-MS system, the outlet of the GC is directly connected to the MS via a heated transfer line, meaning the analytes are eluting from the GC into the MS for further analysis and characterisation [52][54].

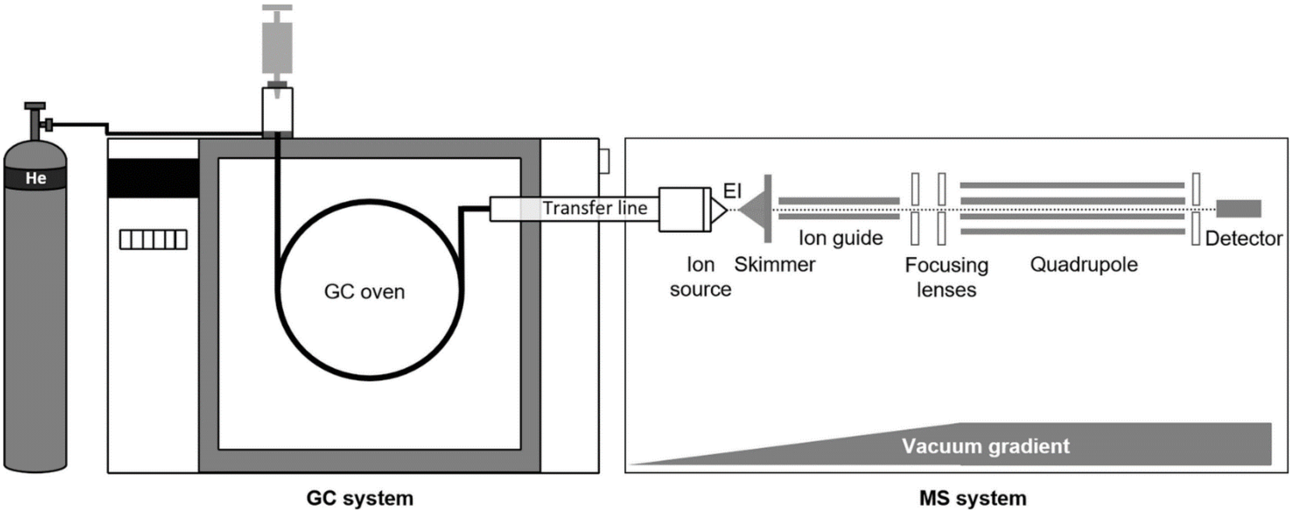

Figure 2 The combined gas chromatography (GC) system and mass spectrometry (MS) system.
The analytes of a sample are injected into the GC injector port, where the analytes are being vaporised and volatilised before being transported to the column by the inert carrier gas, helium (He). The analytes interact with the stationary phase, which causes the analytes to elute at different time points into the MS via a heated transfer line. The ion source in this example is an electron ionisation (EI), which has the function to turn volatile compounds into gas-phase ions when they pass through a focused beam made of emitted electrons. After the analytes are ionised, the ions are being accelerated through the quadrupole analyser, which consists of four parallel metal rods arranged in pairs of two. The quadrupole mass filter operates in a mass-selective mode, which is created by the combination of DC (constant) and RF (alternating) voltages connected to each pair of electrostatically connected rods. The voltages create a mass-dependent deflection/transmission of the gas phase ions, where the increase in both voltages over time allows the analysis and detection of a broad range of mass-to-charge ratio (m/z) values. The result is converted into an MS-spectrum [54].

1.4.1.3. Mass Spectrometry

Mass spectrometry is a technique used to analyse and characterise a wide variety of analytes. The principle of MS is to create a charge on the analytes, which is used to sort the analytes based on the mass-to-charge ratio (m/z) [55]. Typically, the setup of the MS consists of three major components: the ion source, the mass analyser, and the detector, where the analytes are ionised using the ion source, and the ions are resolved by the mass analyser before detection by the detector [57]. The MS instrument and its capability are defined based on the specific choice of the ion source, mass analyser, and detector [55].

Ion Source

The ion source is, as stated above, an essential part of an MS setup since it is where the ionisation of the analytes in a sample is performed. Different ionisation methods can be chosen when using different types of ion sources such as Electron Ionisation (EI), also known as Electron Impact Ionisation [52]. EI is an ionisation method, which has the function to turn volatile compounds into gas-phase ions when they pass through a focused beam made of emitted electrons from a heated filament since the electron beam results in electrostatic repulsion, which removes the molecular electron [52][55]. EI creates a fragmentation of precursor ions using high kinetic energy and the ionising electrons at 70 eV. All EI-based MS systems have consistent fragmentation patterns when using the standardised 70 eV and have thereby resulted in the creation of the standardised National Institute of Standards and Technology (NIST) Mass Spectral Library with more than 200,000 compounds to compare the final results from the GC-MS with and help identify the sample analytes [57][58].

Mass Analyser

The mass analyser of the MS setup separates the gas phase ions based on their specific m/z ratio. There are several different methods used to separate the ions [52]. This next part will focus on the Quadrupole Mass Filter.

After the analytes are ionised in the ion source, the ions are being accelerated through the quadrupole analyser, which consists of four parallel metal rods arranged in pairs of two. The quadrupole mass filter operates in the mass-selective mode, which is created by a combination of DC (constant) and RF (alternating) voltages connected to each pair of electrostatically connected rods [52]. The voltages create a mass-dependent deflection/transmission of the gas phase ions, where the increase in both voltages over time allows the analysis and detection of a broad range of m/z values [55]. The detector of the MS instrument detects and analyses the ions. The full scan MS result is converted into MS spectrums, which are analysed using the NIST Mass Spectral Library [57]. The library can with reasonable confidence identify each chemical analyte, which has been emitted from the sample, but does not lead to the discovery of novel chemicals [57]. The identification confidence is provided by a forward and reverse search, which under ideal conditions, are equally valid. The forward search method matches the mass/intensity values of each peak in the unknown spectrum with those in the reference spectrum, while the reverse search method is matching the peaks in the reference spectrum with the peaks in the unknown spectrum [59]. The library database "only" consists of 243,893 spectra of 212,961 different chemical compounds, wherefore some substances might not be included in the database [58].

When the chemicals are quantitatively identified, and the amount of VOC is quantified using a standard curve, statistical tests will be used for comparison between triplicates and batches.

Furthermore, characterisation factors will be applied to assess the embedded toxicity of each building material.

1.4.1.4. Characterisation Factors

The toxicological impact of the embedded toxicity in the building materials is assessed by characterisation factors from the life cycle impact assessment (LCIA) method of International Reference Life Cycle Data System (ILCD) 2011 v.1.0.10, midpoint from the OpenLCA LCIA methods 1.5.7 in the OpenLCA 1.10.2 software [43][60]. The characterisation factors specified for the assessment of human toxicity is given by the USEtox model, which covers around 3,100 different organic and inorganic substances [43][60]. The USEtox model is developed under the Life Cycle Initiative created by the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC). The USEtox covers several impact pathways (see Figure 3), where the focus in this project is the human toxicity, which is why we only need the midpoint human toxicity substance-specific characterisation factors [43].

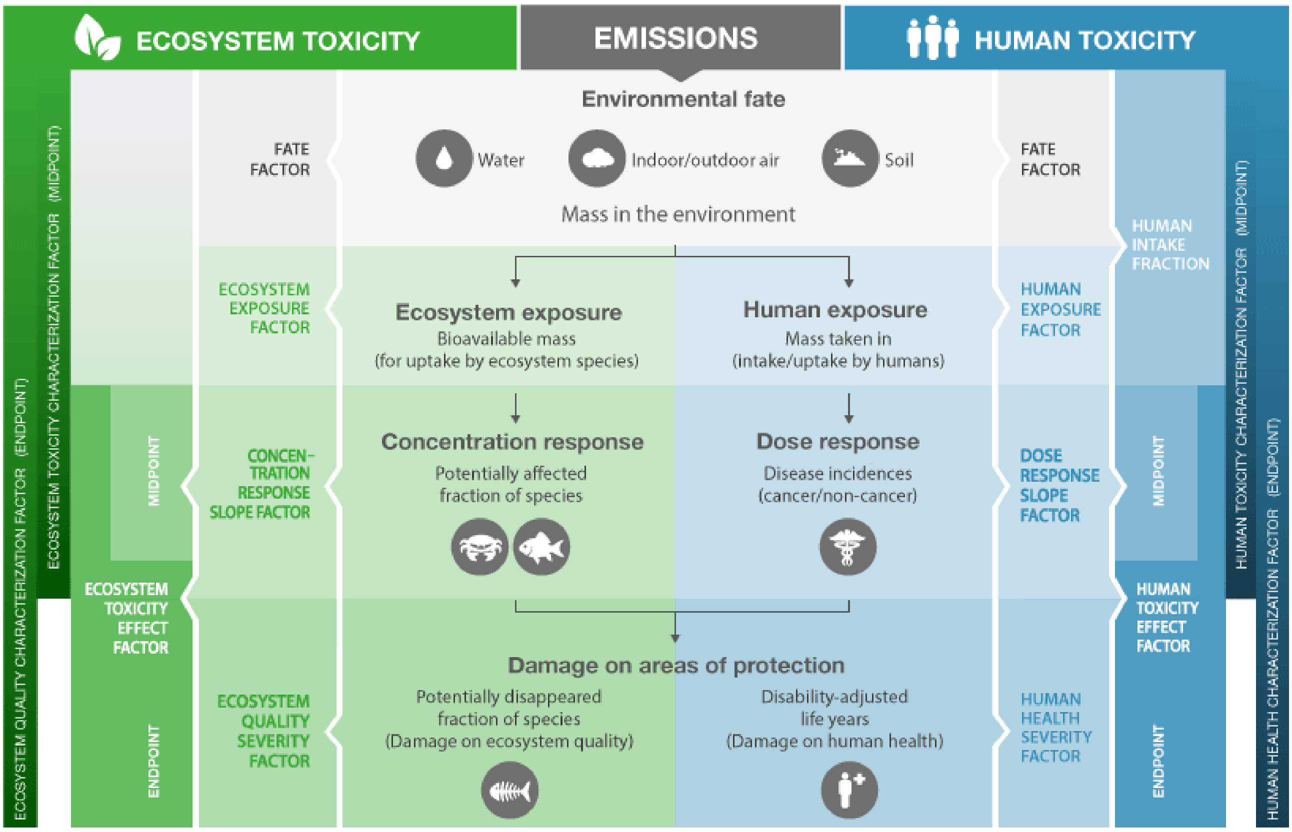

Figure 3 An overview of the USEtox model coverage

The USEtox model covers emissions to water, soil, and indoor/outdoor air and the effect on ecosystem toxicity and human toxicity, when a substance is released into the environment. The characterisation factors (CF) for either human or ecosystem toxicity are calculated using environmental fate factors (FF), exposure factors (XF), and effects factors (EF) [43]. *The focus of this project will be on the human toxicity arising from emissions of a substance to indoor air.*

As seen in Figure 3, the characterisation factors (CF) are calculated by three steps, which include environmental fate factors (FF), exposure factors (XF), and effects factors (EF):

$$CF = EF * XF * FF$$

The environmental fate in our project includes the distribution and degradation of the modelled substance in indoor air. The exposure factors include human exposure to VOC either by inhalation or getting in contact with the substance. The effect factors include the response to and damage of a substance dose, e.g. diseases such as cancer and damage of human health. The product of the fate factors and exposure factors result in the human intake fraction (iF), which is the quantity released into an environmental compartment that is taken in by human population where inhalation or ingestion routes is most commonly used [61]:

$$iF = XF * FF$$

The toxicological damage of human health at the midpoint level can be assessed with characterisation factors both for carcinogenic human health effects and non-carcinogenic human health effects. The toxicological damage is reported in Comparative Toxic Unit for humans (CTUh) per kg emitted, also known as disease cases per kg emitted [43]. Thereby, the human health impacts for all substances in the sampled building material are calculated in the same unit. The USEtox midpoint characterisation factors are not normalised to a specific substance. However, the modelling results can be converted into endpoint effects, which is reported in Disability-Adjusted Life Years (DALY) for human health impacts [43][62]. DALY is a standard operating unit approved by WHO, which is used to quantify the burden of injuries, diseases, and risk factors [63]. Weighting factors, also called damage factors, are applied to the CTUh to account for the years of disabled and the years of life lost due to the specific disease and thereby determine the endpoint effects. To account for carcinogenic effects the relationship is 1 CTUh = 11.5 DALY, while for non-carcinogenic effects the relationship is 1 CTUh = 2.7 DALY [62]. These weighting factors are without age weighting and could, therefore, be higher than anticipated [62]. By converting the results from CTUh to DALY, they can be compared to results of embedded toxicity in other studies, as well as be compared to the embodied toxicity.

1.4.2. Embodied Toxicity

The assessment of the embodied toxicity is carried out with the LCA holistic approach, thereby studying the whole product system, including all flows and processes throughout the whole life cycle from cradle-to-grave. LCA is a standardised method following the ISO 14040/14044 standards and the ILCD guidelines, which allows us to quantify the environmental impacts while preventing a burden shift between life cycle stages. The framework of LCA includes four separately related phases: Goal and scope definition, inventory analysis, impact assessment, and interpretation (see Figure 4) [41].

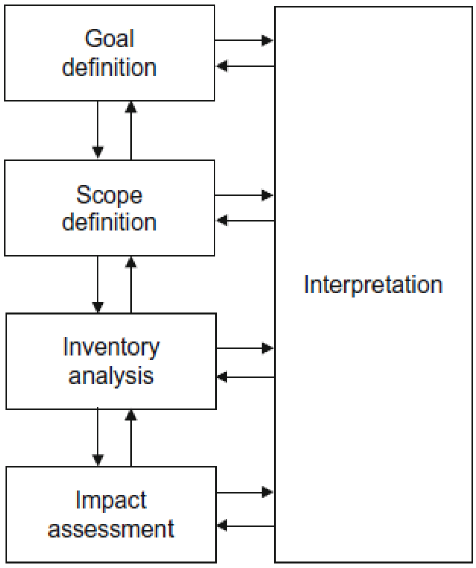

Figure 4 An overview of the LCA framework

1.4.2.1. Goal and Scope

The goal is defined as the aim of the environmental assessment, while the scope frames and outlines the assessment by a defined FU, system boundaries, life cycle inventory (LCI) modelling framework and assessment parameters [41]. The FU is a description of the product system function, which defines the quantitative and qualitative aspects of the studied system. The FU should include a description of quantity, duration, and qualities/properties. The product lifespan defined in the FU can be divided into life cycle stages, such as raw materials processing, production, use, disposal, and transport [41].

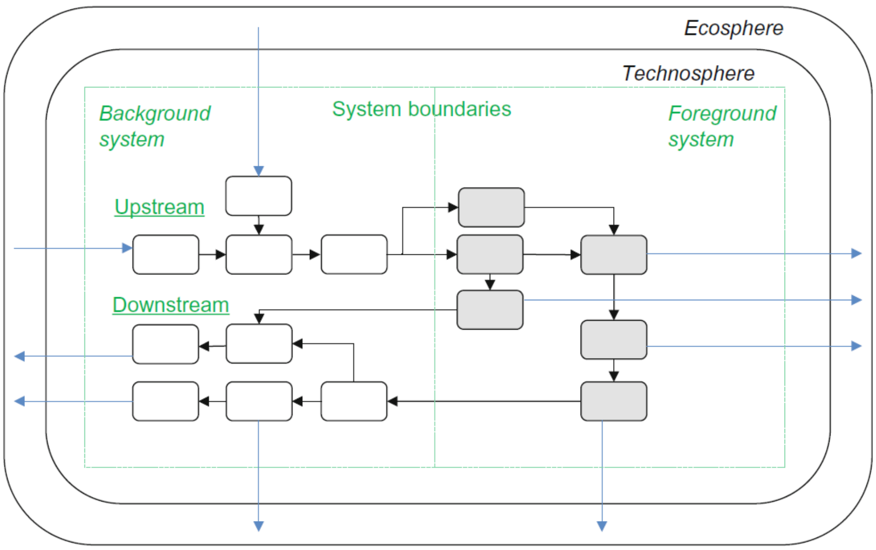

Figure 5 Visualisation of the LCI modelling framework of a product system

The framework includes boundaries between the foreground system (grey rectangles) and the background system (white rectangles) as well as the boundary between the technosphere and ecosphere. The foreground system includes processes specific to a product system, while the background system has processes not specific to the product system, which can either be upstream or downstream. Black arrows show flows between processes (rectangles). Blue arrows show elementary flows from the technosphere to the ecosphere.

The assessment parameters are the impacts assessed in the study, such as the human toxicological impact or the impact on climate change. The system boundaries determine the inclusion of unit processes in the model by setting boundaries between the product system and the techno- and ecosphere. The foreground system includes processes specific to the product system. In contrast, the background system includes processes not specific to the product system, which can either be upstream or downstream (See Figure 5) [41]. The representativeness of the LCI data for the unit processes can be examined in three different dimensions: time-related, geographical, and technological. Differences between unit processes can occur due to geographical or technological differences as well as when in time, the processes occur.

1.4.2.2. Life Cycle Inventory Analysis

System boundaries are defined differently concerning the type of LCI modelling framework, which can either be attributional, cut-off, or consequential [41]. The attributional modelling framework represents a product system separated from the eco- and technosphere, which simplifies the production system using allocation. The cut-off modelling framework is similar to the attributional except for the management of recyclable materials, which is cut-off before recycling [41]. With the cut-off modelling framework, all embodied impacts are allocated with the primary user. However, when looking at embodied toxicity, it is not possible to cut-off since the toxicity follows the material. The consequential modelling framework describes the consequences or changes caused by introducing the product system to the eco- and technosphere, where it uses marginal processes for modelling the background system. Marginal processes are processes that change in response to the demand for a product, which can either be short-term or long-term [41].

LCI analysis is a continuation of the goal and scope definition and serves as the basis of the LCIA. The inventory analysis is the collection of information on the elementary flows from all processes in the product system life cycle [41]. The information for the foreground system is most often modelled using primary data, e.g. scientific articles. In contrast, the information of the background system is given by LCI databases such as the Ecoinvent v.3.4 Database in OpenLCA 1.10.2 [41]. When data is limited certain assumptions and simplification are necessary to model the product system. The product systems for the materials analysed in this study are modelled using the OpenLCA 1.10.2 software.

1.4.2.3. Life Cycle Impact Assessment

LCIA considers three mandatory steps: the selection of impact category, classification, and characterisation, along with three optional steps: normalisation, weighting, and grouping. These are distinguished by the ISO 14040/14044 standards [41]. The area of protection "human health" is affected by various impact categories such as human toxicity, climate change, ionising radiation, water use, resource use, ozone formation, and particulate matter formation [41].

The focus of this project is the human toxicological impact of building materials, which is assessed using the ILCD 2011 v.1.0.10 midpoint impact assessment method, where the human toxicological impact is divided into carcinogenic and non-carcinogenic effects. The result of the LCIA will be expressed as the human toxicological impact in CTUh per FU of the studied building material, which can be converted to DALY per FU using weighting factors as mentioned in chapter 1.4.1.4 [62]. The embodied toxicity can be examined for the whole life cycle or as the contribution of impact by the specific life cycle stage. The embodied toxicity for the whole life cycle can be compared with the embedded toxicity results from the experiment with SPME fiber extraction of VOCs in building materials to understand the total health impact from a unit mass (i.e., one kg) of building material.

1.5. Objectives

The following hypothesis and research questions have been formulated for this thesis:

1.5.1. Hypothesis

H1 Recycling construction materials in new buildings causes human health damages due to toxic chemical emissions to indoor air from recycled construction materials. Construction materials should be examined and stripped from toxic chemicals before being recycled if the materials are to be used for indoor construction purposes.

H2 The motivation for exploring the embedded and embodied toxicity and the relation between those two, comes from the need to be able to account for occupant exposure in building LCA. It is not possible to account for occupant exposure since a user-exposure-indicator for use in LCA is missing. It is not an impact assessment methodology, which is aimed to establish, however, the necessary inventory data needed to account for the occupant exposure in buildings.

1.5.2. Research questions

RQ1 What are the human toxicological challenges of circular economy product contaminations?

RQ2 Compare whether the way the embodied toxicity is assessed and how this measure relates to the embedded toxicity. Is there any general relation between embedded and embodied toxicity? If so, can the embodied toxicity be used as an indicator of embedded toxicity or *vice versa*?

RQ3 Can we use embodied toxicity to express the risk of transferring toxicity between value chains (which is the whole point of circular economy)?

RQ4 What are the data available to account for the embedded toxicity?

RQ5 Could it be that for chemicals, since the direct exposure of the users is unaccounted for in LCA, that the embedded toxicity is more representative than the embodied toxicity?

2. Methodology

The experimental part of the project will consist of an accelerated release of the material's emissions also known as "thermal stripping", which are captured using SPME fibers and analysed by GC-MS analysis. The substances emitted during the thermal treatment of the materials are qualitatively identified, as well as quantified and characterised for different types of materials. Chapter 2.1 describes how I have performed the experiment from start to end, and the improvement process the experimental method underwent.

All materials used for the experiment is modelled in OpenLCA 1.10.2 to assess the human toxicity impact of embodied toxicity. The toxicity impact is also assessed for building components and complete external wall systems. Chapter 0 provides a detailed description of how I have modelled the different building materials to assess toxicity.

2.1. Embedded Toxicity

In October 2019 samples of concrete and wood were self-prepared and collected from RGS Nordic to be transported to the university. The samples of wood fibreboard, wood, straw, and clay were received from Small Planet in December. All samples were stored in the LC-MS laboratory room at TEK, SDU until the start of the experiment. Appendix A contains photo documentation of the sampling site at RGS Nordic as well as documentation of the different material batches analysed.

Table 2 Information about the sampling of concrete, wood, clay, straw, and wood fibreboard for the experiment, including the number of batches, size/type of material, the origin of the samples, and the receive/collection date.

	Batches	Size/type	Sampled from	Collected/Received
Concrete	10	Small pieces	RGS Nordic	October 22nd
Wood	1	Small pieces	RGS Nordic	October 22nd
Wood	2	Whole chunks	Small Planet	December 5th
Clay	3	Fine clay (top and base coat)	Small Planet	December 5th
Straw	5	Whole straws	Small Planet	December 5th
Wood fibreboard	3	Wood fibreboard	Small Planet	December 5th

2.1.1. Experimental Setup

For each run, I am analysing triplicates of the same material from the same batch. Each sample is downsized to fit into 250 mL blue cap flasks. The triplicated samples are placed in 250 mL blue cap flasks with septum caps in an oven for incubation at 70 degrees Celsius. The incubation at high temperature is necessary to create a "worst-case scenario" without ventilation and where the evaporation proceeds faster. The septum in the caps is required to insert the SPME fiber through the caps to extract the emitted substance. Before the first run, the SPME fiber is placed inside the manual SPME holder (seen in Figure 6) to be pre-conditioned in the GC injector port for 0.5 hrs at 270 degrees Celsius [51].

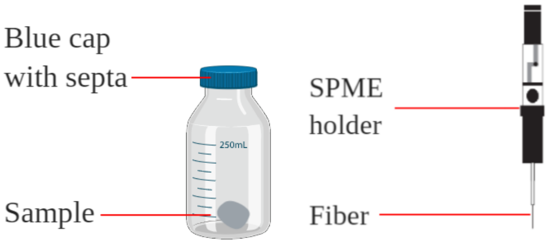

Figure 6 A detailed overview of the sampled building material in a 250 mL blue cap flask with septa, SPME fiber and manual SPME holder created in BioRender [64]

Triplicates of a blank sample is run to test if there is any contamination in the flasks I am using, which is an essential factor to know before starting the experiment. Between each sampling, the fiber is stored in small glass vials to avoid contaminations.

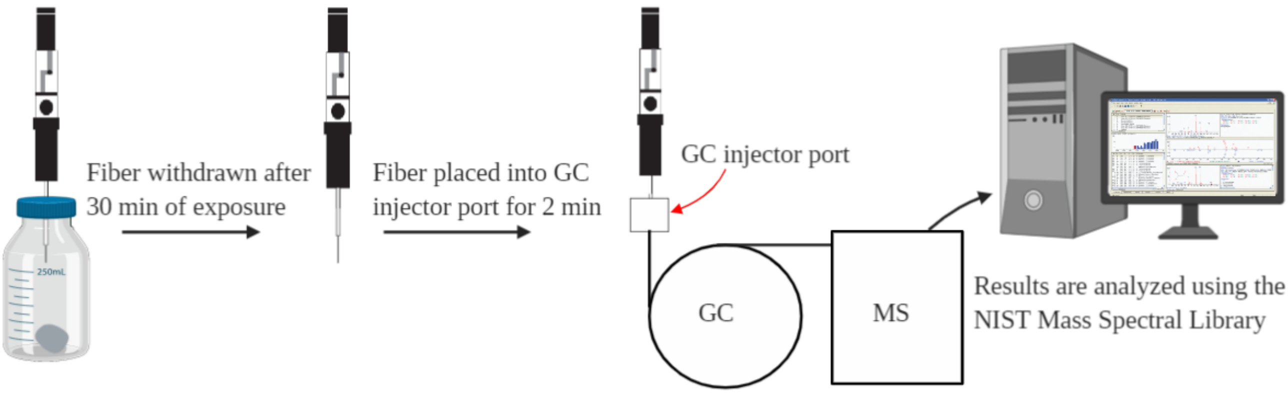

Figure 7 The experimental setup for analysing the embedded toxicity. [64]
The samples are incubated at 70 degrees Celsius for 24 hrs in 250 mL blue cap flasks with septum caps. After the incubation, the SPME fiber is exposed to the gaseous phase inside the flask for 30 minutes before being injected into the GC-MS injector port for 2 minutes desorption at 230 degrees Celsius. The injected sample runs through the GC-MS for 60 minutes, to separate, detect, and analyse the sample giving a full CG-MS chromatogram with the substances in the sample. The substances emitted from each sample can be qualitatively identified using the Xcalibur Qual Browser and the NIST library

The triplicated samples are stored in an oven for a total of 24 hrs to ensure equilibrium between the sample and the gaseous phase, before the target analytes of the sample can be quantitatively analysed [52]. Every 30 minutes of SPME fiber extraction is followed by 2 minutes desorption of the fibers into the GC injector port at 230 degrees Celsius (seen in Figure 7)[51]. The desorption also has the purpose of cleaning the fiber, and it can, therefore, be used for a new set of triplicates. Each extraction will run in the GC-MS for 60 minutes. The GC oven is heated from 30 degrees Celsius to 325 degrees Celsius at a rate of 5 degrees per minute, when the analytes are transported through the DB-5MS capillary column (Dimensions: 30 m, 0.25 mm, 0.25 µm, 7 inches) [51]. All settings for the GC-MS are individually programmed for this experiment in Xcalibur.

2.1.2. Improvement of the Experimental Setup

An additional experiment was performed, to ensure equilibrium extraction, with 2x triplicates of each sampled material in 250 mL flasks incubated in the oven at 70 degrees Celsius for 24 hrs and 48 hrs, respectively. Both incubation times resulted in similar chromatograms and quantified amounts of compounds, thereby concluding, that there is no adverse change between incubation in the oven for 24 hrs and 48 hrs. It is therefore believed that we have reached the equilibrium at 24 hrs as suggested by [19]. The experiment was continued in 250 mL flasks incubated at 70 degrees Celsius in the oven for 24 hrs. An extraction time of 15-30 minutes was recommended by [51] and to ensure the best extraction, the extraction time was set at 30 minutes for all triplicates. Due to the lockdown of the university (COVID-19), it was not possible to confirm whether the extraction time with the SPME fiber should be longer than 30 minutes to extract other sorts of compounds.

2.1.3. Qualitative Assessment of Embedded Toxicity

The results from the MS detection is shown in a chromatogram with peaks in the program Xcalibur Qual Browser, which is analysed using the NIST Mass Spectral Library, thereby identifying the different VOC analytes extracted from the materials. The identification of chemicals is performed by looking at all the peaks in the chromatogram individually and searching for similar spectra for each peak in the NIST library [58]. In Figure 8, a GC-MS chromatogram from the GC-MS analysis of the blank sample, triplicate 1, is shown, where the x-axis represents the RT, and the y-axis represents the relative abundance also known as the relative intensity of the signal.

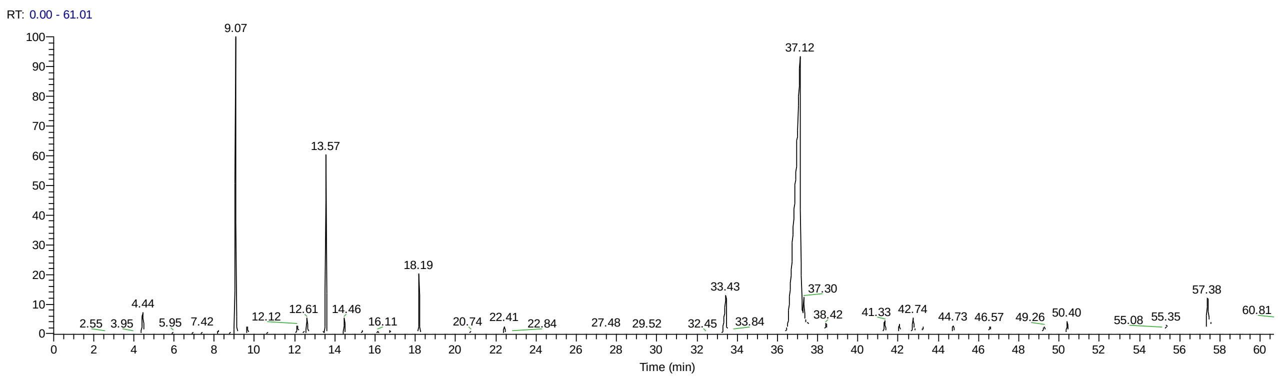

Figure 8 A GC-MS chromatogram acquired from the GC-MS analysis of the blank sample, triplicate 1

In the chromatogram, the y-axis represents the relative abundance, while the retention time (RT, min) is on the x-axis. The peaks I have identified are at RT 4.44, 9.07, 13.57, 18.19, 22.41, 33.43, 37.12, 41.33, and 42.74. The compounds identified in this chromatogram are different types of X-siloxane (in the first five peaks), hexadecanoic acid, octadecanoic acid, 2.3-Dihydroxypropylelaidate, and dronabinol, respectively.

The Xcalibur Qual Browser examines each peak of the GC-MS chromatogram, which is identified by a specific MS-spectrum in the NIST library. Each peak is identified with a chemical name, and the forward and reverse match between the reference MS-spectrum and the analysed MS-spectrum. With reasonable confidence, the unknown chemical is identified as the chemical from the NIST library, which is the most similar [58]. The peaks at RT 13.57 and 33.43 gives the MS spectra seen in Figure 9 and Figure 10. The similarities between the unknown MS-spectrum and the reference spectrum are shown in Figure 9 and Figure 10 underneath. The unknown substance spectrum (red) in Figure 10 is very similar to the reference spectrum (blue), while for Figure 9 the reference spectrum (blue) includes peaks, that the unknown substance spectrum (red) does not have. The forward and reverse match (unitless [-]) explains how good the confidence is regarding if the unknown substance can be identified as the reference spectrum [55][58]. To ensure high confidence in the identification process, reference chemicals were only considered if the forward and reverse match were preferably as close to 800 [-] as possible or above. Both unknown MS spectra in Figure 9 and Figure 10 have forward and reverse match above 800 [-]. Therefore, it is possible to identify the unknown MS spectra as the chemicals cyclopentasiloxane and hexadecanoic acid, respectively.

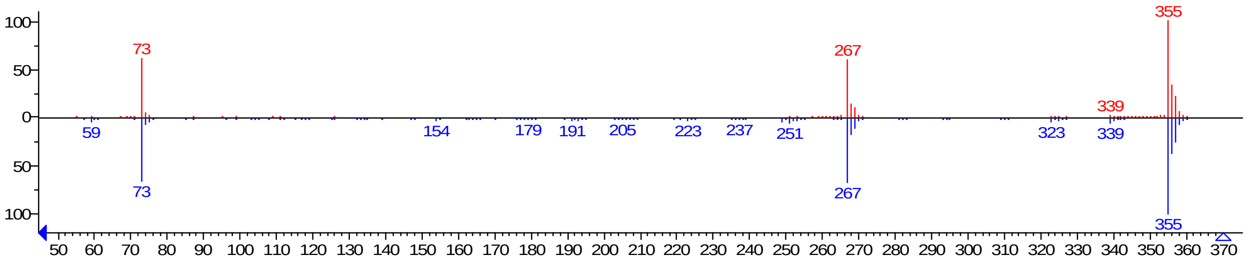

Figure 9 The identification of an unknown compound using reference MS spectra from the NIST library

The identification of an unknown MS spectra (red) is performed by comparing the similarities to reference MS spectra (blue) in the NIST library. In this case, the similarities between the unknown MS spectrum and the reference MS spectrum for the chemical cyclopentasiloxane in the NIST library does not look very similar, because of all the other peaks in the reference spectra. The forward and reverse match is above 800 [-], and therefore the unknown chemical is identified as cyclopentasiloxane.

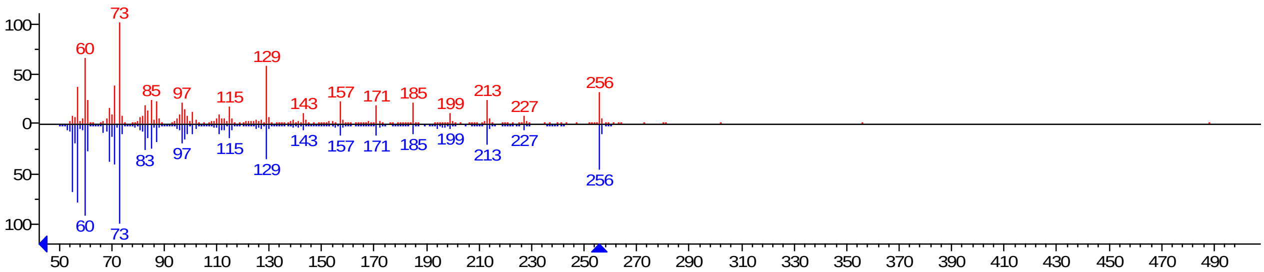

Figure 10 The identification of an unknown compound using reference MS spectra from the NIST library

The identification of an unknown MS spectra (red) is performed by comparing the similarities to reference MS spectra (blue) in the NIST library. In this case, the similarities between the unknown MS spectrum and the reference MS spectrum for the chemical hexadecanoic acid in the NIST library are very similar. The forward and reverse match is above 800 [-], and therefore the unknown chemical is identified as hexadecanoic acid.

The SPME fiber, the column, and the glassware can emit VOC; thus, it needs to be subtracted from the GC-MS chromatogram results of all the building material. After identifying all the chemicals emitted by each sampled building material, the individual distribution and potency of chemicals in the sample are examined.

2.1.4. Quantitative Assessment of Embedded Toxicity

The areas under all the identified peak in each chromatogram is used for the quantification of the specific chemical compound. The Xcalibur determines a value for the area under each peak, which is proportional to the concentration of the identified chemical in the emitted substance [55]. The identified chemicals are quantified by calculating the relationship between the peak area and the concentration. The calculation is performed using standards such as alkanes to create a standard curve. A standard curve is generated by injecting known amounts of alkane into the GC-MS injector port with a syringe, resulting in chromatograms with the peak area vs the known concentration [55]. The standard curve is then used to calculate the quantity of the unknown amounts of identified chemicals. Due to the lockdown of the university by COVID-19 a calibration curve from standards was not created; therefore, the area values could not be quantified to an exact mass per unit.

The quantitative assessment of the identified chemical was continued by working with the value for the area under a peak, since it gives an understanding of the relative amount of a chemical in each sample. The relative amount is converted into a percentage of the total relative amount of substance in each sample. The percentages are converted into an amount per 1 kg to assess the impact from a total of 1 kg emitted substance. Graphs with standard deviation (SD) are created with the program GraphPad PRISM 5 to show the quantitative difference between the triplicates as well as to visualise the difference between batches of each material.

In the program OpenLCA 1.10.2, under the group "Indicators and parameters" in the subgroup "Impact assessment methods, OpenLCA LCIA methods 1.5.7", impact assessment methods such as ILCD or USEtox can be found to assess the human toxicity of several chemicals. The human toxicity for the identified chemicals is characterised by impact factors found in the impact assessment method ILCD 2011 v.1.0.10 midpoint under the impact categories "human health - carcinogenic and non-carcinogenic for low and high population density". The category “emission to air” in rural and urban areas are chosen to assess the fraction of humans being exposed. Data from the USEtox 2.12 model was examined to ensure, that chemical compounds that were not present in the ILCD 2011 v.1.0.10 midpoint was characterised by the newest data available. The characterisation factors from the ILCD 2011 v.1.0.10 midpoint is provided in the reference unit CTUh, which can be converted into DALY, as mentioned in chapter 1.4.1.4. The impact of each characterised chemical in DALY is added to the amount of chemical present in the emitted substance. As a result, the ratio of impact potential for non-carcinogenic and carcinogenic health effects caused by the mixed compound in a total of 1 kg emitted substance is acquired.

Graphs are created to visualise the difference in impact between chemicals being emitted to air in rural and urban areas. The total average human toxicity impact is summed for each material, and the share of chemicals characterised with an impact in DALY per kg chemical emitted is calculated to understand which and how much each chemical contribute to the average human toxicity impact for each material.

2.2. Embodied Toxicity

The goal of the LCA is to assess the embodied toxicity of building materials on three different levels: 1) Singular building materials, 2) Building components, and 3) Complete external wall system. The embodied toxicity impact of the singular building materials will be interpreted and compared with the embedded toxicity impact results. Furthermore, impact results for the building components and the complete external wall systems are interpreted and compared at their specific level of assessment.

This study is focusing on building materials used for Danish construction in a circular economy perspective. The scope of the study is described in detail in the following chapters, including the assessment parameters, the FU, the LCI modelling approach, and the system boundaries.

2.2.1. Assessment Parameters and Functional Unit Definition

To compare the embedded toxicity of the building materials analysed in the experiment, i.e. concrete, wood, clay, straw, and wood fibreboards, with the embodied toxicity of the singular building materials, 1 kg of each singular building material is modelled throughout its whole life cycle.

The embodied toxicity of building components such as a concrete component or the EcoCocon element with straw and wood only is modelled for 1 m^3.

The complete external wall systems, with insulation, exterior cladding, and interior finish, need to be the same size to compare the embodied toxicity throughout the whole life cycle of the two wall systems. The size of a standard EcoCocon wall system is 1.5 m^3 (L 3000 mm x W 800 mm x H 625 mm) with insulation, interior, and exterior layers covering a surface of 2.4 m^2 [65]. The concrete wall system modelled in OpenLCA is also 1.5 m^3 with a surface area of 2.4 m^2. The results after modelling are scaled according to 1 m^3 for future work and comparison.

SBI durability tables ("Levetidstabeller") are available for building materials, however, estimating the lifetime of singular building materials or the building components, using these SBI durability tables without a given purpose, will only increase the uncertainty of the results [66]. The two constructed wall sections are assumed to last equally long (50 years) and thereby, scaling the lifetime according to the durability tables is not considered.

The assessment parameters, on which the embodied toxicity is assessed, is the human toxicological impact. Three separate FUs are described to compare and quantify the embodied human toxicity impacts of the singular building materials, the building components, and the complete external wall systems:

1) For the singular building materials, the human toxicity impact is assessed for the FU of 1 kg building material during the whole life cycle from production to end-of-life (EOL), without maintenance. The human toxicity impact is described as DALY per 1 kg of building material.
2) The human toxicity impact for building components is assessed for the FU of 1 m^3 of building material during the whole life cycle from production to EOL, without maintenance. The human toxicity impact is described as DALY per 1 m^3 building component.
3) For complete external wall systems, the human toxicity impact is assessed for the FU of 1 m^3 complete external wall system during its whole life cycle from production to EOL. The durability of the wall is assumed to be 50 years with maintenance. The human toxicity impact is described as DALY per 1 m^3 complete external wall system.

2.2.2. LCI Modelling Framework and System Boundaries

In this study, a consequential LCI modelling framework is chosen as the modelling approach to assess the human toxicity impact on the different life cycle stages on all three levels of building materials. The consequential modelling framework describes the changes to the eco- or technosphere caused by the introduction of the product system. The consequential approach uses marginal processes for modelling the background system, which are processes that change in response to the demand for a product, which can either be short-term or long-term changes [41].

The system boundaries determine which unit process are to be included in the model by establishing the border between the life cycle of the product system and the techno- and ecosphere [41]. To understand the geographical, the time-related, and the technological representativeness of the LCI data, it is essential to consider the influence on the impact of the geographical location of the mix of marginal processes as well as in which time the process happens and with what technology the process is created. The data for all processes involved in the product systems modelling is accurate for today's time since all processes have been used for many years without any major changes [67]. The product systems for the different materials have slight geographical changes since some materials are produced in Lithuania and Estonia, whereas others are produced in Denmark and Germany. The geographical changes are not relevant since all materials are produced inside Europe, and it is assumed that there are no substantial differences in this region. Furthermore, there is also not considered technological differences in this region, and it is therefore assumed that the technologies used to produce each building material are the most advanced or the best available technologies.

The life cycles of the complete external wall systems are divided into four stages: Production, Transport, Use, and EOL (see Table 3). In contrast, the use stage is not considered in the life cycles for building materials and building components, since the use-ability and durability are neglected.

Table 3: Classification and description of the four life cycle stages: production, transport, use, and EOL.

Stages 1: Production	The production stage includes the process of raw material mining/production needed to produce the building material as well as the production process itself.
Stage 2: Transport	The stage of transport only includes the transportation of the finished building material to the construction site, where it is installed. The transportation is neglected for transporting raw materials to the production facility, as well as transporting building material to a disposal facility or for recycling in a production facility.
Stage 3: Use	The use stage includes the embodied toxicity during use from maintaining the material, e.g. preservation, as well as from replacing existing materials with new materials during use.
Stage 4: End-of-life	The EOL stage includes disposal of the building material either for landfill, incineration, reuse, or recycling.

The system boundaries of the life cycles for each material, component or external wall system are described and visualised in process flow diagrams in the following chapters.

2.2.2.1. Process Flow Diagrams for Singular Building Materials

The production and transport of the singular building materials is modelled according to the building component in which the singular building material is required. Wood and straw are modelled according to the EcoCocon element, which is produced in Lithuania [31]. The clay used for the EcoCocon is produced by the company UKU in Estonia [33]. In contrast, the wood fibreboard used for the EcoCocon is modelled as STEICO insulation board, that is produced in Germany [68]. The concrete and wood produced in Denmark are not modelled according to a specific building component, and for both materials, recycling is considered. Stage 3: Use is neglected for all singular building materials.

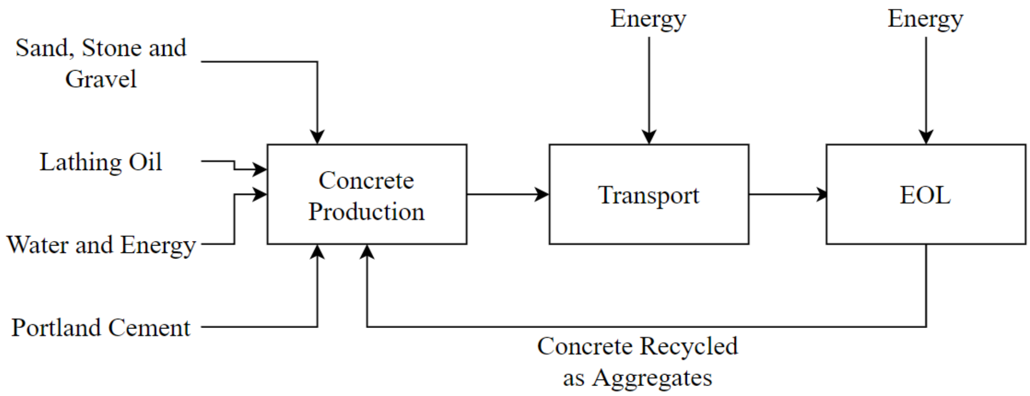

Figure 11 A flow diagram giving an overview of the life cycle of concrete as an indoor building material
The life cycle stages (rectangles) of concrete is production, transport, and EOL. Resources/raw materials are needed for each stage (arrows). In the concrete production, raw materials such as sand, stone, gravel, water, lathing oil, Portland cement, and energy are required. The concrete is transported from the production facility to the construction site, where it is poured. After being used, the concrete is recycled on-site, where the aggregates can be recycled and replace gravel in new concrete. The transport stage and EOL are processes, which requires energy.

Figure 11 illustrates the life cycle of concrete with three major processes: Concrete production, transport, and EOL. Production of concrete requires raw materials such as sand, stone, gravel, water, and energy along with Portland cement. From the production facility, 1 kg of concrete is transported in a concrete mixer to the construction site, where it is poured and placed. It is assumed that ready-mixed concrete is not transported more than 100 km since it would harden. As the EOL scenario, the concrete is broken up and recycled on-site, where it is replacing gravel in new concrete production.

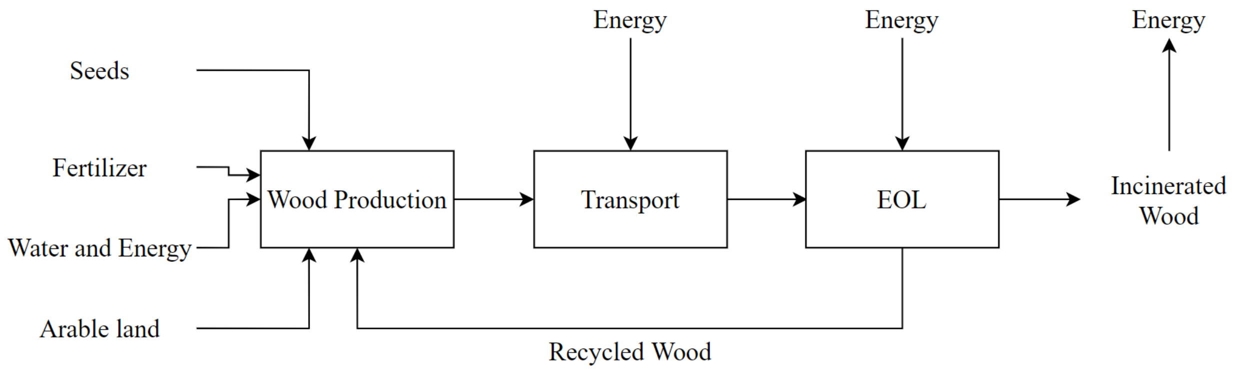

Figure 12 A flow diagram giving an overview of the life cycle of wood as an indoor building material
The life cycle stages (rectangles) of wood is production, transport, and EOL. Resources/raw materials are needed for each stage (arrows). In the wood production, raw materials such as seeds, fertiliser, water, energy, and arable land are required. Energy is also required for the transport and EOL stage. The wood is transported from the production facility to the construction site, where it is used as an indoor construction material. After demolition, the wood is either recycled in the production of wooden building materials or incinerated to produce heat and energy.

Figure 12 is an illustration of the life cycle stages of wood, where arable land, as well as tree seeds, fertiliser, and water, are required to grow the tree. Energy is needed to cut down the tree and produce the wooden building material. The wood is transported to the construction site, where it is installed.

Two scenarios for transport of the wood are created to compare the impact of transporting wood for the EcoCocon module from Lithuania to Denmark (approx.1,500 km) with the impact of transporting wood in Denmark (approx. 100 km). As EOL of the wooden building material, it can be incinerated to produce heat and energy or recycled in the production of new wooden building materials.

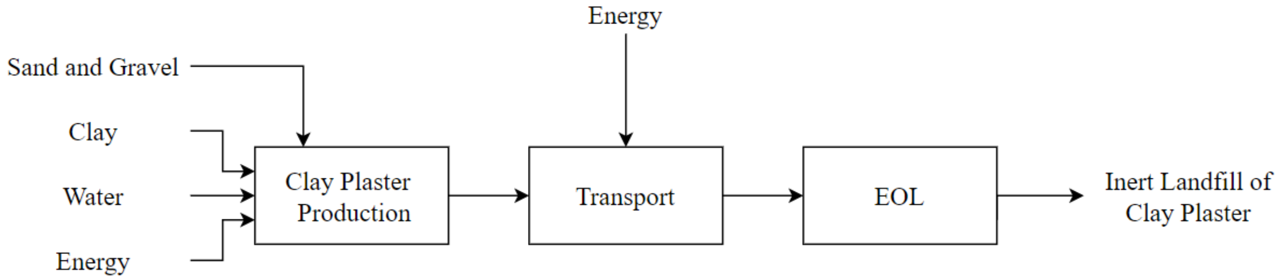

Figure 13 A flow diagram giving an overview of the life cycle of clay plaster

The life cycle stages (rectangles) of clay plaster is production, transport, and EOL. Resources/raw materials are needed for each stage (arrows). In the clay plaster production, raw materials such as sand, gravel, clay, water, and energy are required. The clay plaster (without water) is transported from the production facility to the construction site, where it is mixed with water and plastered on the surface of an indoor wall. The clay plaster is separated from the wall upon demolition and disposed as inert landfill.

Figure 13 illustrates the life cycle stages of clay plaster, where the clay plaster production requires raw materials such as clay, sand, gravel, and water as well as energy for the crushing and sorting of gravel and clay. The production of clay plaster takes place in Estonia by the company UKU (Saviukumaja OÜ) [33]. Before mixing, the clay plaster (without water) is transported to Denmark (approx. 1,500 km). Upon construction site, the clay plaster is mixed and plastered onto the internal surface of a constructed wall. In the demolition process, clay is separated from the wall and disposed as inert landfill [69].

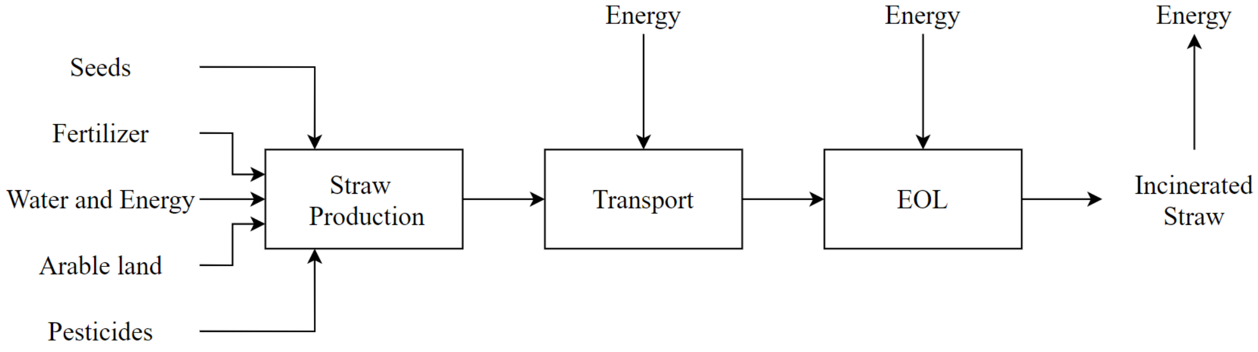

Figure 14 A flow diagram giving an overview of the life cycle of straw as an indoor building material

The life cycle stages (rectangles) of straw is production, transport, and EOL. Resources/raw materials are needed for each stage (arrows). In the straw production, raw materials such as seeds, fertiliser, water, energy, pesticides, and arable land are required. Energy is required for the transport and EOL stage. The straw is transported from the production facility to the construction site, where it is used as an indoor construction material. After demolition, the straw is incinerated to produce heat and energy.

Figure 14 is an illustration of the life cycle stages for straw used as a building material. The arable land is prepared before sowing the seeds. Water and fertiliser are needed during the growth of the crops. When the crops are ready, they are harvested, and the straw is left on the field. The straws are cut and pressed into bales by a straw baler machine. The strawbales are collected and stored in dry surroundings. If the straws are not dry, there is a high chance of fungus and decomposing. The strawbales produced in Lithuania are transported to Denmark (approx. 1,500 km), where the straws are installed as a part of a wall, e.g. the EcoCocon element. As an EOL scenario, the straw will be incinerated to produces heat and energy.

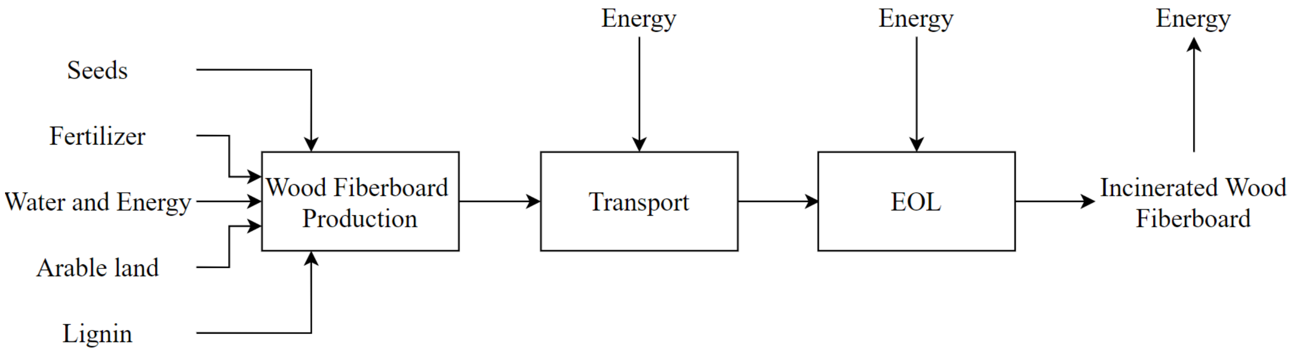

Figure 15 A flow diagram giving an overview of the life cycle of wood fibreboard

The life cycle stages (rectangles) of wood fibreboard is production, transport, and EOL. Resources/raw materials are needed for each stage (arrows). In the wood fibreboard production, raw materials such as seeds, fertiliser, water, energy, lignin, and arable land are required. Energy is also required for the transport and the EOL stage. The wood fibreboard is transported from the production facility to the construction site, where it is used as an indoor construction material. After demolition, the wood fibreboard is incinerated to produce heat and energy.

Figure 15 illustrates the life cycle of wood fibreboard, where wood is an essential part and therefore, arable land, as well as tree seeds, fertiliser, and water, are required to grow the tree. Energy is needed for cutting down the trees and for peeling and subdividing the wood. The wood is pressed into wood fibreboards with the addition of water and bound together with the naturally occurring substance in wood, lignin. The wood fibreboards are transported from STEICO in Germany [68] to the construction site in Denmark (approx. 1,000 km), where it is installed as insulation on a constructed wall, e.g. the EcoCocon Element. After demolition, the wood fibreboards will be incinerated.

2.2.2.2. Process Flow Diagrams for Building Components

The life cycle of a 1 m^3 building component, either a concrete wall or EcoCocon element, is visualised in process flow diagrams. The concrete wall is modelled according to the process flow diagram for concrete in Figure 11; therefore the only change between the concrete building material and the concrete building component is the upscaling from 1 kg to 1 m^3.

The 1 m^3 EcoCocon element consists of straw and wood; therefore the process flow diagrams for wood (Figure 12) and straw (Figure 14) is combined to create the process flow diagram for the EcoCocon element (Figure 16).

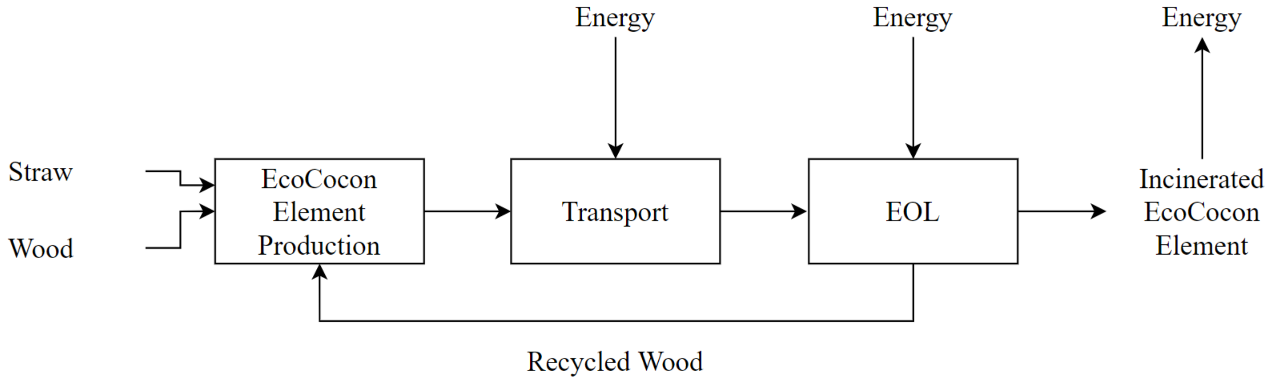

Figure 16 A flow diagram giving an overview of the life cycle of the EcoCocon element
The life cycle stages (rectangles) of the EcoCocon element is production, transport, and EOL. Resources/raw materials are needed for each stage (arrows). In the production of the EcoCocon element, raw materials for producing straw and wood is required. Energy is also required for the transport and the EOL stage. The EcoCocon element is sampled and transported from the production facility to the construction site, where it is installed as a part of a wall in the new building. After demolition, the EcoCocon element is incinerated to produce heat and energy. A future EOL scenario for the EcoCocon element is recycling of the wood.

The strawbales are sampled with the wood to produce the EcoCocon modules in Lithuania [31]. The EcoCocon modules are transported to Denmark, where they are installed at the construction site as part of a wall of the new building. The detailed descriptions of the life cycles for straw and wood are found by their respective process flow diagrams, while the amount of straw and wood needed for the EcoCocon element is listed in Table 4.

Table 4 The materials needed per 1 m^3 EcoCocon element with a surface area of 2.4 m^2
The information for wood and straw needed for the EcoCocon element is given as the producer, thickness [m], area [m^3], weight [kg], and reference

Material	Producer	Thickness [m]	Area [m^3]	Weight [kg]	Reference
Wood	EcoCocon	EcoCocon element 0.4	EcoCocon element 1	41.424	[34]
Straw	EcoCocon			97.488	[34]

After demolition, the EcoCocon element is incinerated to produce heat and energy. A future EOL scenario of the wood in the EcoCocon element is recycling.

2.2.2.3. Process Flow Diagrams for Complete External Wall Systems

The constructed wall systems modelled as a 1.5 m^3 wall with 50 years of service life are described in detail along with process flow diagrams.

The complete EcoCocon wall system consists of a straw isolated wood element (the EcoCocon element), where the inner layer consists of 2-3 layers of clay and wood fibreboard. The external layer consists of a Tyvek® breathable membrane, Siga air sealing tape, wood fibreboard, plywood and timber cladding [34][65][70]. In total, the size of a standard EcoCocon wall section is 1.5 m^3 with the measures L 3000 mm x W 800 mm x H 625 mm, while the inner and external surface is 2.4 m^2 [71].

All amounts of materials needed for the EcoCocon external wall system is described in Table 5. The sum of thermal resistance, also known as the U-value, for the EcoCocon wall section is 0.11 W/m^{2}K as calculated by EcoCocon [71]. Table 5 gives information on the materials needed, including thickness [m], area [m^3], weight [kg], the producer and reference. The wooden cladding is assumed to be vertical one on two cladding, thereby overlapping approximately 1.5 times on the 2.4 m^2 surface area. The weight of each material is calculated according to the density [kg/m^3] [34].

Table 5 Amount of materials needed per 1.5 m^3 complete EcoCocon external wall system with a surface area of 2.4 m^2.
The information for wood and straw needed for the EcoCocon external wall system is given as the thickness [m], area [m^3], weight [kg], the producer, and reference

Material	Producer	Thickness [m]	Area [m^3]	Weight [kg]	Reference
EcoCocon element	EcoCocon	0.4	1	138.912	[34]
Wood fibreboard	STEICO	0.107	0.2568	0.552	[68], [71]
Plywood	Unknown	0.005	0.012	10.44	[31], [34]
Wood cladding	Unknown	0.02	0.048	16.464	[72]
Breathable membrane	Siga/TYVEK	0.06	0.144	0.544	[73], [74]
Clay plaster (top and base coat)	UKU	0.03	0.024	12	[33]

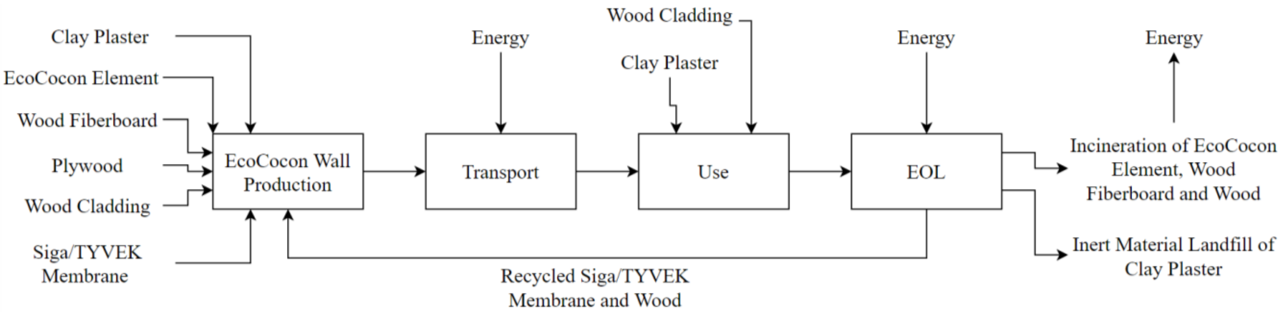

Figure 17 A flow diagram giving an overview of the life cycle of a complete EcoCocon external wall system
The life cycle stages (rectangles) of the EcoCocon external wall system is production, transport, use, and EOL. Resources/raw materials are needed for each stage (arrows). In the production of the complete EcoCocon external wall system, raw materials for producing the EcoCocon element, clay plaster, wood fibreboard, plywood, wood cladding, and Siga/TYVEK membrane are required. The transport and EOL stage also requires energy. The materials required for the complete EcoCocon external wall are transported from the production facility to the construction site, where the complete wall is assembled as a wall in the new building. During the use stage, a new layer of clay plaster is required as well as replacement of 10 % of the wooden surface. After demolition, the complete EcoCocon wall system is separated, where the EcoCocon element, the wood fibreboard, and the wood are incinerated to produce heat and energy, and the Siga/TYVEK membrane is recycled. A future EOL scenario for the complete EcoCocon wall system is recycling of the wood used in the EcoCocon element.

All materials required for constructing the EcoCocon wall (Figure 17) are transported to Denmark, where the EcoCocon wall system is assembled as a complete external wall of a building. During the use stage, there is no maintenance of the EcoCocon element itself, and if the module is protected from water, it can last for a long time. Throughout the use stage, the complete external wall system needs maintenance in the form of new clay plaster on the inner surface and changing of the wood cladding on the external surface. It is assumed that 10 % of the surface wood needs to be replaced during the 50 years of service life. After use, the wall is demolished, and the EcoCocon module is incinerated along with the surface wood and the wood fibreboard to produce heat and energy. In the demolition process clay plaster is assumed to be separated from the EcoCocon module and disposed as inert landfill. The Siga/TYVEK membrane is recycled to produce polyethene for new Siga/TYVEK membrane production [74]. Future EOL scenario of the wood in the EcoCocon element is recycling.

The modelled concrete wall section has the same size and U-value as the modelled EcoCocon wall section to make them comparable. To acquire a U-value of 0.11 W/m^{2}K (calculated by [75]), the concrete wall section needs 300 mm of insulation (REDAir BATTS, Rockwool A/S) with a 100 mm concrete element, and where the weight of the cladding does not exceed 50 kg/m^2 [72][75]. In this model, the cladding of the concrete wall section is assumed to be timber, to get the same expression as the EcoCocon external wall system. Furthermore, the complete external wall system also consists of inner layers of mineral plaster, and external layers of plywood, wooden lathing, and breathable membrane (TYVEK/Siga) [72][75]. Specifications of the external wall system is listed in Table 6 with thickness [m], area [m^3], weight [kg] and the producer. The wooden cladding is assumed to be vertical one on two cladding, thereby overlapping approximately 1.5 times on the 2.4 m^2 surface area. The weight of each material is calculated according to the density [kg/m^3] [72][75].

Table 6 Amount of materials needed per 1.5 m^3 concrete external wall system with a surface area of 2.4 m^2. The information for wood and straw needed for the concrete external wall system is given as the thickness [m], area [m^3], weight [kg], the producer, and reference

Material	Producer	Thickness [m]	Area [m^3]	Weight [kg]	Reference
Concrete	Unknown	0.1	0.24	560.4	[72], [75]
REDAir BATTS	ROCKWOOL	0.3	0.72	72	[72], [75]
Plywood	Unknown	0.027	0.0648	43.416	[72]
Wooden lathing	Unknown	0.038	0.0912	31.92	[72]
Wood cladding	Unknown	0.05	0.12	24.696	[72]
Breathable membrane	Siga/TYVEK	0.06	0.144	0.544	[73], [74]
Mineral plaster	Ytong	0.01	0.024	25.92	[76]

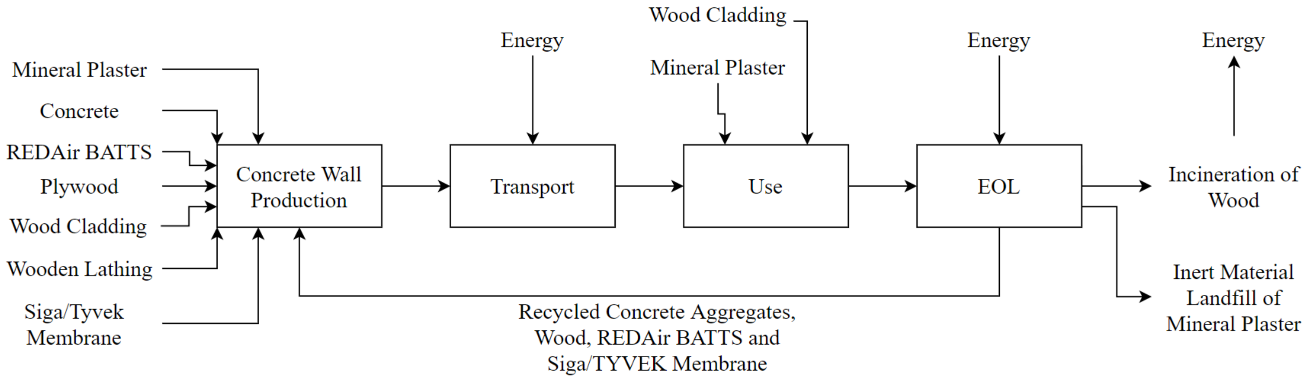

Figure 18 A flow diagram giving an overview of the life cycle of a constructed concrete external wall system
The life cycle stages (rectangles) of the concrete external wall system is production, transport, use, and EOL. Resources/raw materials are needed for each stage (arrows). In the production of the complete concrete external wall system, raw materials for producing the concrete, mineral plaster, REDAir BATTS, plywood, wood cladding, wooden lathing, and the Siga/TYVEK membrane are required. The transport and EOL stages also require energy. The materials required for the complete concrete external wall are transported from the production facility to the construction site, where the wall is assembled in the new building. During the use stage, a new layer of mineral plaster is required as well as replacement of 10 % of the wooden surface. After demolition, the complete concrete wall system is separated, where the wood is incinerated to produce heat and energy. The wood, the concrete, the REDAir BATTS, and the Siga/TYVEK membrane are recycled separately.

All required materials for the concrete external wall system (Figure 18) are produced and transported to the construction site in Denmark, where the concrete external wall system is built. For the concrete external wall system, it is also assumed that maintenance in the form of new mineral plaster is needed along with the replacement of 10 % of the surface wood during the 50 years of service life. After use, the wall is demolished, and building materials such as timber cladding is incinerated to produce heat and energy. At the same time, the mineral plaster is disposed as inert landfill. The concrete is recycled on-site to replace gravel in new concrete constructions. The wooden lathing is recycled as new wooden building materials. The REDAir BATTS is recycled by ROCKWOOL for new stone wool production [77]. The Siga/TYVEK membrane is recycled to produce polyethene for new Siga/TYVEK membrane production [74].

2.2.3. Inventory Analysis

The LCI is based upon the goal and scope definition and serves as the basis of the LCIA. The inventory analysis is the collection of data regarding the elementary flows from all processes in the product systems life cycle.

For conducting the inventory analysis, data is obtained from several sources, where the foreground data is obtained from academic papers, producers of the building materials, and other LCA studies, amongst others. Detailed description of the EcoCocon element itself, as well as inner and external layers of the constructed wall section, were given by the EcoCocon company [34]. Rockwool A/S also had a major influence on how the concrete wall section is constructed, since all data were acquired through them [72][75]. Due to the limitation of data, it was necessary to set up assumptions and simplifications to model the product system.

The background data for the inventory analysis is obtained through the LCI database, Ecoinvent v.3.4, which contains inventory data for more than 12,500 processes divided into sectors such as agriculture, manufacturing, transport, and waste management [67].

The product systems have been modelled in the OpenLCA 1.10.2 software to assess the embodied human toxicological impact. The LCIA method used for assessing the embodied human toxicological impact is the ILCD 2011 v.1.0.10 midpoint. The human toxicological impact is assessed towards the subcategories "carcinogenic effects" and "non-carcinogenic effects". Weighting factors have been used for converting the human toxicity impact from CTUh to DALY; these are 11.5 and 2.7 as years lost for carcinogenic and non-carcinogenic effects, respectively.

2.2.4. OpenLCA Model Description

The process flow diagrams presented in chapters 2.2.2.1, 2.2.2.2, and 2.2.2.3 were used as the basis for creating the models in OpenLCA. The modelling was divided into the same four stages, production, transportation, use, and EOL. For modelling of the different processes, system processes (S) were most often chosen, since the input and output data give an aggregated result, represented by the unit processes. Unit processes (U) were chosen when the input and output of the system processes had to be changed to fit better, e.g. transport and Danish electricity grid [67].

The marginal suppliers are the processes suppliers that respond to the studied change in demand either by increasing or decreasing the supply [41]. As the provider, the market for Europe or more preferably the market for the specific country were chosen to ensure the geographical and technological coverage for the process. Choosing the Swiss market as a provider was considered the next best compared to choosing the country-specific market since it is a part of the European region [67].

Transport from the production facility to the construction site was considered for all models created. In contrast, the transport to the production and the disposal facilities was neglected since much uncertainty lies within. The use stage was only considered for the modelling of the complete external wall systems, e.g. concrete wall system and EcoCocon wall system, since the service-life and use-ability is not considered in the modelling of the singular building materials or the building components.

2.2.4.1. Modelling of 1 kg Singular Building Materials

Concrete:

For the production of concrete, the following was chosen to model the inputs: the Europe without Switzerland market for "cement, Portland" (0.0874 kg) to model Portland cement, the Swiss market for "gravel, crushed" (0.432 kg) to model crushed gravel, the global market for "lubricating oil" (5.1E-6 kg), the Danish "gravel and sand operation" (0.396 kg) for sand as well as water (0.0685 kg) as an elementary flow. The values for production of concrete are taken from the Ecoinvent Database process “concrete production 20 MPa” [67]. The transportation of the ready-mixed concrete was assumed not to be transported more than 100 km; therefore, the transportation was modelled using the European "transport, freight, lorry 16-32 metric ton" (0.1 t*km). The concrete recycling is performed on the demolition site, where concrete is crushed into gravel using a crushing machine. The energy used by the crushing machine is modelled using the global market for "diesel burned in building machine" (0.0437 MJ) [67]. The avoided gravel production is modelled using the Swiss market for "gravel, crushed" (-1 kg).

Wood:

Two different versions of wood were modelled; wood produced in Denmark (wood DK) and wood produced in Lithuania (wood LT). For both versions, the production of wood was modelled using the European market for "sawnwood, softwood, dried (u=10%), planed" (1 kg). For wood DK, the transportation is modelled using the European "transport, freight, lorry 16-32 metric ton" (0.1 t*km), while for wood LT the European "transport, freight, lorry 16-32 metric ton" (1.5 t*km). The EOL of wood LT was modelled as incineration using the market for Europe without Switzerland for "process-specific burdens, municipal waste incineration" (1 kg). The generation of heat from incineration is modelled as the avoided heat production with the market for Europe without Switzerland for “heat, district or industrial, other than natural gas” (-18.5 MJ) [78]. The EOL of wood DK was modelled as recycling with the Swiss process “treatment of waste wood, post-consumer, sorting and shredding” (1 kg) along with the avoided production of wood (-1 kg) for wood building materials.

Clay:

For modelling the production of clay plaster, the Swiss market for "clay" (0.25 kg) and the Estonian "gravel and sand operation" (0.55 kg) were chosen to model clay and sand as well as the input of water (0.20 kg) as an elementary flow [67]. The transportation of the mixed clay and sand without water was modelled using the European "transport, freight, lorry 16-32 metric ton" (1.5 t*km). The EOL for clay plaster is inert material landfill, which was modelled with the Swiss market for "process-specific burdens, inert material landfill" (1 kg).

Straw:

The production of straw is modelled using the existing unit process "straw production, stand-alone production" for creating a system process with Lithuanian market for "fodder loading", "irrigation", and "mowing by rotary kiln", where the output was "straw product" (1 kg) [67]. Transportation of the straw was modelled using the European "transport, freight, lorry 16-32 metric ton" (1.5 t*km). The EOL of straw is incineration, which was modelled with the market for Europe without Switzerland for "process-specific burdens, municipal waste incineration" (1 kg). The generation of heat from incineration is modelled as the avoided heat production with the market for Europe without Switzerland for “heat, district or industrial, other than natural gas” (-15.98 MJ) [79].

Wood fibreboard:

The production of wood fibreboard is modelled using the existing unit process "fibreboard production, soft, from wet-dry processes" for creating a system process with the German market for energy [67]. The individual numbers inside the process was not changed, and the output was "wood fibreboard product" (1 kg). The transportation of the wood fibreboard was modelled using the European "transport, freight, lorry 16-32 metric ton" (1.1 t*km). The EOL option of wood fibreboard is incineration, which was modelled with the market for Europe without Switzerland for "process-specific burdens, municipal waste incineration" (1 kg). The generation of heat from incineration is modelled as the avoided heat production with the market for Europe without Switzerland for “heat, district or industrial, other than natural gas” (-19.3 MJ) [80].

2.2.4.2. Modelling of 1 m^3 Building Components

Concrete building component:

The 1 m^3 of concrete building component is modelled the same way as 1 kg concrete building material; the only alteration is the upscaling. The life cycle stages created in the modelling of 1 kg concrete, were used as an input for modelling of the concrete building component. Concrete has a density of 2,335 kg/m^3 [67]; therefore, the input amount for all life cycle stage are 2,335 kg for 1 m^3 concrete component.

EcoCocon element:

The 1 m^3 of EcoCocon element consisting of straw and wood only was modelled by changing the amount of the life cycle stages created for modelling 1 kg of straw and wood. The weight given by EcoCocon per 1 m^3 panel of straw and wood is 97.488 kg and 41.424 kg, respectively [34]. These values have been inserted as an input amount for the life cycle of straw and wood to model the life cycle of 1 m^3 EcoCocon element.

1 m^3 of the EcoCocon element was modelled a second time to consider recycling as a future EOL scenario of the wood in the EcoCocon element. Here incineration of wood was changed to recycling using the Swiss process “treatment of waste wood, post-consumer, sorting and shredding” (41.424 kg) along with the avoided production of wood (-41.424 kg) for wood building materials.

2.2.4.3. Modelling of 1.5 m^3 Complete External Wall System

Concrete external wall system:

In the production of the 1.5 m^3 external concrete wall system, the following inputs have been chosen for modelling: the European market for "mineral plaster production" (25.92 kg), the Danish "concrete product" (560.4 kg), the European market for "plywood, indoor use" (0.0648 m^3) to model wooden planks, the global market for "glued laminated timber for outdoor use" (24.696 kg) to model the wooden external surface, the global market for "sealing tape, aluminium/PE, 50 mm wide" (0.144 m^3), the global market for "stone wool, packed" (0.72 m^3) to model Rockwool REDAir BATTS, and the Danish "wood product" (31.92 kg) to model the wooden lathing. For the transportation of sealing tape, glued laminated timber, plywood, and REDAir BATTS to the construction site 100 km of transportation is assumed; therefore the input amount modelled for the European market for "transport, freight, lorry 16-32 metric ton" is 0.0544 t*km, 2.4696 t*km, 4.3416 t*km, and 7.2 t*km. For transport of wood, concrete, and clay plaster the transportation distances are the same as for the singular material modelling just upscaled to the kg of produced material. As EOL for concrete, wood, and clay plaster, the same modelling is performed as for the singular building materials scaled up to the amount needed for the external concrete wall system. For glued laminated timber and plywood, the EOL is incineration, which is modelled using Europe without Switzerland market for "process-specific burdens, municipal waste incineration" with the input amount of 24.696 kg and 43.416 kg, respectively. Along with the market for Europe without Switzerland for “heat, district or industrial, other than natural gas” with the input of -456.876 MJ and -803.196 MJ, respectively. Sealing tape is recycled, which is modelled with the swiss process “treatment of used sealing tape aluminium/PE, 50 mm wide” (6 m) and the global market for “packaging film, low-density polyethene” (-0.00942 kg) [74]. The REDAir BATTS is recycled with a recycling rate of 60 % as new stone wool, which is modelled with the Europe without Switzerland “treatment of waste mineral wool, collection for recycling” (72 kg) and the global market for stone wool packed (-43.2 kg) [77].

EcoCocon external wall system:

In the production of the 1.5 m^3 EcoCocon external wall system, the following inputs have been chosen for modelling: the Estonian "clay plaster production" (12 kg), the European market for "plywood, indoor use" (0.012 m^3), the global market for "glued laminated timber for outdoor use" (16.464 kg), the global market for "sealing tape, aluminium/PE, 50 mm wide" (0.144 m^3), the Lithuanian "straw product" (97.488 kg), the German "wood fibreboard product" (0.552 kg), and the Lithuanian "wood product" (41.424 kg). For transport of sealing tape, glued laminated timber, and plywood it was considered 100 km transport with the European market for "transport, freight, lorry 16-32 metric ton" with the input amount of 0.0544 t*km, 1.6464 t*km, and 1.044 t*km, respectively. For transport of straw, wood, wood fibreboard, and clay, the transportation distances are the same as for the singular material modelling just upscaled to the kg of produced material. The maintenance during the use stage of the EcoCocon wall section is a new layer of clay and replacement of 10 % of the wooden external surface. The maintenance is modelled using the input of Estonian "clay product" (12 kg) and the global market for "glued laminated timber for outdoor use" (1.6464 kg). For the EOL for clay, wood, wood fibreboard, and straw, the same modelling is performed as for the singular building materials scaled up to the amount needed for the EcoCocon wall section. For glued laminated timber and plywood, the EOL is incineration. The incineration for these materials is modelled using Europe without Switzerland market for "process-specific burdens, municipal waste incineration" with the input amount of 16.464 kg and 10.44 kg, respectively. Along with the market for Europe without Switzerland for “heat, district or industrial, other than natural gas” with the input of -304.854 MJ and -193.14 MJ, respectively. The sealing tape is recycled, which is modelled with the swiss process “treatment of used sealing tape aluminium/PE, 50 mm wide” (6 m) and the global market for “packaging film, low-density polyethene” (-0.00942 kg) [74].

To consider recycling as a future EOL scenario of the wood in the EcoCocon element, the EcoCocon external wall system were modelled a second time, where incineration of wood was changed to recycling using the Swiss process “treatment of waste wood, post-consumer, sorting and shredding” (41.424 kg) along with the avoided production of wood (-41.424 kg) for wood building materials.

2.2.5. Avoided Processes

Processes can be avoided, when the outputs of the life cycles of the modelled building material, components and wall sections are replacing the need for production of new materials or resources. In this project, processes are avoided from the output of the EOL stage, e.g. incineration and recycling.

Incineration of the building materials generates heat and energy, which can be used in the grid, thereby avoiding the process of producing heat and electricity, e.g. by burning of coal [67]. Furthermore, the avoided heat an energy production from coal power and combined heat and power plants also leads to an avoided generation of toxic chemical emission. Even though toxic chemical emissions are also produced from the incineration process itself, there is a saving of toxic chemical emissions in the end [67].

When concrete is recycled, it is assumed, that it is crushed into gravel (1:1), thereby avoiding the process of mining new gravel for new concrete. The amount of gravel from 1 kg recycled concrete can make twice as much concrete, since only 0.432 kg of gravel is needed for concrete production [67]. The recycling process of the wood leads to an avoided production of new wood for wooden building materials such as chipboard and wood fibreboard. When REDAir BATTS by ROCKWOOL is recycled, there is an avoided process of producing new stone wool [77]. The production of polyethene is avoided when the TYVEK/Siga sealing tape/membrane is recycled [74].

2.2.6. Uncertainties and Assumptions

In Table 7 and Table 8, the assumptions and simplifications necessary to model the product system are listed and described. When assumptions and simplifications are used in LCA, it is inevitable to get uncertainties regarding the results. The uncertainty can be quantified and reduced by understanding how it arises.

The data used for calculating the LCIA of the different building materials are found in the Ecoinvent v3.4 database [67]. One way to ensure the reduction of uncertainty would be to look through the references used for the values in the database. In the assessment of human toxicity impact on the three levels of modelling from the building material to the building component to the complete external wall system, the uncertainty increases the higher the level of building materials being assessed.

Table 7 The simplifications used during the modelling of materials in OpenLCA

Simplifications
Loss of material during production (as well as in other life cycle stages) is neglected
Transport to the production facility and transport to the disposal facility is neglected
Raw materials for clay plaster production is locally mined in Estonia and produced by UKU
Raw materials for the EcoCocon element are produced close to the production facilities in Lithuania
Raw materials for concrete and wood fibreboard are mined locally in Denmark
Maintenance is neglected for the singular building materials and the building components
All transport is modelled to be with lorry 16-32, EURO6
Transport for building materials for the EcoCocon wall section and the concrete wall section is simplified to 100 km for each building material, except for the EcoCocon element, clay plaster, and wood fibreboard.
Both external wall systems have timber cladding, while the inner layer is plastered with mineral plaster for the concrete wall system and clay plaster for the EcoCocon wall system
Future EOL (recycling) is only considered for the wood in the EcoCocon modules

Table 8 The assumptions used during the modelling of materials in OpenLCA

Assumptions	**Reference**
Moisture of straw product is 15 %, Straw calorific value is 15.9 MJ/kg	[79]
Wood calorific value is approx. 18.5 MJ/kg	[78]
Wood fibreboard calorific value is 19.3 MJ/kg	[80]
EcoCocon materials (straw, wood, and clay) are transported 1,500 km to Denmark from EcoCocon, Lithuania and UKU, Estonia	[31], [33]
STEICO wood fibreboards are produced in Germany and transported 1,100 km	[68]
Concrete wall is built as described by ROCKWOOL	[72], [75]
Concrete (ready mixed) is transported maximum 100 km to prevent hardening	Assumption
The wall systems are assumed to last equally long, and expected to last 50 years	Assumption
Preservation of wood is not considered, since it is assumed, that the wood chosen is naturally preserved to some extent	Assumption
Maintenance of the external wall systems is assumed to include a new inner layer of plaster and replacing 10 % of the wooden external surface	Assumption
EOL for straw, wood, wood fibreboard, plywood, and glued laminated timber is incineration with heat and energy generation	Assumption
Recycling of wood to new wooden building material	[23]
Recycling of REDAir BATTS by the provided ROCKWOOL	[77]
Recycling of TYVEK/Siga membrane to avoid production of polyethene	[74]
Concrete is recycled on-site, where it is crushed into gravel 1:1	Assumption
Clay plaster is separately disposed as inert material landfill	Assumption

The assumptions and simplifications in Table 7 and Table 8 relates to the transportation, consumer behaviour, and the EOL scenarios. Transportation to production and disposal facilities are neglected for all materials since the uncertainty will only increase. In the modelling, it is assumed that the transportation is so small that it is neglectable. Consumer-wise, the durability and maintenance for building materials and components, are neglected, since it would not make sense to model the use stage for materials where the service is not assumed, besides being a building material used in constructions. Timber cladding is assumed for the external wall systems. At the same time, many other possibilities of cladding exist, such as aluminium and bricks, which is highly influenced by consumer preferences. The disposal of building material is also highly influenced by consumer behaviour; therefore, the most used disposal option is chosen for the different materials. For wood, both incineration and recycling are considered.

3. Results and Discussion

In the following chapter, the results given by the experimental laboratory work and the modelling will be presented and discussed individually. The results are divided into embedded toxicity (chapter 3.1) and embodied toxicity (chapter 3.2), which will be compared (chapter 3.3) and discussed in an overall discussion (chapter 3.4).

3.1. Embedded Toxicity

Thermal stripping have been used to release the embedded emissions from building materials such as concrete, wood, clay, straw, and wood fibreboard. The experimental setup has been presented in detail in chapter 2.1.1. The qualitative and quantitative assessment of embedded toxicity is presented in chapter 3.1.1 and 3.1.2, and the results are discussed in chapter 3.1.3.

3.1.1. Qualitative Assessment of Embedded Toxicity

In chapter 2.1.3, the methodology for identifying VOCs using the Xcalibur Qual Browser and the NIST library have been presented. The following substances in Table 9 have been identified in the GC-MS chromatogram results from runs with desorption of the SPME fiber only in the GC DB-5MS column and from thermal stripping of contaminants in empty (blank) blue cap flasks. The compounds are presented with their respective Chemical Abstracts Service (CAS) number found in the NIST library [26].

Table 9 A list of all VOCs emitted from the SPME fiber and the GC-MS column itself, and contaminants found in the blank samples. Each compound is identified with a CAS number (CAS no.) from the NIST library. However, for the compounds 2,4,6-Tris(1,1-dimethylethyl)-4-methylcyclohexa-2,5-dien-1-one and X-siloxane, a CAS number was not available (N/A).

Compound	**CAS no.**
1-(2,3-dimethyl-furan-3-yl)ethanone	10599-70-9
1-Hexanol	111-27-3
2,3-Dihydroxypropylelaidate	25496-72-4
2,4,6-Tris(1,1-dimethylethyl)-4-methylcyclohexa-2,5-dien-1-one	N/A
Dodecane	112-40-3
Dronabinol	1972-08-3
Hexadecanoic acid	10499-94-2
Octadecanoic acid	57-11-4
Octane	111-65-9
Oleic acid	112-80-1
Oxime (Acetophenone)	613-91-2
Pentadecanoic acid	1002-84-2
Phenol	108-95-2
Propanoic acid	79-09-4
Toluene	108-88-3
X-siloxane	N/A

The results in Table 9 have been subtracted from the qualitative identification of substances in the sample with building materials, thereby giving the following results shown in Table 10 and Table 11 for VOCs emitted by each material group. The origin of the identified chemicals has been classified either as naturally occurring/constituent chemicals (biogenic) or incorporated chemicals (xenobiotic). As mentioned in chapter 1.3.1 biogenic substances in wood, and wood fibreboard as well, are acetic acid, formaldehyde, formic acid, and many types of terpenes. While in cereal some alkanes and ketones are considered naturally occurring and might therefore also be present in straw. Not naturally occurring chemicals, is considered xenobiotic and thereby incorporated into the material, which can happen both intentionally and unintentionally.

Table 10 The individual VOCs emitted from concrete, wood, and clay with CAS number (CAS no.) from the NIST library as well as biogenic (B) or Xenobiotic (X) classification. N/A is when the CAS no. was not available.

Material	**VOC emitted**	**CAS no.**	**Biogenic/Xenobiotic**
Concrete	1-Heptene	592-76-7	X
	2,4-Hexadieneoic acid	110-44-1	X
	3-Heptene-2,6-dione	99809-46-8	X
	Benzaldehyde	100-52-7	X
	Benzene	71-43-2	X
	Decane	124-18-5	X
	Hexane	110-54-3	X
	Naphthalene	91-20-3	X
	Pyridine	110-86-1	X
Wood	1H-Cyclopropa[a]naphthalene	489-29-2	X
	2-Norpinene, 3,6,6-trimethyl-	4889-83-2	B
	2(10)-Pinene	127-91-3	B
	3-carene	13466-78-9	B
	α-Pinene	80-56-8	B
	α-Longipinene	5989-08-2	B
	α-Terpinene	99-86-5	B
	α-Terpineol	98-55-5	B
	Bornylacetate	5655-61-8	B
	Cyclohexene	110-83-8	X
	Hexanal	66-25-1	B
	Naphthalene	91-20-3	X
	Ylangene	14912-44-8	B
Clay	2-oxo-4-phenyl-6-(4-chlorophenyl)-1,2-dihydropyrimidine	N/A	X
	Benzene	71-43-2	X
	Camphene	79-92-5	X

Table 11 The individual VOCs emitted from straw and wood fibreboard with CAS number (CAS no.) from the NIST library as well as biogenic (B) or Xenobiotic (X) classification

Material	VOC emitted	CAS no.	Biogenic/Xenobiotic
Straw	1-Hexanone	942-92-7	X
	2-Pentadecanone	2345-28-0	B
	2-Pentene	109-68-2	X
	3-Acetyl-2,5-dimethyl-furan	10599-70-9	X
	3-Hexen-2-one	4376-23-2	X
	Decane	124-18-5	B
	Naphthalene	91-20-3	X
Wood fibreboard	Bicyclo[3.1.0]hex-2-ene, 2-methyl-5-(1-methylethyl)-	2867-05-2	X
	Furan	110-00-9	X
	Hexanal	66-25-1	B

In Table 10 and Table 11, it is shown that several naturally occurring chemical substances are being emitted from the "green" materials: wood, straw, and wood fibreboards. Aldehydes such as hexanal is a naturally occurring chemical in wood and wood fibreboard, where it is formed from oxidative degradation of fatty acids like linoleic acid in the wood and functions as an antimicrobial agent. Even though chemicals are classified as naturally occurring, they still present some form of impact on human toxicity [35]. Regarding human toxicity, chronic exposure to hexanal can lead to organ diseases or in the worst-case organ failure [81].

Using Kemibrug.dk [82], it is possible to assess the health-damaging properties of the chemicals listed above. The TLV can give a quantitative toxicity value for the health-damaging chemicals (as mentioned in chapter 1.3.2) and has been found for the following chemical substances: Benzene 0.5 ppm, Pyridine 5 ppm, Naphthalene 10 ppm, and Hexane 20 ppm [82]. As the TLV value describes, benzene is the most dangerous chemical substance found and identified in this experiment, since only a small amount of benzene during a lifetime is needed to cause a series of human health diseases, e.g. organ failure and cancer. Chemical substances such as naphthalene and hexane are considered toxic and, in some cases, also believed to be carcinogenic [82].

Looking closer at the result of the identified chemicals in Appendix B, it can be seen that there is a difference in the chemical substances emitted between the triplicates. In some cases, one compound is only found in one of the triplicates, e.g. pyridine, which is only found in concrete replicate 1.1, but not in the concrete replicates 1.2 and 1.3. When comparing batch 1-10 of concrete, the identified chemical substances vary. For concrete batch 1, a total of ten chemical substances are identified, while for other batches of concrete, only five chemical substances are identified. The same goes for the wood sample, where ten chemical substances are identified in wood batch 3, and only three chemical substances are identified in wood batch 2.

3.1.2. Quantification and Characterisation of Embedded Toxicity

The identified chemical substances are quantified to understand the impact of the emitted VOCs from the building materials on human toxicity. As mentioned in chapter 2.1.4, it was planned to create standard curves for the identified chemical substances. However, due to the lockdown of the university caused by COVID-19, this could not be performed. Therefore, the relative amount [unitless (-)] of chemical substance given by the peak area in the GC-MS chromatogram was converted into % of the total analysed sample. Thereby, a relative ratio of all chemicals present in the emitted substance were given. The ratio (%) was used to calculate the weight of each identified chemical if a total of 1 kg sample were emitted. For clay material batch 2, the values are presented in Table 12, while the results for all other analysed building materials can be found in Appendix B.

Table 12 Identified chemical substances in clay batch 2

The identified chemicals in clay include benzene, 2-oxo-4-phenyl-6-(4-chlorophenyl)-1.2-dihydro-pyrimidine, and camphene. For each replicate, the following is given: Area under the peak (Area, unitless), % of the total amount of chemical substances identified in the analysed sample (%), and the weight of the chemical substance per kg emitted substance (per kg).

Clay Batch 2	**2.1**			**2.2**			**2.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	2.4E+5	65%	6.5E-1	6.3E+5	72%	7.2E-1	3.5E+5	76%	7.6E-1
2-oxo-4-phenyl-6-(4-chlorophenyl)-1.2-dihydropyrimidine	1.3E+5	35%	3.5E-1	1.4E+5	16%	1.6E-1	1.1E+5	24%	2.4E-1
Camphene	0	0%	0	1.1E+5	12%	1.2E-1	0	0%	0

For benzene in clay batch 2, the peak area value for the triplicates are between 2.4E+05 [-] and 6.3E+05 [-], while for 2-oxo-4-phenyl-6-(4-chlorophenyl)-1.2-dihydropyrimidine the peak area value are between 1.1E+05 [-] and 1.4E+05 [-]. Only replicate 2.2 contains camphene with a peak area value of 1.1E+05 [-]. It is seen that the area value affects the % of total identified chemical substances in the analysed sample and therefore, also the amount per kg emitted substance. The presence of camphene in replicate 2.2 of clay, results in a lowered amount per kg emitted substance of benzene and 2-oxo-4-phenyl-6-(4-chlorophenyl)-1.2-dihydropyrimidine even though the peak area for these two compounds are higher for replicate 2.2 when compared to replicate 2.1 and 2.3.

Graphs were created in GraphPad PRISM 5 for the ratio per kg emitted substance with mean and SD between the replicates to visualise the difference between triplicates and to compare between the batches of building materials. All graphs, except for the graph visualising the clay batches, is in Appendix C. Figure 19 shows the content of the chemical substance found in the clay batches 1-3 and the SD between the amount of chemical substance in each replicate. The SD is low for all triplicates of the three clay batches. The presence of camphene in replicate 2.2 results in a high SD compared to the ratio per kg emitted substance since camphene is not present in the other two replicates. The ratios per kg emitted substance between the batches of clay are very similar.

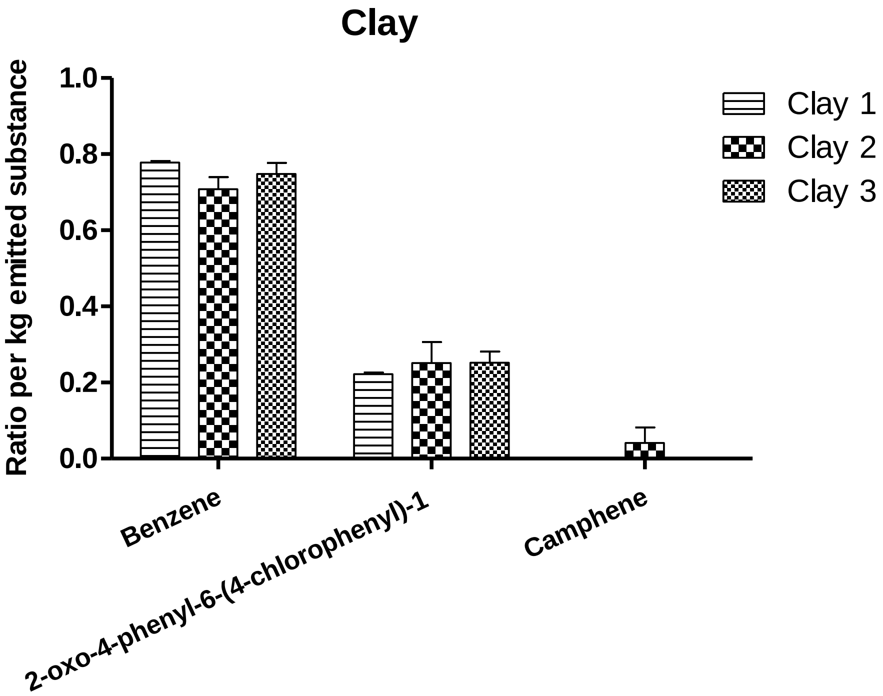

Figure 19 Ratio of chemical content per kg emitted substance from clay batch 1-3
The figure shows the ratio per kg emitted substance of benzene, 2-oxo-4-phenyl-6-(4-chlorophenyl)-1.2-dihydro-pyrimidine, and camphene with mean and standard deviation (SD) between replicates. Camphene is only present in Clay 2, while the ratios of benzene and 2-oxo-4-phenyl-6-(4-chlorophenyl)-1.2-dihydro-pyrimidine are very similar for all batches.

As seen in Appendix C, most concrete and wood replicates have high SDs. The SD for replicates of wood fibreboard samples is low. Between the wood fibreboard batches, there are vast differences in chemicals present.

The ratio of identified chemicals per kg emitted substance can be characterised to assess the impact of the chemical substance in comparison to human toxicity. The ILCD 2011 v.1.0.10 midpoint assessment method was used to assess the identified chemicals with characterisation factors for carcinogenic and non-carcinogenic human toxicity by emission to air in rural (low population density (LPD)) and urban (high population density (HPD)) area. Data from the newest version of USEtox (USEtox 2.12) was examined to ensure the newest available data on characterisation factors were used for the assessment of embedded human toxicity [43]. Even though the chemical pyridine was not found in the ILCD 2011 v.1.0.10 midpoint database, it was possible to find it in the newest version of USEtox. Thereby, the following six compounds could be characterised: benzaldehyde, benzene, furan, hexane, naphthalene, and pyridine. The human impact characterisation factors for the six compounds were given in CTUh per kg emitted substance. The impact in CTUh have been converted to DALY, as mentioned in chapter 1.4.1.4. The characterisation factors are presented in Table 13 both in CTUh and DALY.

Table 13 Characterisation factors for assessing the impact of identified chemicals
The characterisation factors (shown in CTUh and DALY per kg emitted chemical) from the ILCD impact assessment method for human toxicity resulting from emission to air of the six chemicals; Benzaldehyde, benzene, furan, hexane, naphthalene, and pyridine. LPD = Low population density, HPD = High population density, C = Carcinogenic, and NC = Non-carcinogenic.

Characterisation Factors								
Impact Assessment Method			Benzaldehyde	Benzene	Furan	Hexane	Naphthalene	Pyridine
ILCD [CTUh per kg emitted chemical]	LPD	C	2.21E-9	1.20E-7	1.39E-6	1.93E-10	6.4E-7	5.40E-7
		NC	2.87E-9	3.04E-8	1.54E-7	2.62E-8	8.74E-7	1.64E-6
	HPD	C	3.39E-8	4.74E-7	3.21E-5	1.79E-9	1.22E-6	2.84E-6
		NC	4.40E-8	1.20E-7	3.58E-6	2.44E-7	1.68E-6	8.62E-6
ILCD [DALY per kg emitted chemical]	LPD	C	2.54E-8	1.38E-6	1.60E-5	2.22E-9	7.30E-6	6.21E-6
		NC	7.75E-9	8.21E-8	4.16E-7	7.07E-8	2.36E-6	4.43E-6
	HPD	C	3.90E-7	5.45E-6	3.69E-4	2.06E-8	7.30E-6	2.94E-5
		NC	1.19E-7	3.24E-7	9.67E-6	6.59E-7	2.36E-6	2.10E-5

The characterisation factors in Table 13 are added to the weight of a chemical per kg emitted substance from Appendix B. Thereby a ratio of impact potential for non-carcinogenic and carcinogenic health effects caused by the amount of chemical in a total of 1 kg emitted substance is acquired (see Appendix D*)*. The impact potential is given in the unit DALY per kg emitted substance. The carcinogenic and non-carcinogenic impacts are summed to get the total LPD and total HPD, to compare the difference between LPD impact and HPD impact for each amount of extracted chemicals from each building material batch. The results are visualised as graphs with mean and SD between replicates in Appendix E.

The chemicals benzaldehyde, benzene, hexane, furan, and naphthalene have a higher impact when being emitted in an urban area compared to being emitted to a rural area as seen in Appendix E. The impact of benzaldehyde in rural and urban area changes with more than a factor 10. In comparison, the impact of benzene and hexane is approximately five times greater for urban areas. The impact of emitting furan in urban areas is 100 times greater than emitting it in rural areas, while the impact of naphthalene is only two times greater. However, the human toxicity impact of pyridine being emitted is very similar regarding the impact on urban or rural areas, as seen in Appendix figure OO and Table

13. The total human embedded toxicity is given by estimating the average exposure-specific LPD impacts and HPD impacts in DALY per kg emitted substance for all characterised chemicals. Afterwards, the average embedded human toxicity impact is calculated for the batches of material.

Table 14 The total human embedded toxicity for each group of building material
The embedded human toxicity [DALY per kg emitted substance] is given in average human toxicity as well as the highest and lowest human toxicity between the batches. Wood fibreboard has the highest average embedded toxicity compared to the four other materials, while wood has the lowest average toxicity. One of the concrete batches has the overall lowest embedded toxicity.

		Concrete	Wood	Clay	Straw	Wood fibreboard
Embedded human toxicity [DALY per kg emitted substance]	**Average toxicity**	3.68E-06	5.98E-07	2.69E-06	1.77E-06	1.68E-04
	Highest toxicity	1.22E-05	1.04E-06	2.91E-06	3.80E-06	2.75E-04
	Lowest toxicity	2.49E-08	2.96E-07	2.35E-06	3.10E-07	8.06E-06

As seen in Table 14, the lowest and highest embedded toxicity varies a lot from the average for concrete and wood fibreboard. As an example, for concrete, the lowest embedded toxicity is 2.49E-08 DALY per kg emitted, while the average embedded toxicity is 3.68E-06 DALY per kg emitted. For building materials such as wood, clay, and straw, the lowest and highest embedded toxicity are not varying as much from the average.

The embedded toxicity for concrete, wood, clay, straw, and wood fibreboard from Table 14 is only characterised and assessed as the impact from the six characterised chemicals: benzene, benzaldehyde, hexane, naphthalene, pyridine, and furan. The average mass share of chemicals per kg emitted substance was calculated and visualised in Figure 20 to show the influence of each chemical.

In the wood and straw samples, the share is approximately 4 %, where only naphthalene is present. Wood has the lowest average embedded toxicity of 5.98E-07 DALY per kg emitted substance. Straw has the second-lowest average toxicity of 1.77E-06 DALY per kg emitted substance. The average toxicity of concrete is 3.68E-06 DALY per kg emitted substance, where the share of characterised chemicals is approx. 45 % shared among 10 % benzene, 13 % benzaldehyde, 1 % hexane, and 21 % naphthalene. The share of characterised chemicals in clay and wood fibreboard is approx. 75 % and 86 %, respectively. For clay, the average embedded toxicity is 2.69E-06 DALY per kg emitted substance, which only comes from the impact of exposure to benzene. However, for wood fibreboard, the impact of embedded toxicity is 1.68E-04 DALY per kg emitted substance, which is shared among 24 % pyridine and 62 % furan.

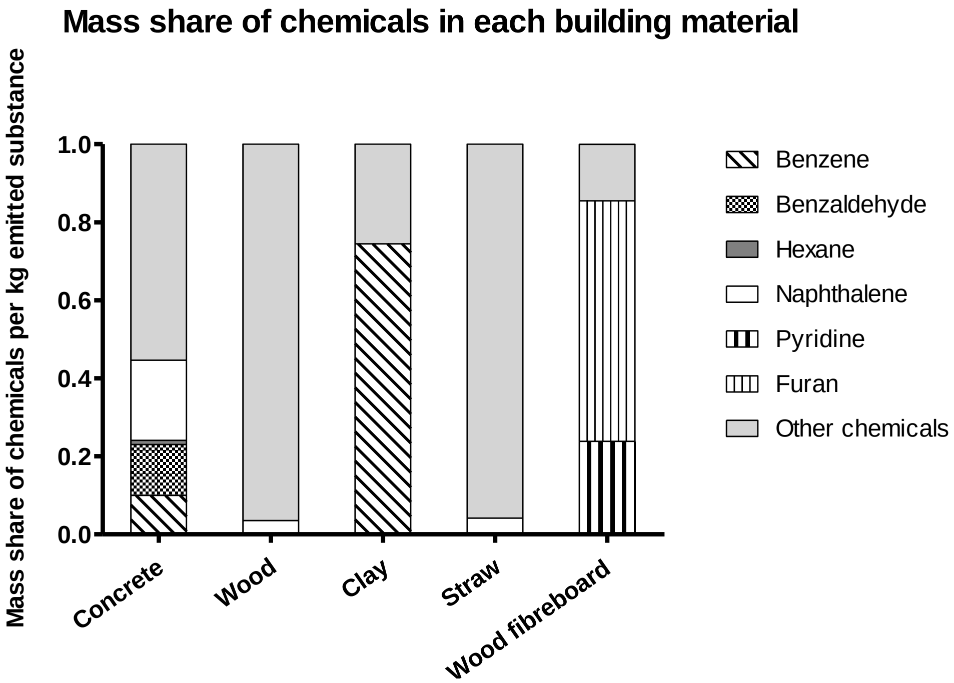

Figure 20 The average mass share of characterised chemical per kg emitted substance in each building material

The mass share of characterised chemical varies between the different building materials. The share of characterised chemicals in 1 kg concrete is 45 %, which is shared between benzene 10 %, benzaldehyde 13 %, hexane 1 %, and naphthalene 21 %. In 1 kg of clay, the share of characterised chemicals is 75 %, which only comes from benzene. For straw and wood, only 4 % of 1 kg emitted sample is naphthalene, while for wood fibreboard 86 % of 1 kg comes from 24 % pyridine and 62 % furan.

3.1.3. Discussion of the Assessment of Embedded Toxicity

The results of the experiment are dependent on the VOCs in the material being released during thermal stripping of the materials at 70 degrees Celsius. The boiling point for VOCs is between 60-280 degrees, and therefore there is a possibility, that we can miss some VOCs, because they are not present in the gaseous equilibrium phase inside the 250 mL blue cap flasks [51]. Furthermore, VOCs from the gaseous phase is selectively extracted according to their affinity to interact with the coating of the SPME fiber. Even though the DVB/CAR/PDMS coating has the most specificity towards VOCs, there is still an uncertainty regarding some VOCs having higher binding affinity to the SPME fiber than other VOCs. The extraction of emitted substance was 30 minutes recommended by [51]; however, it has not been analysed, whether longer or shorter extraction times would have been better.

The release of material is dependent on the sampling size, which in this project have been the size of a material, that could fit into the 3.3 cm top hole opening of a 250 mL blue cap flask [83]. When the Danish EPA samples concrete, they use a maximum size of 4 mm, which is the layer they assume can influence or trigger with the environment. Also, they use sampling from all over Denmark to get more precise statistics [27]. A specific sampling size is not used in this project; however, the sampled building material is inevitably less than 3.3 cm. The sampling size might contribute to the uncertainty of the equilibrium extraction of chemicals released by the materials.

Some of the GC-MS chromatograms had noise from the separation of the analysed sample, which makes it difficult to identify each peak to a specific chemical, since fragments of other chemicals or the noise could be present under the same peak. Therefore, the forward and reverse match between the unknown spectra and reference spectra from the NIST library preferably needed to be above 800 [-] to identify the chemical with reasonable confidence [58]. The identification of VOC present in the GC-MS chromatogram are depending on existing reference spectra in the NIST library; therefore, this experiment is not suited for identifying chemicals absent from the library. With a standard curve, it would also have been possible to identify precisely how much chemical is emitted per kg material. Unfortunately, the standard curve could not be performed due to COVID-19. The ratio (%) of identified chemicals in the emitted substance is the closest thing towards a real quantification of the chemicals emitted from the materials. It was only possible to quantify the ratio of identified chemicals emitted per kg emitted substance, when an equilibrium and steady-state were assumed. It is very likely, that the ratio (%) of identified chemical is lower, since only the total of identified chemicals is used in the estimation, not the total amount of sample extracted.

The VOCs identified in the chromatograms from the runs, where only the SPME fiber was run in the column, as well as the contamination test of the triplicated blank samples, were subtracted from the results of each material. However, these chemicals may be present in our samples, and thereby the embedded toxicity for each material could be much higher than anticipated. The Danish EPA found the presence of the chemical toluene in concrete, as mentioned in chapter 1.3.1 [27]. Toluene is one of the chemicals subtracted from the results in this project for concrete. Toluene is a chemical of great toxic concern, which could have been characterised with characterisation factors and thereby contributed to the embedded toxicity impact of concrete [27][43][82].

Using the NIST library, a total of 30 individual chemicals were identified for the building materials analysed. Most of which were considered xenobiotic of origin and thereby assumed incorporated into the material during its lifetime. The presence of xenobiotic and biogenic chemicals in the materials were not a surprise, since several studies have shown the presence of a variety of chemicals similar to the ones identified in this project, as mentioned in chapter 1.3.1. The classification as either biogenic or xenobiotic sources might be too uncertain since other classification parameters could be included, such as TLV and hazardous/non-hazardous [37].

The variation of emitted chemicals between triplicates is caused by the sampled population. A high SD between triplicates for emitted chemicals is related to the difference in sampled population, e.g. the concrete batches, which were sampled at RGS Nordic from large piles. It is not guaranteed that the sampled population (triplicates of a batch) came from the demolition of the same concrete element since the piles were a mix of concrete from the same demolition site. Therefore, there is a high possibility that the variation between concrete triplicates arises from the sampled population.

The variation of chemicals present between batches of material is caused by the sampled source of material. Different sources of materials increase the difference between batches and therefore, increases the uncertainty for the result of the material. Variation between batches concerns the analysis of concrete, wood, and wood fibreboard. As mentioned above, the concrete was sampled at RGS Nordic, who receive concrete from many different sources, which is why there is a variation of chemicals present between batches. The different sources analysed as wood fibreboard includes two different types of hardwood fibreboard and one type of loose wood fibre. The analysed wood includes recycled wood from RGS Nordic as well as plywood and sawnwood from Small Planet. All clay materials analysed are from Small Planet, and somewhat identical even though it is different types of clay; brown, red, and yellow clay, which is mined from different places. The variation between clay batches is very low, which correlates to the sources being very identical. The result of different sources of materials analysed in the experiment allows to identify the toxicity between related materials and assist in the choice of materials used for construction regarding embedded toxicity.

Six chemicals out of 30 could be characterised using the newest version of ILCD 2011 midpoint along with the newest version of USEtox. The characterisation factors were converted from CTUh to DALY using weighting factors, as mentioned in chapter 1.4.1.4. However, the weighting factors does not include age weighting and might, therefore, be higher than anticipated [62].

Only the characterised chemicals were found on Kemibrug.dk as health-damaging chemicals, which supports the characterisation factors present in the ILCD 2011 midpoint and the USEtox model [82]. The embedded human toxicity impact from the six characterised chemicals is assessed in DALY per kg emitted substance as the fraction of the global population being exposed to the chemicals emitted to air. The probability of getting an impact from the chemicals emitted from a product will depend on the population densities and how likely it is that somebody inhales these chemicals; this depends on how many people are being exposed ergo also the population density. A more substantial fraction of the population is exposed to the chemical in urban areas (HPD) compared to rural areas (LDP) [43]. It was expected to see, that chemicals being emitted to air in urban areas have a higher impact on human toxicity compared to chemicals being emitted to air in rural areas due to the density of the population. The results showed a highly increased human toxicity impact of emitted chemicals such as benzaldehyde, benzene, hexane, naphthalene, and furan, when a more substantial fraction of people is exposed to the emitted chemical. Exposure to pyridine does not increase as much when the exposed population increase, which could be influenced by how pyridine acts as a chemical [82]. Assessing the embedded human toxicity with the LPD and HPD exposure can only give an estimate of the human health impact on the fraction of the population exposed to the chemicals, not how the chemical is emitted or the human intake of the chemical. A high amount of chemical might be emitted from the building materials in the early stages of the material's lifetime [7]. If this is the case, the human toxicity impact of the building material could be more severe for construction workers and users than anticipated. Thereby, there is a gap between the assessment of embedded human toxicity and the real indoor and outdoor environment, which should be sought out to be closed in the future assessment of embedded toxicity.

Furthermore, it is interesting to gain knowledge upon the share of the six characterised chemicals compared to other chemicals emitted from the building material. Wood fibreboard has the highest embedded toxicity of the five materials per kg emitted substance, where 86 % of the total chemical profile comes from the impact of characterised chemicals. Wood and straw have the lowest embedded toxicity, where only 4 % of the total chemical profile influences the impact. It arises the question, whether the embedded human toxicity for straw and wood is even assessable when it only accounts for fractions of the total profile. It could be assumed that the embedded toxicity would be higher if it were possible to assess more of the identified chemicals with characterisation factors or if some of the subtracted chemicals were proven to also be present in the emitted substance.

Even though the experimental setup is not standardised, it is still possible to acquire the VOC profiles with reasonable confidence for each material. Eurofins, who also performs a test of toxic chemicals in materials, only acquire the total amount of VOC, as mentioned in chapter 1.4. Refinement and optimising of the method used in this project could assist the standardised Eurofins measurement of the total VOC-concentration [44]. Also, the embedded toxicity for building materials could be an essential knowledge to ensure the human-health risk is not increased when new materials or recycled materials are chosen for new construction [16]. The knowledge of embedded toxicity is also valuable for the disposal of the materials to avoid the release of embedded emissions to soil and groundwater when the materials are crushed or treated.

3.2. Embodied Toxicity

The third phase of the LCA is the LCIA, which in this study involves the conversion of data from the inventory analysis to the midpoint category human toxicity. The automated conversion of data from the inventory analysis by OpenLCA, is performed in two steps, the classification and characterisation [41]. The classification involves assigning the contribution effects by elementary flows to the impact category "human toxicity". The characterisation involves the determination of how much each elementary flow contributes to the assigned impact category of human toxicity. The characterisation factors for the impact category of human toxicity is given by the ILCD 2011 v.1.0.10 midpoint impact assessment method. The characterisation factors for human toxicity are divided into carcinogenic effects and non-carcinogenic effects.

The impact result from performing the classification and characterisation of the LCIA of all building materials, building component and external wall systems is given as a midpoint indicator for human toxicity in the unit CTUh per FU. The CTUh per FU is converted to DALY per functional, as mentioned in chapter 1.4.1.4. All results acquired by modelling in the OpenLCA software for the FU of each material level can be found in Appendix F.

3.2.1. Impact of 1 kg Singular Building Material

The impact of each singular building material during their life cycle (without use) is visualised in DALY per kg building material for carcinogenic and non-carcinogenic effects in Figure 21.

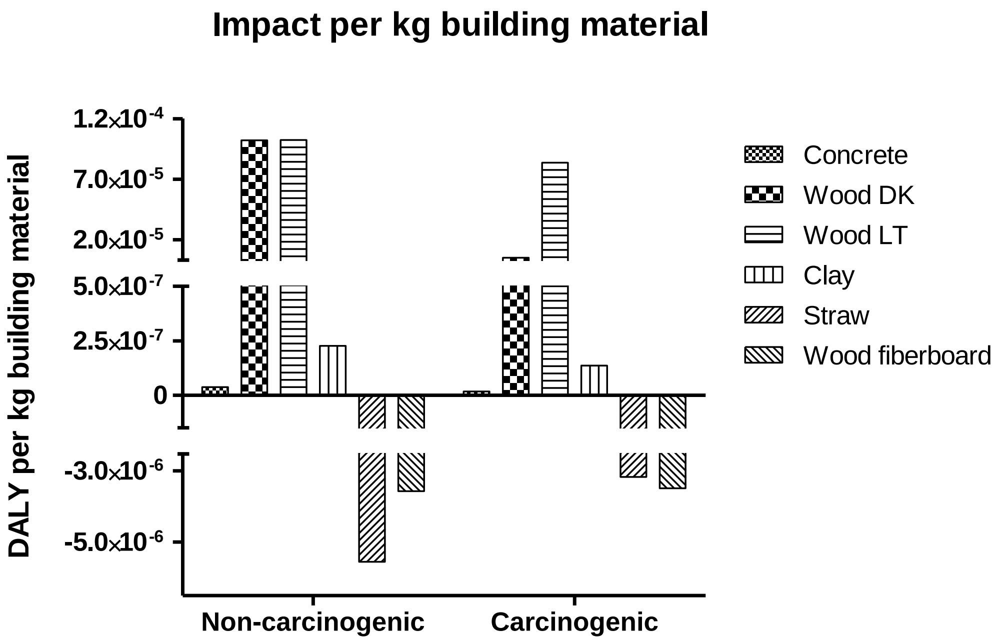

Figure 21 The embodied human toxicity impact of the whole life cycle for singular building materials

The impact for each material is given for carcinogenic and non-carcinogenic effects in the unit DALY per kg building material. The graph shows that Lithuanian wood (Wood LT) and Danish wood (Wood DK) have the highest impact of all materials modelled. Wood LT has a higher carcinogenic impact than Wood DK. Concrete has a lower impact than wood and clay, while straw and wood fibreboard has negative human toxicity impacts

The highest embodied impact per kg, when all building materials are compared, belongs to the modelled wood building materials, where the Wood LT (Lithuanian wood) has a higher impact than the Wood DK (Danish wood) regarding the impact on carcinogenic effects. Clay has a higher embodied toxicity than concrete, straw, and wood fibreboard. It is observed that 1 kg of both straw and wood fibreboard have a substantially negative impact on human toxicity regarding non-carcinogenic effects and carcinogenic effects. The OpenLCA results gives the impact contribution in percentage and CTUh of each life cycle stage, which is converted to DALY and put into tables (see Appendix F) to understand where the impact on human toxicity arises. For all modelled materials, the impact contribution in each stage comes from the emission of heavy metals to soil, water (groundwater or surface water) and air in low population density areas as well as emission to air in high population density areas [67]. The emitted heavy metals arise from the background processes needed for the different life cycle stages and contribute to the human toxicity impact. These include zinc (Zn), chromium (Cr), nickel (Ni), mercury (Hg), arsenic (As), lead (Pb), and barium (Ba) [67].

The total impact (sum of carcinogenic and non-carcinogenic effects) of concrete is 5.03E-08 DALY per kg concrete, which is divided into the three life cycle stages: production, transport, and EOL. 80 %, and thereby also the most substantial contribution to the human toxicity impact comes, from the production stage from the process “market for cement, Portland”, which includes all the background processes needed for mining of raw materials as well as the machines used. The transport of concrete with “freight, lorry 16-32 metric tons, EURO6” contributes approx. 40 % to the total impact, which includes background processes such as road construction and road wear along with the life cycle of a 16 metric ton lorry with maintenance and diesel. The contribution from recycling concrete on the EOL stage is approx. -20 %, which comes from the avoided process of mining gravel for new concrete [67]. The avoided processes lead to the avoided emission of heavy metals into the environment.

Wood is the material with the highest impact on human toxicity regarding both carcinogenic and non-carcinogenic, when compared to the other materials in Figure 21. The “market for sawnwood, softwood” contributes with 104 % of the total impact for wood produced in Lithuania, meaning it has a more substantial impact than the total life cycle impact for wood. The modelling of sawnwood production includes all background processes such as mining of naturally occurring phosphate rock for fertiliser production, chemicals used as pesticides as well as the life cycle of the machines used for harvesting and sawing. Wood production is a highly toxicity burdened process, which most often occurs in rural areas, where the use of fertilisers and pesticides can lead to soil and groundwater contamination [67]. The impact of transporting wood from Lithuania to Denmark only contributes with 0.16 %. The disposal of wood in municipal waste incineration leads to the avoided production of heat for the "market for heat, district or industrial", which causes the negative contribution of -4 % to the total human toxicity impact. The production of heat substitutes the heat production elsewhere, thereby being able to avoid the production of heat from, e.g. coal or heavy fuel oil [67].

The modelled Danish wood has a lower total embodied human toxicity impact (8.69E-06 DALY per kg wood DK) compared to the Lithuanian modelled wood (1.82E-04 DALY per kg wood LT). The only difference between the two is the transportation distance and the EOL scenario. Danish wood is recycled, thereby avoiding the production of new wood for the "market for sawnwood, softwood". During recycling "treatment of waste wood, post-consumer, sorting and shredding" leads to a substantial contribution (99.8 %) to the total life cycle impact. The impact comes from the sawmill and the machines needed. The transportation only accounts for 0.2 % of the total life cycle impact for Danish wood. The transportation contribution to human toxicity is visualised in the carcinogenic effects of wood DK and wood LT, where the only difference between the two materials is the distance of transportation, which is 100 km and 1,500 km, respectively. The transportation using EURO6 lorry is highly influenced by the amount of kg transported as well as the distance travelled [67].

The total human toxicity impact of clay is 3.64E-07 DALY per kg clay, where the different life cycle stages contribution is 16 % for the production stage, 83 % for the transportation stage, and less than 1 % for the EOL stage. The production of clay includes the "gravel and sand quarry operation", that requires energy for the machines used for the sorting. The transportation of clay contributes as much as the transportation of wood from Lithuania; however, the contribution (%) of transporting clay from Estonia is much higher when it is compared to the other life cycle stages for clay.

The total human toxicity impact of straw is -1.23E-05 DALY per kg straw, wherefore the contribution (in %) from the different life cycle stages symbolises a negative impact on human toxicity. The production of straw contributes with 46.7 % of the total impact of straw, which comes from the background processes needed to produce fertilisers, pesticides and the machines used for agriculture purposes. The transportation of straw from Lithuania to Denmark with "freight, lorry 16-32 metric tons, EURO6" influences the total impact of straw with -2.4 %. The disposal of straw in municipal waste incineration leads to the avoided production of heat for the "market for heat, district or industrial", which contributes with 54.5 % to the total human toxicity impact of straw [67].

Like straw, wood fibreboard also has a negative total human toxicity impact, which is -7.10E-06 DALY per kg wood fibreboard. Production of wood fibreboard contributes with -12 % of the total human toxicity impact, while the transportation and EOL contributes with -2 % and 114 %, respectively. The EOL of wood fibreboard has a profoundly negative impact on the human toxicity impact due to the municipal waste incineration that leads to the avoided production of heat for the "market for heat, district or industrial". The contribution by the production stage comes from processes including the production of wood and other raw materials, as well as factories and machinery needed to produce the wood fibreboard [67].

3.2.2. Impact of 1 m^3 Building Component

The impact of the building component during their life cycle (without use) is visualised in DALY per 1 m^3 building component for carcinogenic and non-carcinogenic effects in Figure 22.

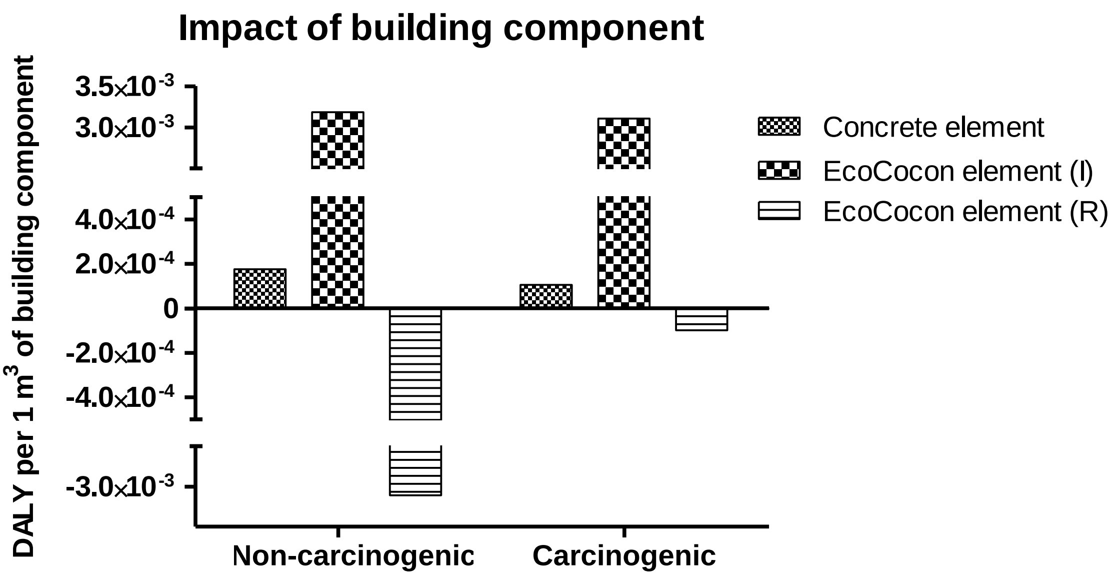

Figure 22 The embodied human toxicity impact of the whole life cycle for the building components.

The impacts of the building components are given for carcinogenic and non-carcinogenic effects in the unit DALY per 1 m^3 building component. The EcoCocon results is shown with either incineration (I) or recycling (R) of wood. The EcoCocon with incineration of wood has a larger human toxicity compared to the concrete element, while recycling of wood causes a negative human toxicity impact.

Figure 22 shows that the EcoCocon element with the incineration of wood (I) has a human toxicity impact of 6.29E-03 DALY per 1 m^3 EcoCocon element, which is higher than the human toxicity impact of the concrete element (2.83E-04 DALY per 1 m^3 concrete element). The impact contribution of each life cycle stage for the building components is calculated and put into tables see Appendix F. Like for 1 kg concrete, the 1 m^3 of concrete element has the same life cycle stage contribution (%) to the human toxicity impact, since the same processes are used for the modelling: 80 % production stage, 40 % transportation stage, and -20 % EOL stage.

The modelling of the EcoCocon element (I) consists of the same processes used for modelling wood and straw. The production of wood and straw contributes with 114.6 % and -0.12 %, respectively. The transportation stages contribute with 0.13 % and 0.31 %, respectively. The EOL stages of wood and straw contributes to the total impact with -4.91 % and -9.98 %, respectively. The processes that are included or avoided by the life cycle of straw and wood are described in chapter 3.2.1.

In Figure 22, the future EOL scenario for the wood in the EcoCocon element is shown. The future recycling of the wood changes the total embodied impact per 1 m^3 from 6.29E-03 DALY to -3.20E-03 DALY, since the recycling itself has a negative impact of -2.08E-02 DALY, which accounts as 650 % of the total contribution. The other life cycle stages of the EcoCocon element has the same embodied toxicity impact whether it is recycled or incinerated, the only difference is the contribution (%), which is -592 % for the production stage and -4 % for the transportation stage. The incineration of straw accounts for 85 % of the total contribution (%). Recycling wood in the EcoCocon benefit substantially because the production of wood for the EcoCocon is one of the processes with the highest embodied impact on human toxicity. Recycling the wood in the EcoCocon element causes a substantially lower embodied toxicity impact than the concrete element.

3.2.3. Impact of 1 m^3 Complete External Wall System

The impact results acquired by modelling of a 1.5 m^3 wall system is scaled down to 1 m^3 to make the results more accessible. The impact of each wall system during their life cycle (with use) is visualised in DALY per 1 m^3 wall system for carcinogenic and non-carcinogenic effects in Figure 23. Each life cycle stage contributes differently to the impact of each wall system, and these impact values can be found in Appendix F.

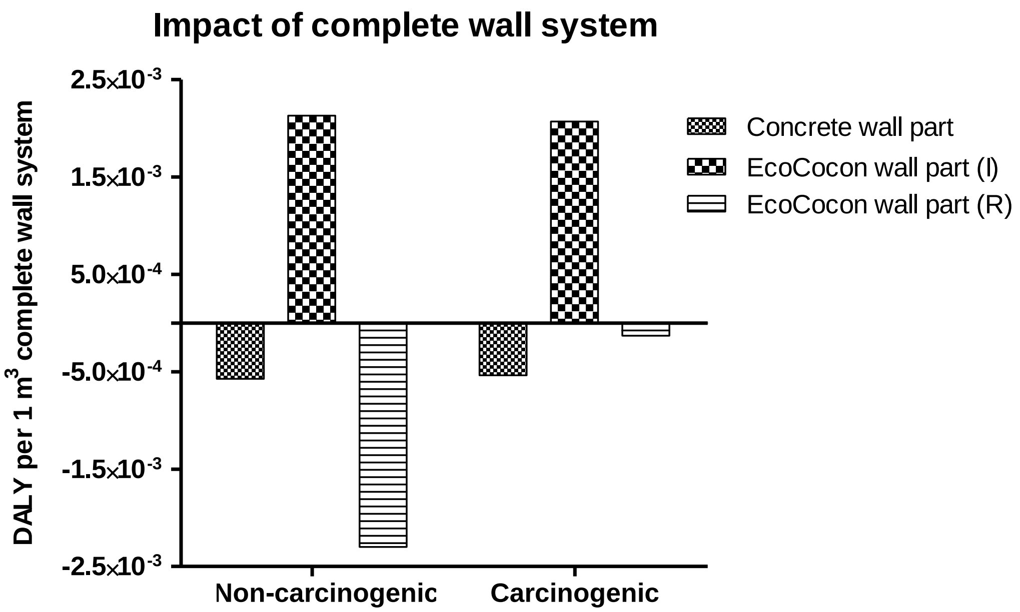

Figure 23 The embodied human toxicity impact of the whole life cycle of the complete wall systems.
The impacts for the building components are given for carcinogenic and non-carcinogenic effects in the unit DALY per 1 m^3 building component. The EcoCocon wall system results are shown with either incineration (I) or recycling (R) of wood. The complete EcoCocon wall system with the incineration of wood have a larger human toxicity compared to the concrete element. In contrast, recycling of wood causes a more substantial negative human toxicity impact than concrete.

The total human toxicity impact for the modelled external concrete wall system is -1.11E-03 DALY per 1 m^3 concrete wall system with insulation, inner and external cladding. The external concrete wall system has a meagre contribution to the human toxicity impact coming from the transport and use stage, which is -1 % and 0.1 %, respectively. Both production stage and disposal stage have substantial contributions, -358.25 % and 459.13 %, respectively. The negative impact of human toxicity of the external concrete wall system is influenced by the recycling of concrete, wood, REDAir BATTS, and the TYVEK/Siga breathable membrane, which avoids all the background processes needed in the production of new materials [67]. Incineration of wooden cladding leads to an essential contribution to the negative impact on human toxicity, since the process generates heat, thereby avoiding the heat production from other sources [67].

The total human toxicity impact per 1 m^3 external EcoCocon wall system with the incineration of wood is 4.15E-03 DALY and thereby substantially larger than the toxicity impact of 1 m^3 concrete external wall system. The impact contribution from the external EcoCocon wall system is very low for the transportation stage and use stage, which only contributes with 0.70 % and -0.01 %, respectively. The EOL stage contributes to the total human toxicity impact with -19 %, which arises from the recycling of the TYVEK/Siga breathable membrane, as well as the incineration of the EcoCocon element, wood fibreboard, and wood. The production stage contributes approximately 119 % to the total impact of the EcoCocon wall system, where the most considerable contribution comes from the wood production. In contrast, the straw production has a high negative contribution. The specific process included are described in detail in chapter 3.2.1.

In Figure 23, the future EOL scenario for the wood in the EcoCocon element is shown. The future recycling of wood changes the total embodied impact from 4.15E-03 DALY to -2.43E-03 DALY, since the recycling itself has a negative impact of -1.29E-02, which accounts as 634 % of the total contribution. The other life cycle stages of the external EcoCocon wall system has the same impact whether it is recycled or incinerated, the only difference is the contribution, which is -533 % for the production stage, -4 % for the transportation stage, and 0.03 % for the use stage. The recycling of wood has such an immense contribution because the production of wood for the EcoCocon is one of the processes with the highest impact on human toxicity [67]. Recycling the wood leads to an avoided production of wood for new building materials, which is a higher benefit than the benefit from the incineration of the wood [67]. When the wood in the EcoCocon wall is recycled, it has a lower embodied toxicity impact than the concrete wall.

3.2.4. Discussion of the Assessment of Embodied Toxicity

The embodied toxicity is the toxicological footprint of all the emissions that take place in the value chain. The embodied human toxicity impact for building materials have been assessed on three different levels: 1) building material, 2) building component, and 3) complete external wall system. The main contributors to the embodied human toxicity impact in all the modelled building materials are the background processes needed in each life cycle stage. Especially the disposal and the production stage have a strong influence on the total embodied human toxicity impact. In contrast, the transportation and maintenance of the materials causes substantially lower influence.

The results of the LCIA shows that 1 kg of wood has the highest impact compared to the four other building materials. In contrast, straw and wood fibreboard has negative impacts on human toxicity, meaning the total life cycles benefits the human toxicity, since embodied emissions from avoided processes can be avoided. However, the positive benefit on human toxicity comes from background processes, which does not necessarily have anything to do with the specific materials and therefore, overcompensating the benefit regarding human toxicity [67]. Concrete have a lower impact per kg material than clay. However, when the materials are scaled up to a complete constructed house, concrete will most likely have the highest contribution of the two materials to the total embodied toxicity of the house. Therefore, it is not only essential to know the embodied toxicity of 1 kg singular building material, but also for an integrated building component or a wall system of a constructed building.

A 1 m^3 EcoCocon component with straw and wood has a higher impact compared to a 1 m^3 concrete component. The impact of the EcoCocon component could differ if another EOL option were chosen, e.g. recycling instead of incineration. A substantially lower total human toxicity is shown when the wood of the external EcoCocon wall system is recycled instead of incinerated. Recycling of the wood causes the external EcoCocon wall system to perform better than the external concrete wall system.

The embodied toxicity results of building material are dependent on how the modelling is performed in OpenLCA. Firstly, the system boundaries set by the LCI framework have a strong influence, since choosing the cut-off or attributional approach instead of the consequential would result in entirely different human toxicity impacts [41]. For many of the materials modelled, there are huge advantages from the disposal stage, when recycling and incineration leads to avoided processes of producing new resources [67]. If the cut-off approach were used instead, all embodied impacts would be allocated to the primary user, and the avoided processes would not be accounted for in the total embodied impact [41]. It could be useful for comparison to model with an attributional or cut-off approach to gain knowledge of which framework best represent the embodied toxicity.

Secondly, the spatial and technological outreach of the assessment of embodied toxicity in building materials is only focused on the life cycle of materials produced in Europe, as well as used and disposed of in Denmark. The embodied toxicity will most likely be different for similar materials in other parts of the world due to the differences in the technology used and the electricity grid [41].

Thirdly, the data availability and quality of the data used for the modelling have a considerable influence on the results. To model the materials in OpenLCA, the search for foreground and background data as well as the assumptions and simplifications were necessary. Foreground data were collected from research literature, the internet, and product descriptions by ROCKWOOL, UKU, STEICO, and EcoCocon. The background data for the consequential processes is provided by the Ecoinvent v.3.4 in OpenLCA 1.10.2 [67]. Even though it covers more than 12,500 processes, these processes can, for instance, not assess FSC-certified wood, why the embodied toxicity impact for the wood used in the EcoCocon element can seem higher than it is. Unit processes were only chosen when the input and output of the system processes had to be changed to fit better, e.g. to the transport and the Danish electricity grid [67]. Most often, a country-specific or European provider of the process were chosen, since all processes are carried out in the European region; however, when this was not possible, the Swiss provider was chosen. Choosing a Swiss provider could influence the results. However, on the contrary, Switzerland is comparable to the European region, and it provides lower uncertainty than choosing a "Rest-of the-World"-provider [41][67].

The limitation of data is presented as the simplifications and assumptions used for the modelling of the building material's life cycle. The waste created during the life cycle of a material is neglected, along with the transportation to the production or disposal facility. Other simplifications and assumptions involve the consumer-behaviour, mining of raw materials and the different EOL scenarios. The simplifications and assumptions can cause high uncertainty on the results, since changing any of these parameters would also change the total embodied toxicity. E.g. the impact of the external wall systems is influenced by consumer-behaviour since many other types of external wall cladding exists such as aluminium and bricks. The walls are modelled to have the same outlook, function, and thermal resistance, therefore changing any of these parameters would also change the total embodied toxicity.

The heat generated from incineration of building materials can substitute the heat production elsewhere, thereby is it possible to avoid the production of heat from hard coal, heavy fuel oil, wood, and lignite (the market for heat) [67]. Many background processes are needed to produce these materials, and these lead to toxic emissions to the environment, which is highly influential on human toxicity. The avoided market for heat might be overcompensating the emissions since the Danish heat market is not chosen as the provider [67]. Furthermore, Denmark has planned to phase out the coal and lignite incineration by 2030, why the chosen Ecoinvent process for market for heat generation might contain more heat generated by coal and lignite than reality [84].

In the future, the EOL scenario of materials such as wood, wood fibreboard, and straw will most likely be recycling instead of incineration since there is an excellent encouragement for expanding circular economy and improvement of recycling technologies [6]. Also, the embodied toxicity impact of wood is lower when it is recycled compared to being incinerated. Therefore, recycling of wood should always be the first choice, while incineration should only be chosen if the wood is contaminated or damaged in a way, that it cannot be used. The straw and wood fibreboard already have a negative human toxicity impact; therefore, it should be calculated how recycling would influence the total human toxicity impact for the two materials. The EOL for other materials such as concrete and clay will most likely not change in the future; therefore, recycling, and inert landfill are the best available options.

3.3. Comparison of Embedded and Embodied Toxicity

The toxicological footprints of the concrete, wood, clay, straw, and wood fibreboard were modelled with a consequential framework using OpenLCA 1.10.2. The embodied toxicity includes all emissions caused by the background processes needed for the life cycle of the material. However, since the emitted amount of pollutants is unknown, it is not possible to quantify the embodied toxicity [41]. A way to assess the toxicity of the modelled building materials is by using the embedded toxicity. In Table 15, the human toxicity for all five materials (including two different origins of wood) is visualised for the embedded and embodied toxicity. The two types of toxicity are compared by calculating the breakeven point, which is when the embedded toxicity [DALY per kg emitted substance] is equal to the embodied toxicity [DALY per kg material].

Table 15 The breakeven point between the embedded and embodied toxicity

The breakeven point [kg emitted substance] between embedded toxicity [DALY per kg emitted substance] and embodied toxicity [DALY per kg material] of concrete, wood, clay, straw, and wood fibreboard (W.F). The breakeven point is when the embedded toxicity is equal to the embodied toxicity. The embodied toxicity for wood is shown as Danish wood (DK) and Lithuanian wood (LT).

	Concrete	Wood DK	Wood LT	Clay	Straw	W.F
Average embedded human toxicity [DALY per kg emitted substance]	3.68E-6	5.98E-7	5.98E-7	2.69E-6	1.77E-6	1.68E-4
Total embodied toxicity [DALY per kg material]	5.03E-8	8.69E-6	1.82E-4	3.64E-7	-1.22E-5	-7.06E-6
Breakeven point [kg emitted substance]	1.37E-2	1.45E+1	3.04E+2	1.35E-1	-6.89E+0	-4.21E-2

More specific the breakeven point is the kg of emitted substance needed to be equal to the total toxicity throughout the value chain of 1 kg material. If the breakeven point for each material is exceeded, the embedded toxicity [DALY per kg emitted substance] would be higher than the embodied toxicity [DALY per kg material]. Therefore, to exceed the embodied toxicity of 1 kg concrete, more than 0.0137 kg of emitted substance is necessary. On the other hand, more than 14.5 kg emitted substance of wood or 304.2 kg emitted substance of wood is needed to exceed the embodied toxicity of 1 kg Danish or Lithuanian wood, respectively. More than 0.135 kg of emitted substance of clay is needed to exceed the embodied toxicity of 1 kg clay.

A negative amount of emitted substance is needed for straw and wood fibreboard, since they both have negative total embodied toxicity which primarily comes from the disposal, where the materials are incinerated to produce heat. If the EOL for wood fibreboard were not considered, there would be a positive embodied toxicity impact of 1.07E-06 DALY per kg material. Thereby, a little more than 0.0064 kg emitted substance from the wood fibreboard would be needed to exceed the embodied toxicity impact of the production and transportations stage of wood fibreboard. The consequential framework of the modelling and the incineration plays a large role on the impact. Furthermore, it is not possible to assess the embodied toxicity of straw and wood fibreboard using the embedded toxicity when the embodied toxicity is negative, since the embedded toxicity will always be higher. The embodied toxicity of wood is substantially higher than all the other materials and certainly also high, considering that wood has the lowest embedded toxicity of all materials analysed. It is possible that choosing a different LCI framework, could lead to embodied toxicity results for all material, which are more comparable with the embedded toxicity.

3.4. Circular economy and chemical emission from building materials

The construction sector is one of the most resource-consuming sectors, which it will continue to be until the resource use is changed from a linear to a circular economy approach, where the use of resources is minimised, and waste is eliminated by increasing the reuse and recycling of resources in a continuous cycle [6]. The embedded human toxicity of new and recycled materials can be a problem to human health since chemicals are being emitted into the environment, which can be taken up by human respiration. At the same time, it is known that people spend on average 80-90 % of their time indoors, where bad IAQ is increasing the effects of the chemicals emitted from building materials [14]. Bad IAQ is a substantial problem for energy-efficient buildings, where indoor air ventilation is reduced. It is not possible to stop using materials with either an embedded or embodied toxicity, since there will always be some toxicity present, as well as a toxicological footprint throughout the value chain. Therefore, the first option should always be to recycle building materials since it will avoid pollution from the background processes needed for the generation of new materials. If the embedded toxicity of a material is known, it would be possible to strip or "clean" the material from chemicals, that provides a human-health risk, before recycling.

To lower the exposure of chemicals emitted from building materials technologies such as indoor air treatment devices have been suggested by [26]. The devices can reduce the concentration of some IAQ pollutants as well as viable particulate matter such as microorganisms by photocatalytic oxidation using TiO_2 [26]. Other strategies will be to strip materials from the most toxic contaminants before recycling in new building materials, e.g. the Danish company "Gamle Mursten" which cleans and upcycles bricks [85].

The indoor environment and human exposure to chemicals cannot be assessed through OpenLCA. However, using OpenLCA is the best way to get a compatible modelling principle [41]. Embodied and embedded toxicity is the closest to understand the indoor environment. However, the embodied toxicity involves both the direct and indirect impact, thereby also accounting for processes, which might not even be a part of the product system, e.g. avoided heat generation from coal and lignite [67]. The processes might also occur on different continents, why embodied toxicity is not very present or compatible with embedded toxicity, which consists of the direct and indirect exposure from a product. It is not possible to relate the embedded and embodied toxicity when the embodied toxicity is negative because of avoided emissions. Further research needs to be performed to be able to relate the embedded and embodied toxicity as well as using one of the two as an indicator for the other.

If the impact from the chemical emission to the indoor environment could be calculated instead of emission to rural or urban areas, it would be easier to relate the embedded toxicity for building materials to human exposure in an indoor environment. The embedded toxicity impact would most likely be lower, since a smaller fraction of people would be exposed to the chemicals. Exposure models could be a way of closing the gap between the estimated embedded toxicity and how much chemical people would be exposed to both indoor and outdoor [37][38]. The exposure models for each characterised chemical can help assess whether using and recycling the materials would influence human health. The combination of embedded toxicity and exposure models could lead the way to a modelling principle, that makes it possible to account for the embedded toxicity of materials.

Furthermore, the results of the embedded and embodied human toxicity can benefit in the design and production stage of future building materials as well as play a role in the choice of the material used for construction. Also, the results of embodied toxicity could help assist in lowering the polluting human toxicity across the value chain of new or existing materials.

4. Future Perspective

The further study on embedded and embodied toxicity of building materials with a circular economy approach has been funded by "Aase og Ejner Danielsens Fond". It will be performed in collaboration with Henning Larsen Architects A/S and RGS Nordic A/S. Both collaborators contribute to the pioneering work (and possible problems) in the field of circular economy in construction, and both have shown great interest in working with me on this project. Henning Larsen Architects A/S is interested in developing a model for the combined determination of embedded toxicity in building materials intended for recycling.

Throughout the further study, the following work is planned:

- The chromatograms from the GC-MS analysis should be examined again. Unidentified peaks could belong to compounds not available in the NIST library; therefore, creating a standard curve with alkanes on their Kovats-index/retention-index could be a way to identify more chemicals [86].
- Another way to improve the experiment would be to extract VOCs from the materials with hexane/acetyl acetate. A 1 mL syringe with the extracted sample would be inserted into GC-MS, and if this gives a similar chromatogram as with the fiber, it would be possible to perform automatic GC-FID. GC-FID has even better sensitivity and quantification than the GC-MS [49].
- The final data will be quantified as the exact weight of the emitted chemical per kg building material by creating a standard curve for all chemicals identified.
- The embodied toxicity should be modelled using other system boundaries and LCI framework to understand which modelling type gets closer to the embedded toxicity and reality. Future EOL scenarios for straw and wood fibreboard should also be modelled. Avoided processes and background processes could also be searched deeper to find potential problems.
- Exposure models for all characterised chemicals should be created to calculate how much chemical people would be exposed to both indoor and outdoor to assess whether the use and recycling of the materials would influence human health [38].
- The outcome of the further study is to use the new data on the embedded and embodied toxicity of building materials as well as exposure modelling of the chemicals for a paper describing the relationship between embedded and embodied toxicity of new and recycled building materials.

5. Conclusion

The aim of this master project was to assess the human health risk of chemical emission from both new and recycled building materials. The human toxicity of building materials such as concrete, wood, clay, straw, and wood fibreboard were assessed using two different assessment methods: Embodied and embedded toxicity. The embodied toxicity was modelled using OpenLCA 1.10.2 for three levels of materials: building materials, building components and constructed wall system. The embedded toxicity of the materials was extracted using SPME-fibers, analysed and quantified using GC-MS and characterised using ILCD 2011 characterisation factors.

The following can be concluded from the assessment of chemical emissions of building materials:

- The embedded human toxicity per kg emitted substance is highest for wood fibreboard and lowest for wood, while the life cycle of 1 kg wood has the highest contribution to the embodied human toxicity impact
- The embodied human toxicity impact for straw and wood fibreboard is negative, meaning the background processes used in the life cycle of the two materials are avoided processes, that would have contributed to a high embodied human toxicity impact
- Recycling of wood in the EcoCocon element is substantially lowering the embodied human toxicity impact compared to incineration; therefore, recycling should always be the first choice even if the materials have a large embedded toxicity, and incineration should only be considered if the materials cannot be stripped of contaminants or properly recycled
- Embedded toxicity is, for the most part, lower than embodied toxicity; however, the embodied toxicity can be negative. This points towards the embedded and embodied toxicity are not relatable, since embodied toxicity include all direct/indirect toxicological impacts throughout the value chain, while the embedded only consist of the direct/indirect exposure from a product.
- Embedded toxicity is a better method for describing the consumer health-related toxicity of material compared to the embodied toxicity, that possibly accounts for emissions occurring far away from the consumer.
- The embedded and embodied human toxicity can benefit in the design and production stage of future building materials as well as play a role in the choice of material used for construction to lower the polluting human toxicity across the value chain of materials

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Appendices

Appendix A Sampling of Materials and Batch Pictures

Appendix figure A Sampling site at RGS Nordic with different piles of concrete aggregates, massive concrete pillars, wood, and the machines used to crush the concrete


Appendix figure B
Concrete batch 1


Appendix figure C
Concrete batch 2


Appendix figure D
Concrete batch 3


Appendix figure E
Concrete batch 4


Appendix figure F
Concrete batch 5


Appendix figure G
Concrete batch 6


Appendix figure H
Concrete batch 7


Appendix figure I
Concrete batch 8


Appendix figure J
Concrete batch 9

Appendix figure K
Concrete batch 10

Appendix figure L
Wood batch 1

Appendix figure M
Wood batch 2+3

Appendix figure N
Clay batch 1-3

Appendix figure O
Straw batch 1-5

Appendix figure P
Wood fibreboard batch 1

Appendix figure Q
Wood fibreboard batch 2

Appendix figure R
Loose wood fibre batch 3

Appendix B Quantification of Chemicals Present in Each Material

Concrete

Appendix table 1 Identified and quantified GC-MS results for concrete batch 1-10 per kg emitted substance

For each replicate, the following is given: Area under the peak (Area, unitless), % of the total amount of chemical substances identified in the analysed sample (%), and the weight of chemical substance per kg emitted substance (per kg).

	1.1			1.2			1.3		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	2.8E+06	3%	2.9E-02	3.9E+05	1%	6.0E-03	0	0%	0
Benzaldehyde	6.3E+06	7%	6.5E-02	3.5E+06	5%	5.1E-02	4.4E+06	5%	4.6E-02
Pyridine	5.9E+06	6%	6.1E-02	0	0%	0	0	0%	0
Decane	4.3E+06	4%	4.4E-02	2.3E+06	3%	3.4E-02	5.4E+06	6%	5.7E-02
Undecane	1.3E+07	13%	1.3E-01	0	0%	0	0	0%	0
10 methylnonadecane	2.1E+07	21%	2.1E-01	0	0%	0	1.1E+07	11%	1.1E-01
Tridecane	2.0E+07	21%	2.1E-01	2.4E+07	35%	3.5E-01	2.7E+07	29%	2.9E-01
Tetradecane	1.3E+07	13%	1.4E-01	1.9E+07	28%	2.8E-01	2.3E+07	24%	2.4E-01
Pentadecane	8.1E+06	8%	8.4E-02	1.3E+07	19%	1.9E-01	1.6E+07	16%	1.7E-01
Hexadecane	2.6E+06	3%	2.7E-02	6.2E+06	9%	9.0E-02	9.0E+06	10%	9.5E-02

	2.1			2.2			2.3		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	1.3E+06	29%	2.9E-01	7.3E+05	10%	9.9E-02	1.3E+06	17%	1.7E-01
Tridecane	1.0E+06	21%	2.1E-01	1.6E+06	22%	2.2E-01	2.4E+06	32%	3.2E-01
Tetradecane	1.3E+06	28%	2.8E-01	1.9E+06	26%	2.6E-01	2.1E+06	28%	2.8E-01
Pentadecane	4.6E+05	10%	9.9E-02	7.5E+05	10%	1.0E-01	1.4E+06	19%	1.9E-01
Hexadecane	5.7E+05	12%	1.2E-01	0	0%	0	0	0%	0
1-Heptene	0	0%	0	5.9E+05	8%	8.1E-02	0	0%	0
3-Heptene-2.6-dione	0	0%	0	9.5E+05	13%	1.3E-01	0	0%	0
2.4-Hexadienedioic acid	0	0%	0	7.7E+05	11%	1.1E-01	0	0%	0
Hexane	0	0%	0	0	0%	0	2.5E+05	3%	3.3E-02

	3.1			3.2			3.3		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	7.7E+04	0%	4.0E-03	2.6E+06	9%	9.4E-02	1.5E+05	1%	1.2E-02
Undecane	1.8E+06	9%	8.6E-02	1.0E+07	38%	3.9E-01	2.7E+06	22%	2.2E-01
Tridecane	4.4E+06	22%	2.2E-01	2.6E+06	9%	9.5E-02	2.5E+06	21%	2.1E-01
Tetradecane	7.3E+06	36%	3.6E-01	2.0E+06	7%	7.2E-02	2.4E+06	20%	2.0E-01
Pentadecane	6.0E+06	29%	2.9E-01	5.1E+06	19%	1.9E-01	3.5E+06	29%	3.0E-01
Hexadecane	5.0E+05	2%	2.4E-02	1.1E+05	0%	4.0E-03	3.6E+05	3%	3.0E-02
1-Heptene	3.6E+05	2%	1.8E-02	8.9E+05	3%	3.3E-02	1.9E+05	2%	1.6E-02
1H-Naphthalen-2-one	0	0%	0	3.6E+06	13%	1.3E-01	2.4E+05	2%	2.0E-02

	4.1			4.2			4.3		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**

Benzene	8.5E+05	1%	9.0E-03	1.1E+06	33%	3.3E-01	0	0%	0
Benzaldehyde	8.2E+06	9%	8.7E-02	9.4E+04	3%	2.8E-02	6.4E+05	10%	9.7E-02
Undecane	1.5E+07	16%	1.6E-01	4.7E+05	14%	1.4E-01	2.5E+06	38%	3.8E-01
Pentadecane	3.7E+06	4%	3.9E-02	1.8E+05	5%	5.4E-02	2.3E+06	35%	3.5E-01
1-Heptene	4.2E+07	44%	4.4E-01	7.5E+05	22%	2.2E-01	3.1E+05	5%	4.7E-02
1H-Naphthalen-2-one	2.5E+07	27%	2.7E-01	7.9E+05	23%	2.3E-01	7.9E+05	12%	1.2E-01

	5.1			**5.2**			**5.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	1.3E+06	23%	2.3E-01	1.3E+06	23%	2.3E-01	1.3E+06	23%	2.3E-01
Benzaldehyde	3.1E+05	5%	5.4E-02	3.1E+05	5%	5.4E-02	3.1E+05	5%	5.4E-02
Undecane	7.7E+05	13%	1.3E-01	7.7E+05	13%	1.3E-01	7.7E+05	13%	1.3E-01
Pentadecane	1.3E+06	22%	2.2E-01	1.3E+06	22%	2.2E-01	1.3E+06	22%	2.2E-01
1-Heptene	8.1E+05	14%	1.4E-01	8.1E+05	14%	1.4E-01	8.1E+05	14%	1.4E-01
1H-Naphthalen-2-one	1.3E+06	22%	2.2E-01	1.3E+06	22%	2.2E-01	1.3E+06	22%	2.2E-01

	6.1			**6.2**			**6.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	9.8E+04	8%	7.6E-02	1.5E+06	3%	3.3E-02	5.9E+05	12%	1.3E-01
Benzaldehyde	1.7E+05	13%	1.3E-01	2.8E+06	6%	6.3E-02	2.4E+05	5%	5.0E-02
Undecane	3.5E+05	27%	2.7E-01	1.0E+07	23%	2.3E-01	1.1E+06	23%	2.3E-01
Pentadecane	3.6E+05	28%	2.8E-01	1.9E+07	42%	4.3E-01	1.8E+06	39%	3.9E-01
1-Heptene	2.4E+05	18%	1.8E-01	3.1E+05	1%	7.0E-03	3.4E+05	7%	7.1E-02
1H-Naphthalen-2-one	8.5E+04	7%	6.6E-02	1.1E+07	24%	2.4E-01	6.4E+05	13%	1.3E-01

	7.1			**7.2**			**7.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	3.9E+05	14%	1.4E-01	3.9E+05	14%	1.4E-01	4.5E+05	6%	6.1E-02
Benzaldehyde	1.5E+06	51%	5.1E-01	1.5E+06	51%	5.1E-01	1.9E+06	25%	2.5E-01
Undecane	1.8E+05	6%	6.1E-02	1.8E+05	6%	6.1E-02	3.7E+06	50%	5.0E-01
Pentadecane	6.2E+05	21%	2.2E-01	6.2E+05	21%	2.2E-01	1.2E+06	16%	1.6E-01
1-Heptene	2.2E+05	8%	7.5E-02	2.2E+05	8%	7.5E-02	1.5E+05	2%	2.1E-02

	8.1			**8.2**			**8.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	6.8E+05	3%	3.2E-02	4.5E+05	6%	6.1E-02	2.8E+05	11%	1.1E-01
Benzaldehyde	1.9E+06	9%	8.7E-02	1.9E+06	25%	2.5E-01	2.0E+05	8%	7.8E-02
Undecane	4.4E+06	21%	2.1E-01	3.7E+06	50%	5.0E-01	1.2E+06	46%	4.6E-01
Pentadecane	1.4E+07	66%	6.6E-01	1.2E+06	16%	1.6E-01	7.4E+05	29%	2.9E-01
1-Heptene	2.3E+05	1%	1.1E-02	1.5E+05	2%	2.1E-02	1.5E+05	6%	6.0E-02

	9.1			**9.2**			**9.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	1.1E+05	10%	1.0E-01	1.1E+05	10%	1.0E-01	1.1E+05	10%	1.0E-01
Benzaldehyde	1.3E+05	12%	1.2E-01	1.3E+05	12%	1.2E-01	1.3E+05	12%	1.2E-01
Undecane	1.1E+05	10%	1.1E-01	1.1E+05	10%	1.1E-01	1.1E+05	10%	1.1E-01
Pentadecane	9.2E+04	8%	8.4E-02	9.2E+04	8%	8.4E-02	9.2E+04	8%	8.4E-02
1-Heptene	2.0E+05	18%	1.8E-01	2.0E+05	18%	1.8E-01	2.0E+05	18%	1.8E-01

1H-Naphthalen-2-one	4.4E+05	40%	4.0E-01	4.4E+05	40%	4.0E-01	4.4E+05	40%	4.0E-01
	10.1			**10.2**			**10.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	4.3E+04	5%	4.7E-02	8.0E+04	9%	8.6E-02	5.8E+04	6%	5.6E-02
Benzaldehyde	8.8E+04	10%	9.6E-02	8.8E+04	9%	9.5E-02	9.8E+04	9%	9.4E-02
Undecane	4.6E+05	50%	5.0E-01	4.0E+05	43%	4.3E-01	5.1E+05	49%	4.9E-01
Pentadecane	2.6E+05	29%	2.9E-01	2.8E+05	30%	3.0E-01	2.5E+05	24%	2.4E-01
1-Heptene	6.1E+04	7%	6.7E-02	8.7E+04	9%	9.4E-02	1.2E+05	12%	1.2E-01

Wood

Appendix table 2 Identified and quantified GC-MS results for wood batch 1-3 per kg emitted substance

For each replicate, the following is given: Area under the peak (Area, unitless), % of the total amount of chemical substances identified in the analysed sample (%), and the weight of chemical substance per kg emitted substance (per kg).

	1.1			**1.2**			**1.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
2-Norpinene	3.2E+07	33%	3.3E-01	3.2E+07	33%	3.3E-01	3.1E+06	40%	4.0E-01
2(10)-Pinene	2.2E+07	23%	2.3E-01	2.2E+07	23%	2.3E-01	0	0%	0
Cyclohexene	1.9E+07	20%	2.0E-01	1.9E+07	20%	2.0E-01	8.5E+05	11%	1.1E-01
à-Terpinen	3.2E+06	3%	3.3E-02	3.2E+06	3%	3.3E-02	0	0%	0
à-Terpineol	1.8E+07	19%	1.9E-01	1.8E+07	19%	1.9E-01	0	0%	0
Naphthalene	2.0E+06	2%	2.1E-02	2.0E+06	2%	2.1E-02	0	0%	0
3-carene	0	0%	0	0	0%	0	3.7E+06	49%	4.9E-01
	2.1			**2.2**			**2.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
2-Norpinene	2.9E+05	8%	7.6E-02	2.0E+07	93%	9.3E-01	1.6E+05	6%	6.2E-02
2(10)-Pinene	2.0E+06	52%	5.2E-01	1.1E+06	5%	4.9E-02	1.8E+06	69%	7.0E-01
Hexanal	1.5E+06	41%	4.1E-01	4.9E+05	2%	2.3E-02	6.2E+05	24%	2.4E-01
	3.1			**3.2**			**3.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
2-Norpinene	2.0E+07	38%	3.8E-01	6.2E+06	35%	3.5E-01	2.0E+07	38%	3.8E-01
2(10)-Pinene	1.0E+07	20%	2.0E-01	2.9E+06	17%	1.7E-01	1.0E+07	20%	2.0E-01
Cyclohexene	1.1E+07	22%	2.2E-01	2.6E+06	15%	1.5E-01	1.1E+07	22%	2.2E-01
3-carene	7.9E+05	1%	1.4E-02	2.1E+05	1%	1.2E-02	7.9E+05	1%	1.5E-02
Hexanal	6.4E+05	1%	1.2E-02	5.6E+05	3%	3.2E-02	6.4E+05	1%	1.2E-02
à-Longipinene	2.2E+06	4%	4.2E-02	1.2E+06	7%	7.0E-02	2.2E+06	4%	4.2E-02
Bornylacetate	4.6E+05	1%	9.0E-03	1.8E+05	1%	1.0E-02	4.6E+05	1%	9.0E-03
Ylangene	8.2E+05	2%	1.5E-02	5.1E+05	3%	2.9E-02	8.2E+05	2%	1.5E-02
1H-Cyclopropa [a]-naphthalene	3.3E+06	6%	6.3E-02	1.9E+06	11%	1.1E-01	3.3E+06	6%	6.3E-02
Naphthalene	2.5E+06	5%	4.8E-02	1.3E+06	7%	7.4E-02	2.5E+06	5%	4.8E-02

Clay

Appendix table 3 Identified and quantified GC-MS results for clay batch 1-3 per kg emitted substance

For each replicate, the following is given: Area under the peak (Area, unitless), % of the total amount of chemical substances identified in the analysed sample (%), and the weight of chemical substance per kg emitted substance (per kg).

	1.1			1.2			1.3		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	2.8E+05	80%	8.1E-01	2.5E+05	71%	7.1E-01	2.3E+05	73%	7.3E-01
2-oxo-4-phenyl-6-(4-chlorophenyl)-1,2-dihydropyrimidine	6.8E+04	20%	2.0E-01	1.0E+05	29%	2.9E-01	8.7E+04	27%	2.7E-01
	2.1			**2.2**			**2.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	2.5E+05	65%	6.5E-01	6.3E+05	72%	7.2E-01	3.5E+05	76%	7.6E-01
2-oxo-4-phenyl-6-(4-chlorophenyl)-1,2-dihydropyrimidine	1.3E+05	35%	3.5E-01	1.4E+05	16%	1.6E-01	1.1E+05	24%	2.4E-01
Camphene	0	0%	0	1.1E+05	12%	1.2E-01	0	0%	0
	3.1			**3.2**			**3.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Benzene	5.2E+05	78%	7.8E-01	6.3E+05	79%	7.9E-01	5.7E+05	77%	7.7E-01
2-oxo-4-phenyl-6-(4-chlorophenyl)-1,2-dihydropyrimidine	1.5E+05	22%	2.2E-01	1.7E+05	21%	2.1E-01	1.7E+05	23%	2.3E-01

Straw

Appendix table 4 Identified and quantified GC-MS results for straw batch 1-5 per kg emitted substance

For each replicate, the following is given: Area under the peak (Area, unitless), % of the total amount of chemical substances identified in the analysed sample (%), and the weight of chemical substance per kg emitted substance (per kg).

	1.1			1.2			1.3		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
2-Pentene	9.3E+05	16%	1.6E-01	0	0%	0	0	0%	0
1-Hexanone	4.4E+05	7%	7.5E-02	0	0%	0	0	0%	0
3-Acetyl-2,5-dimethyl furan	3.6E+06	61%	6.1E-01	0	0%	0	0	0%	0
2-Pentadecanone	8.9E+05	15%	1.5E-01	8.9E+05	33%	3.3E-01	4.5E+06	80%	8.1E-01
Nonadecane	0	0%	0	6.0E+05	23%	2.3E-01	3.2E+05	6%	5.7E-02
Hexadecane	0	0%	0	4.9E+05	19%	1.9E-01	0	0%	0
Undecane	0	0%	0	6.7E+05	25%	2.5E-01	2.9E+05	5%	5.2E-02
1-H-Napthalen-2-one	0	0%	0	0	0%	0	4.8E+05	9%	8.6E-02
	2.1			**2.2**			**2.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
3-Acetyl-2,5-dimethyl furan	1.0E+06	30%	3.0E-01	7.7E+04	3%	3.1E-02	8.6E+05	14%	1.4E-01
2-Pentadecanone	2.3E+06	68%	6.8E-01	2.0E+06	79%	7.9E-01	3.5E+06	55%	5.5E-01
Nonadecane	7.6E+04	2%	2.2E-02	4.4E+05	18%	1.8E-01	2.6E+05	4%	4.2E-02
1-H-Napthalen-2-one	0	0%	0	0	0%	0	1.7E+06	27%	2.7E-01
	3.1			**3.2**			**3.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
3-Acetyl-2,5-dimethyl furan	1.1E+06	21%	2.1E-01	1.7E+06	13%	1.3E-01	1.3E+06	25%	2.5E-01

2-Pentadecanone	4.2E+06	77%	7.7E-01	1.3E+06	10%	9.7E-02	1.9E+06	35%	3.5E-01
Nonadecane	0	0%	0	2.5E+06	19%	1.9E-01	2.1E+06	40%	4.0E-01
Undecane	0	0%	0	7.5E+06	58%	5.8E-01	0	0%	0
1-H-Napthalen-2-one	1.2E+05	2%	2.2E-02	0	0%	0	0	0%	0
	4.1			**4.2**			**4.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
2-Pentene	4.2E+05	18%	1.8E-01	8.2E+05	7%	7.1E-02	1.2E+06	12%	1.2E-01
1-Hexanone	0	0%	0	2.0E+05	2%	1.8E-02	3.9E+05	4%	4.1E-02
2-Pentadecanone	1.4E+06	58%	5.8E-01	2.4E+06	20%	2.0E-01	3.5E+06	36%	3.6E-01
Nonadecane	2.3E+05	10%	9.8E-02	0	0%	0	0	0%	0
Undecane	3.5E+05	15%	1.5E-01	0	0%	0	0	0%	0
1,3-Benzenediol	0	0%	0	8.2E+06	71%	7.1E-01	4.6E+06	47%	4.8E-01
	5.1			**5.2**			**5.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
2-Pentene	1.4E+05	2%	2.0E-02	3.4E+05	7%	6.9E-02	0	0%	0
2-Pentadecanone	2.7E+06	40%	4.0E-01	1.1E+06	22%	2.2E-01	3.4E+06	100%	1.0E+00
Nonadecane	6.4E+05	9%	9.4E-02	2.7E+05	6%	5.5E-02	0	0%	0
Undecane	3.3E+06	49%	4.9E-01	3.2E+06	66%	6.6E-01	0	0%	0

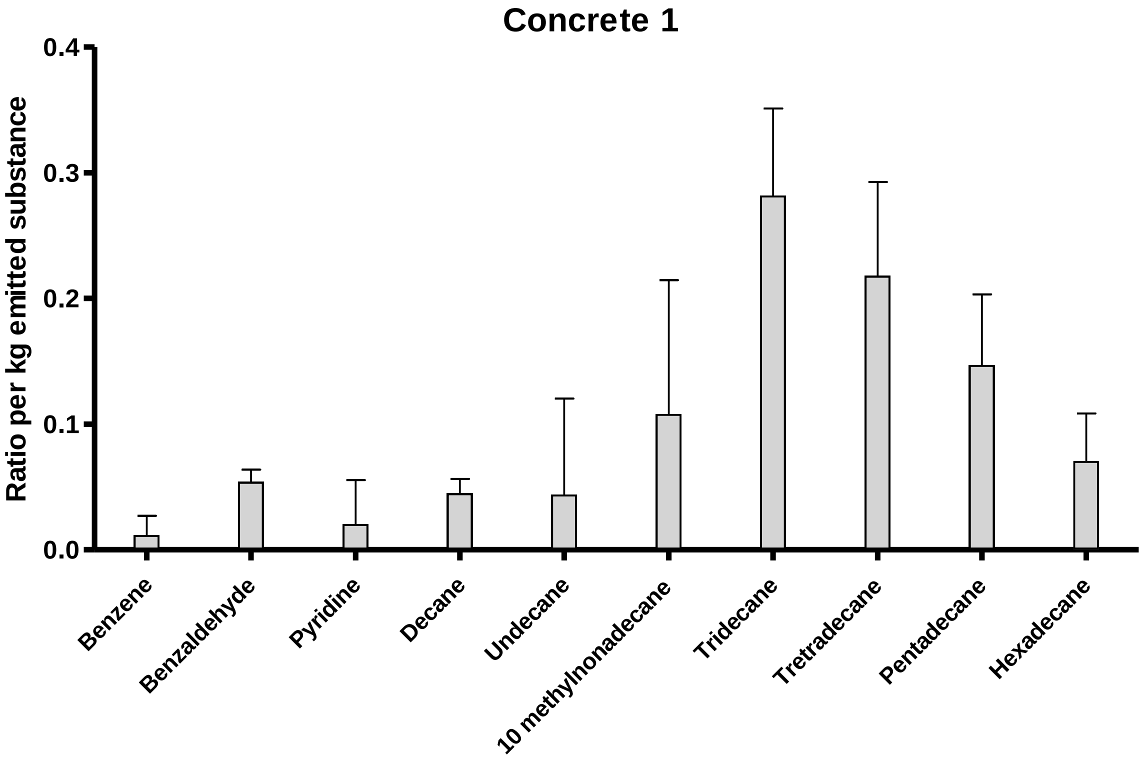
Wood Fibreboards

Appendix table 5 Identified and quantified GC-MS results for wood fibreboard batch 1-3 per kg emitted substance

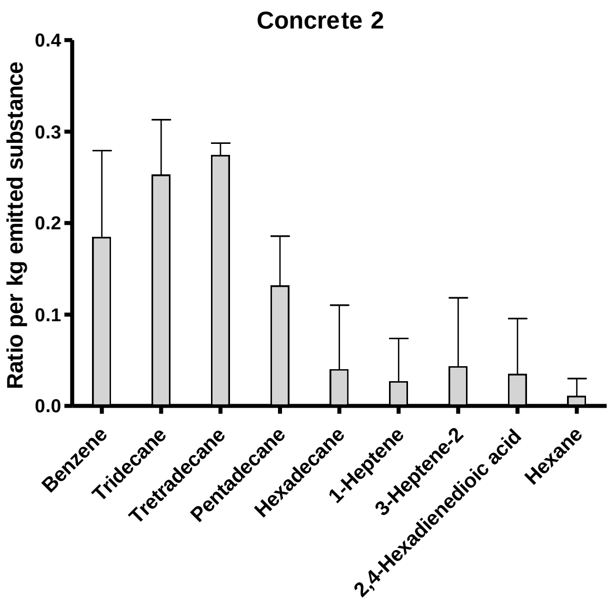
For each replicate, the following is given: Area under the peak (Area, unitless), % of the total amount of chemical substances identified in the analysed sample (%), and the weight of chemical substance per kg emitted substance (per kg).

	1.1			**1.2**			**1.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Hexanal	3.1E+05	25%	2.5E-01	3.1E+05	25%	2.5E-01	3.3E+05	35%	3.5E-01
Bicyclo[3.1.0]hex-2-ene, 2-methyl-5-(1-methylethyl)-	1.7E+05	14%	1.4E-01	1.7E+05	14%	1.4E-01	7.4E+04	8%	7.9E-02
Furan, 2-pentyl-	7.6E+05	61%	6.1E-01	7.6E+05	61%	6.1E-01	5.4E+05	57%	5.8E-01
	2.1			**2.2**			**2.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Pyridine	1.0E+06	36%	3.7E-01	2.0E+05	12%	1.2E-01	5.1E+05	23%	2.3E-01
1,3-Benzenediol	1.8E+06	64%	6.4E-01	1.4E+06	88%	8.8E-01	1.7E+06	77%	7.7E-01
	3.1			**3.2**			**3.3**		
Compound	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**	**Area**	**%**	**per kg**
Hexanal	1.0E+05	30%	3.0E-01	1.3E+05	42%	4.2E-01	1.2E+05	39%	3.9E-01
Furan, 2-pentyl-	2.3E+05	70%	7.0E-01	1.8E+05	58%	5.8E-01	1.9E+05	61%	6.1E-01

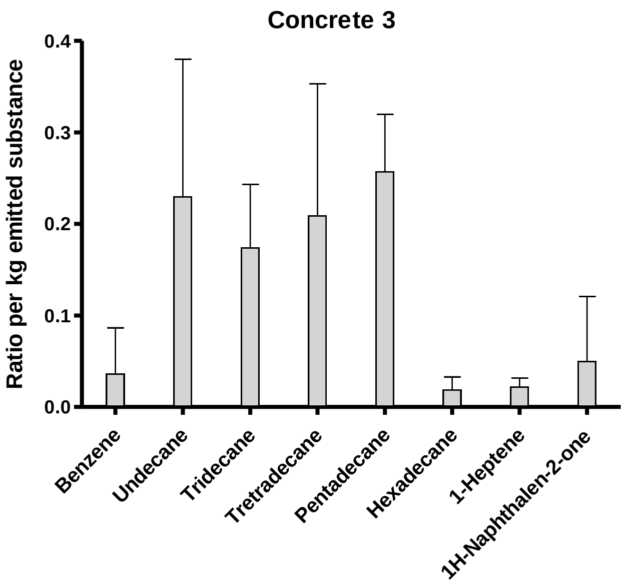
Appendix C Ratio per kg Emitted Substance from all Sampled Materials



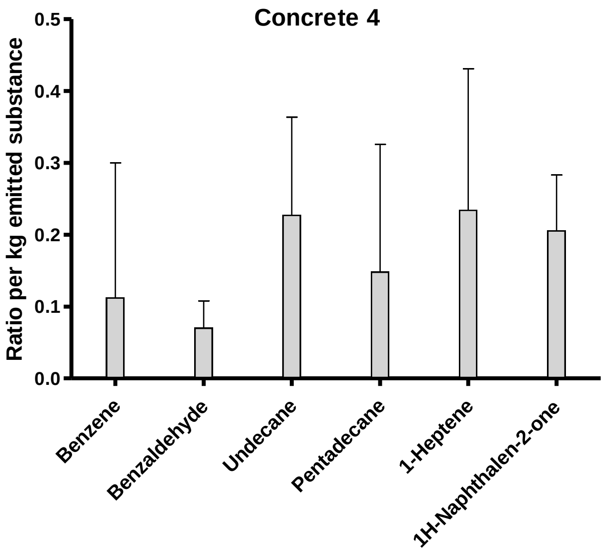
Appendix figure S Ratio of chemicals per kg emitted substance present in concrete batch 1 with mean and SD



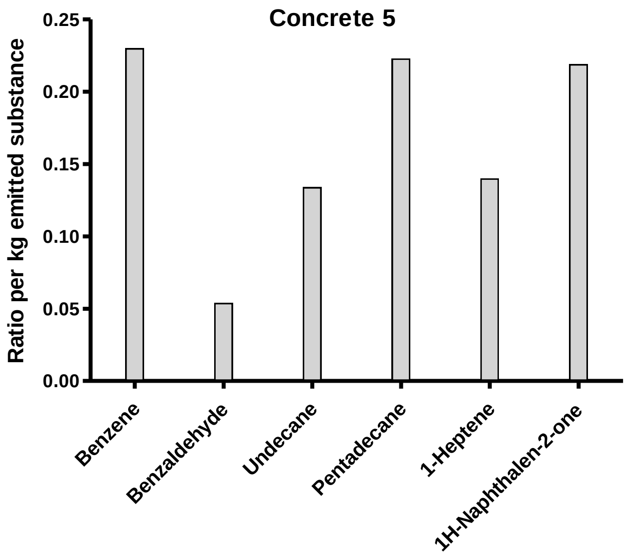
Appendix figure T Ratio of chemicals per kg emitted substance present in concrete batch 2 with mean and SD



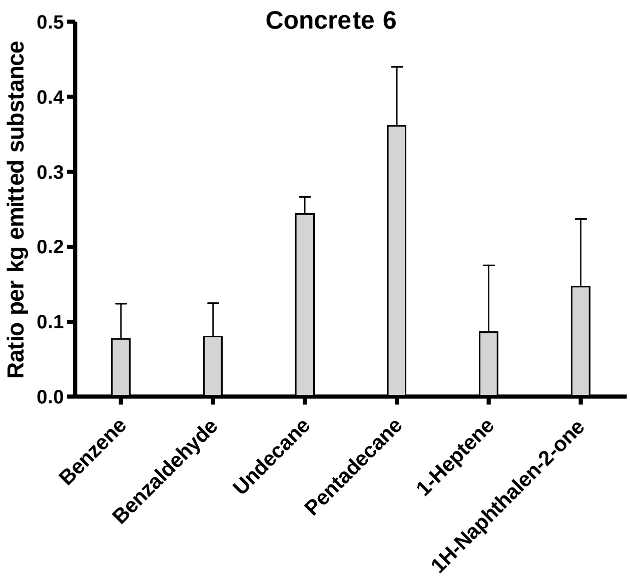
Appendix figure U Ratio of chemicals per kg emitted substance present in concrete batch 3 with mean and SD



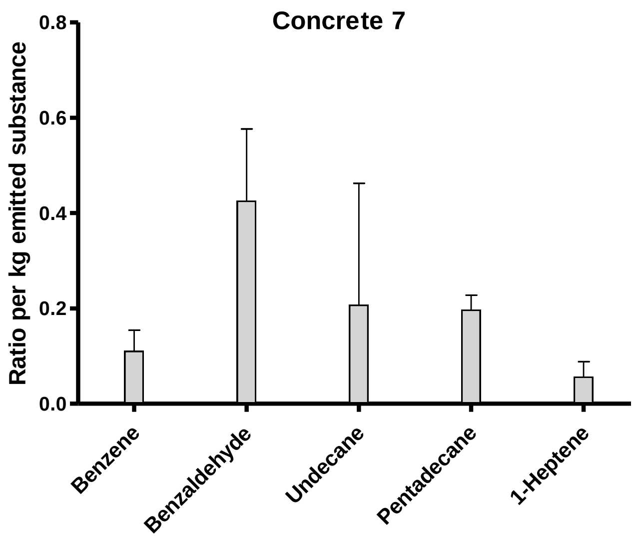
Appendix figure V Ratio of chemicals per kg emitted substance present in concrete batch 4 with mean and SD



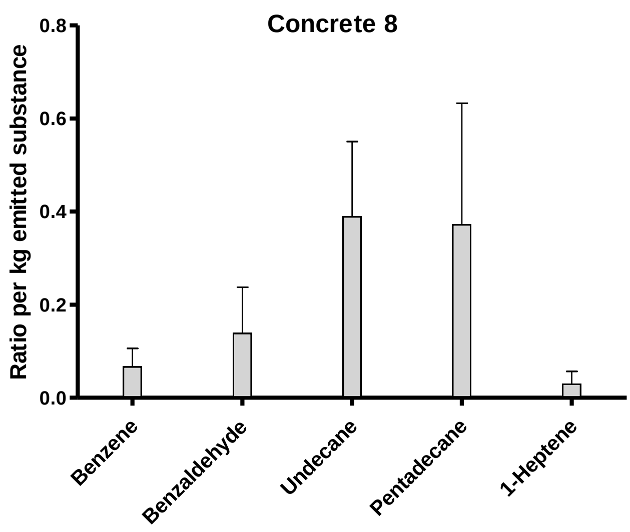
Appendix figure W Ratio of chemicals per kg emitted substance present in concrete batch 5 with mean and SD



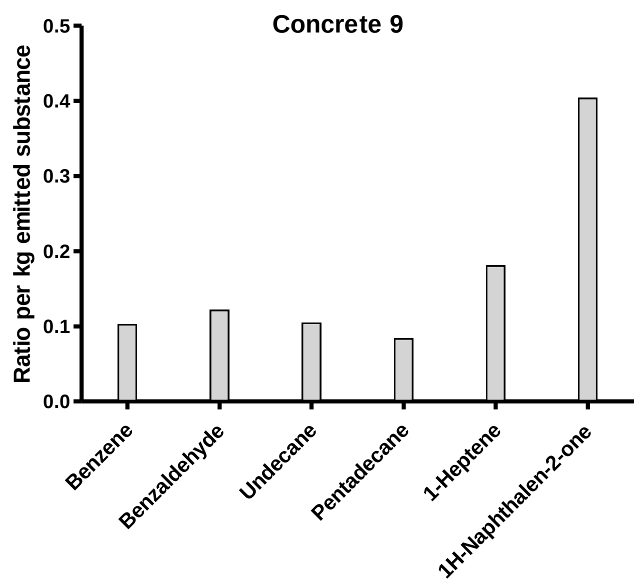
Appendix figure X Ratio of chemicals per kg emitted substance present in concrete batch 6 with mean and SD



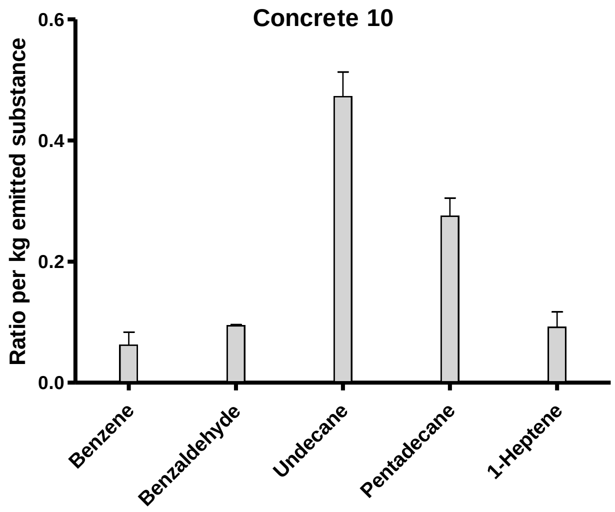
Appendix figure Y Ratio of chemicals per kg emitted substance present in concrete batch 7 with mean and SD



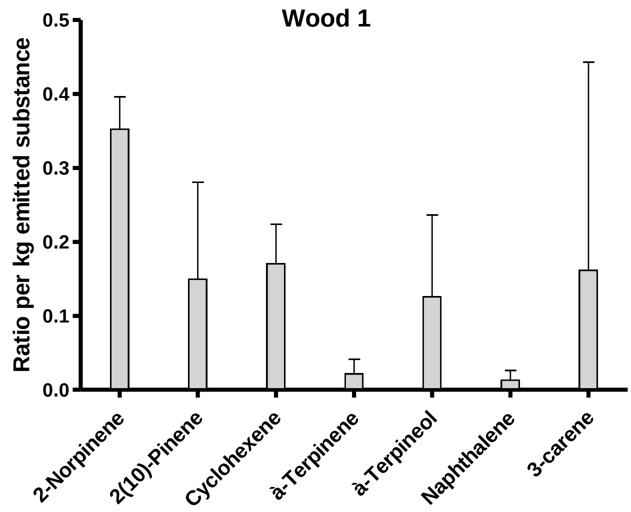
Appendix figure Z Ratio of chemicals per kg emitted substance present in concrete batch 8 with mean and SD



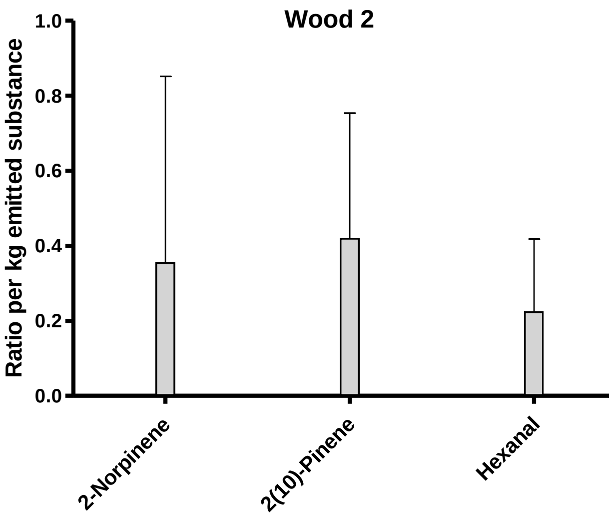
Appendix figure AA Ratio of chemicals per kg emitted substance present in concrete batch 9 with mean and SD



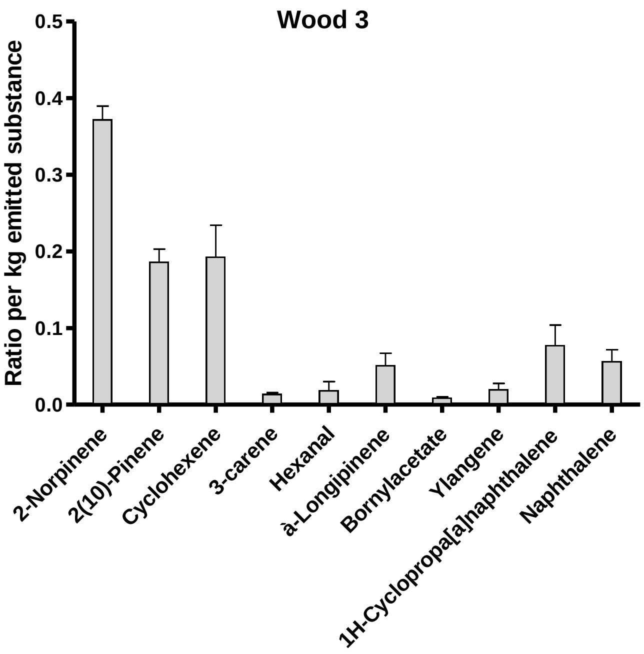
Appendix figure BB Ratio of chemicals per kg emitted substance present in concrete batch 10 with mean and SD



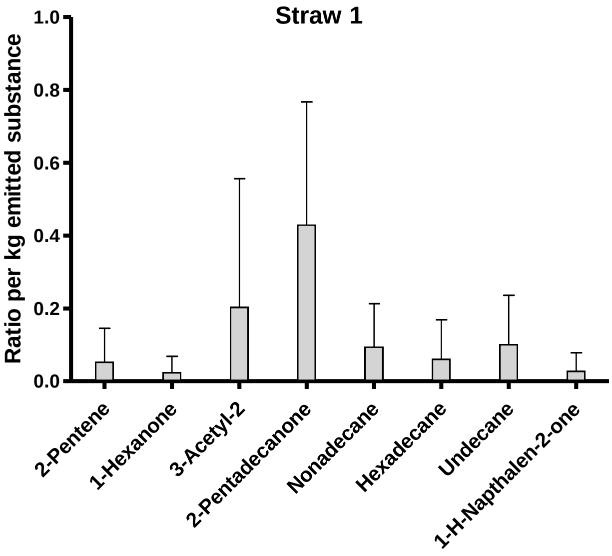
Appendix figure CC Ratio of chemicals per kg emitted substance present in wood batch 1 with mean and SD



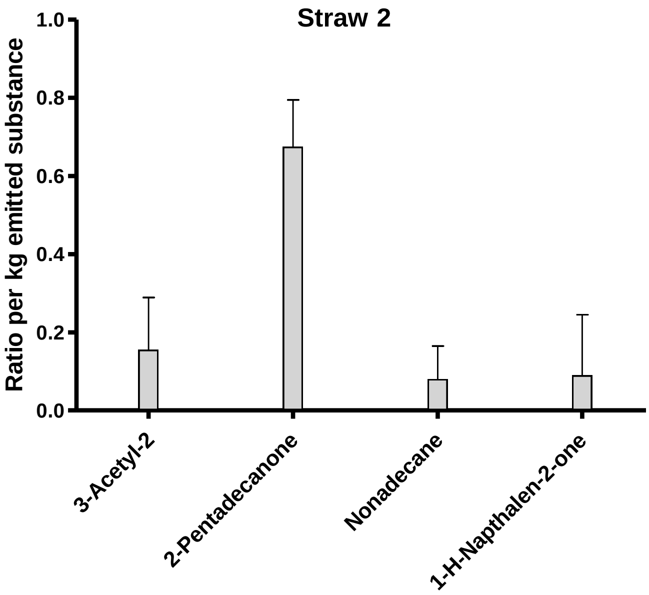
Appendix figure DD Ratio of chemicals per kg emitted substance present in wood batch 2 with mean and SD



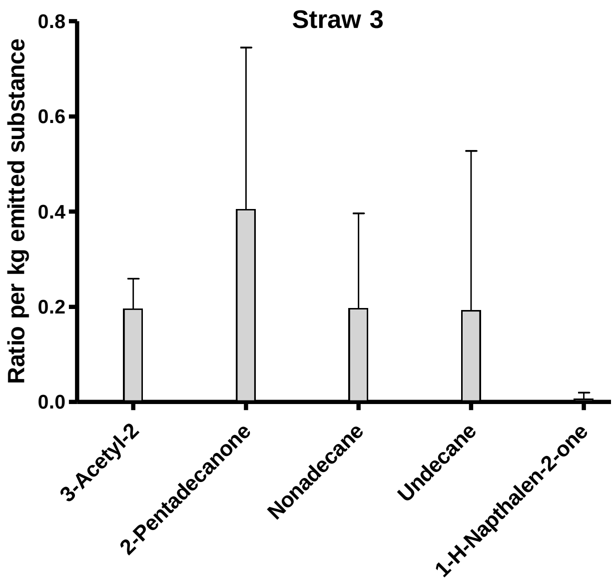
Appendix figure EE Ratio of chemicals per kg emitted substance present in wood batch 3 with mean and SD



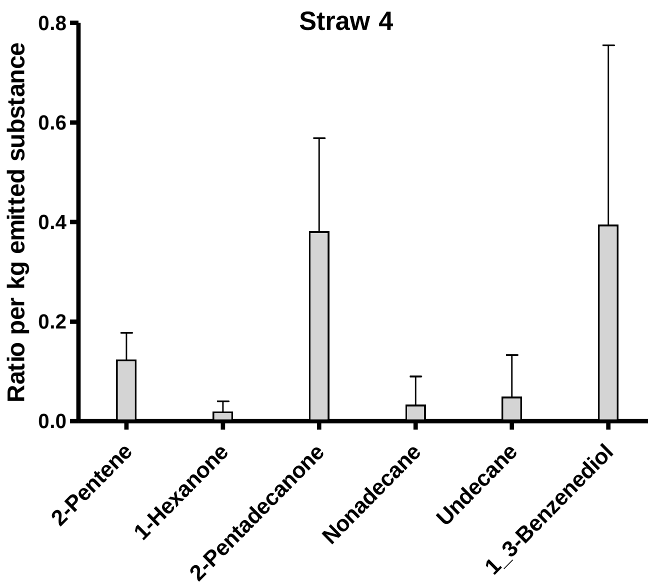
Appendix figure FF Ratio of chemicals per kg emitted substance present in straw batch 1 with mean and SD



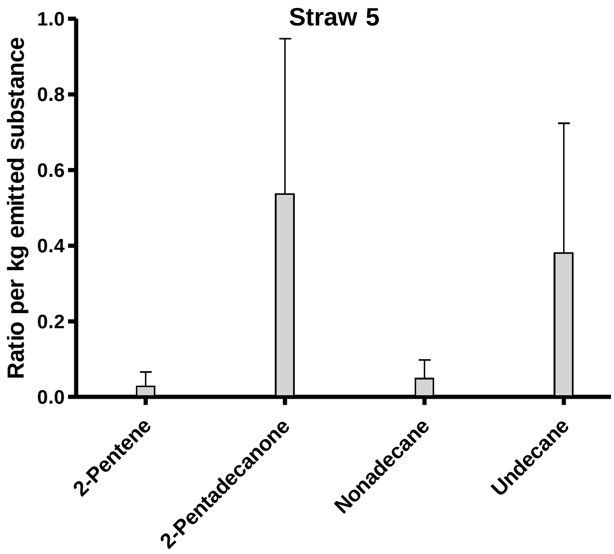
Appendix figure GG Ratio of chemicals per kg emitted substance present in straw batch 2 with mean and SD



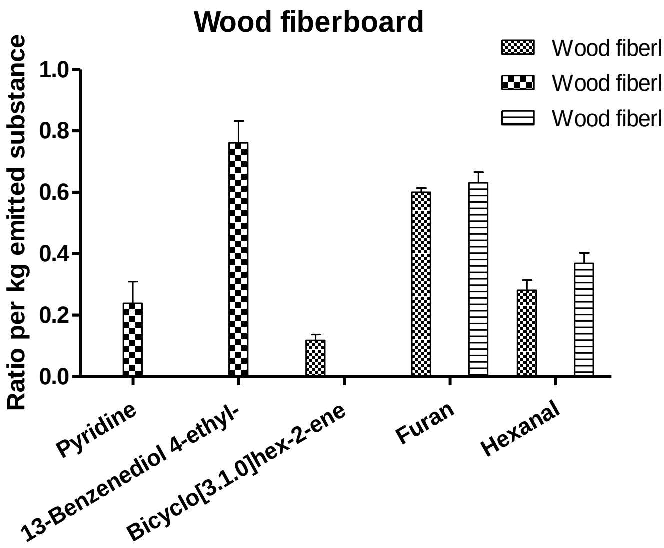
Appendix figure HH Ratio of chemicals per kg emitted substance present in straw batch 3 with mean and SD



Appendix figure II Ratio of chemicals per kg emitted substance present in straw batch 4 with mean and SD



Appendix figure JJ Ratio of chemicals per kg emitted substance present in straw batch 5 with mean and SD



Appendix figure KK Ratio of chemicals per kg emitted substance present in wood fibreboard batch 1-3 with mean and SD

Appendix D Embedded Toxicity of each Material

Concrete Benzene

Appendix table 6 Impact of benzene in concrete batch 1-10 in DALY per kg emitted substance for emission to low population density (LPD) and high population density (HPD) regarding carcinogenic (C), non-carcinogenic (NC) effects and the total impact sum

		1.1	**1.2**	**1.3**	**2.1**	**2.2**	**2.3**	**3.1**	**3.2**	**3.3**
LPD	**C**	4.00E-8	8.28E-9	0	3.95E-7	1.37E-7	2.33E-7	5.52E-9	1.30E-7	1.66E-8
	NC	2.38E-9	4.92E-10	0	2.35E-8	8.13E-9	1.39E-8	3.28E-10	7.72E-9	9.85E-10
	TOTAL	4.24E-8	8.77E-9	0	4.18E-7	1.45E-7	2.47E-7	5.85E-9	1.37E-7	1.75E-8
HPD	**C**	1.58E-7	3.27E-8	0	1.56E-6	5.40E-7	9.21E-7	2.18E-8	5.12E-7	6.54E-8
	NC	9.40E-9	1.94E-9	0	9.27E-8	3.21E-8	5.48E-8	1.30E-9	3.05E-8	3.89E-9
	TOTAL	1.67E-7	3.47E-8	0	1.65E-6	5.72E-7	9.76E-7	2.31E-8	5.43E-07	6.93E-08
		4.1	**4.2**	**4.3**	**5.1**	**5.2**	**5.3**	**6.1**	**6.2**	**6.3**
LPD	**C**	1.24E-8	4.54E-7	0	3.17E-7	3.17E-7	3.17E-7	1.05E-7	4.55E-8	1.73E-7
	NC	7.39E-10	2.70E-8	0	1.89E-8	1.89E-8	1.89E-8	6.24E-9	2.71E-9	1.03E-8
	TOTAL	1.32E-8	4.81E-7	0	3.36E-7	3.36E-7	3.36E-7	1.11E-7	4.82E-8	1.83E-7
HPD	**C**	4.91E-8	1.79E-6	0	1.25E-6	1.25E-6	1.25E-6	4.14E-7	1.80E-7	6.81E-7
	NC	2.92E-9	1.07E-7	0	7.45E-8	7.45E-8	7.45E-8	2.46E-8	1.07E-8	4.05E-8
	TOTAL	5.20E-8	1.90E-6	0	1.33E-6	1.33E-6	1.33E-6	4.39E-7	1.91E-7	7.22E-7
		7.1	**7.2**	**7.3**	**8.1**	**8.2**	**8.3**	**9.1**	**9.2**	**9.3**
LPD	**C**	1.88E-7	1.88E-7	8.42E-8	4.42E-8	8.42E-8	1.50E-7	1.42E-7	1.42E-7	1.42E-7
	NC	1.12E-8	1.12E-8	5.01E-9	2.63E-9	5.01E-9	8.95E-9	8.45E-9	8.45E-9	8.45E-9
	TOTAL	1.99E-7	1.99E-7	8.92E-8	4.68E-8	8.92E-8	1.59E-7	1.51E-7	1.51E-7	1.51E-7
HPD	**C**	7.41E-7	7.41E-7	3.33E-7	1.74E-7	3.33E-7	5.94E-7	5.61E-7	5.61E-7	5.61E-7
	NC	4.41E-8	4.41E-8	1.98E-8	1.04E-8	1.98E-8	3.53E-8	3.34E-8	3.34E-8	3.34E-8
	TOTAL	7.85E-7	7.85E-7	3.52E-7	1.85E-7	3.52E-7	6.29E-7	5.95E-7	5.95E-7	5.95E-7
		10.1	**10.2**	**10.3**						
LPD	**C**	6.49E-8	1.19E-7	7.73E-8						
	NC	3.86E-9	7.06E-9	4.60E-9						
	TOTAL	6.87E-8	1.26E-7	8.19E-8						
HPD	**C**	2.56E-7	4.69E-7	3.05E-7						
	NC	1.52E-8	2.79E-8	1.81E-8						
	TOTAL	2.71E-7	4.97E-7	3.23E-7						

Concrete Benzaldehyde

Appendix table 7 Impact of benzaldehyde in concrete batch 1, 4-10 in DALY per kg emitted substance for emission to low population density (LPD) and high population density (HPD) regarding carcinogenic (C), non-carcinogenic (NC) effects and the total impact sum

		1.1	**1.2**	**1.3**	**4.1**	**4.2**	**4.3**	**5.1**	**5.2**	**5.3**
LPD	**C**	1.65E-9	1.30E-9	1.17E-9	2.21E-9	7.12E-10	2.47E-9	1.37E-9	1.37E-9	1.37E-9
	NC	5.04E-10	3.95E-10	3.56E-10	6.74E-10	2.17E-10	7.52E-10	4.18E-10	4.18E-10	4.18E-10
	TOTAL	2.16E-9	1.69E-9	1.53E-9	2.89E-9	9.29E-10	3.22E-9	1.79E-9	1.79E-9	1.79E-9
HPD	**C**	2.53E-8	1.99E-8	1.79E-8	3.39E-8	1.09E-8	3.78E-8	2.11E-8	2.11E-8	2.11E-8
	NC	7.72E-9	6.06E-9	5.46E-9	1.03E-8	3.33E-9	1.15E-8	6.42E-9	6.42E-9	6.42E-9
	TOTAL	3.31E-8	2.59E-8	2.34E-8	4.43E-8	1.42E-8	4.93E-8	2.75E-8	2.75E-8	2.75E-8
		6.1	**6.2**	**6.3**	**7.1**	**7.2**	**7.3**	**8.1**	**8.2**	**8.3**
LPD	**C**	3.33E-9	1.60E-9	1.27E-9	1.30E-8	1.30E-8	6.43E-9	2.21E-9	6.43E-9	1.98E-9
	NC	1.02E-9	4.88E-10	3.87E-10	3.98E-9	3.98E-9	1.96E-9	6.74E-10	1.96E-9	6.04E-10
	TOTAL	4.34E-9	2.09E-9	1.66E-9	1.70E-8	1.70E-8	8.39E-9	2.89E-9	8.39E-9	2.59E-9
HPD	**C**	5.11E-8	2.46E-8	1.95E-8	2.00E-7	2.00E-7	9.86E-8	3.39E-8	9.86E-8	3.04E-8
	NC	1.56E-8	7.48E-9	5.94E-9	6.09E-8	6.09E-8	3.01E-8	1.03E-8	3.01E-8	9.27E-9
	TOTAL	6.66E-8	3.20E-8	2.54E-8	2.61E-7	2.61E-7	1.29E-7	4.43E-8	1.29E-7	3.97E-8
		9.1	**9.2**	**9.3**	**10.1**	**10.2**	**10.3**			
LPD	**C**	3.10E-9	3.10E-9	3.10E-9	2.44E-9	2.41E-9	2.39E-9			
	NC	9.45E-10	9.45E-10	9.45E-10	7.44E-10	7.36E-10	7.28E-10			
	TOTAL	4.05E-9	4.05E-9	4.05E-9	3.18E-9	3.15E-9	3.12E-9			
HPD	**C**	4.76E-8	4.76E-8	4.76E-8	3.74E-8	3.70E-8	3.66E-8			
	NC	1.45E-8	1.45E-8	1.45E-8	1.14E-8	1.13E-8	1.12E-8			
	TOTAL	6.21E-8	6.21E-8	6.21E-8	4.88E-8	4.83E-8	4.78E-8			

Concrete Hexane

Appendix table 8 Impact of hexane in concrete batch 2 in DALY per kg emitted substance for emission to low population density (LPD) and high population density (HPD) regarding carcinogenic (C), non-carcinogenic (NC) effects and the total impact sum

		2.1	**2.2**	**2.3**
LPD	**C**	0	0	7.32E-11
	NC	0	0	2.33E-9
	TOTAL	0	0	2.41E-9
HPD	**C**	0	0	6.79E-10
	NC	0	0	2.17E-8
	TOTAL	0	0	2.24E-8

Concrete Naphthalene

Appendix table 9 Impact of naphthalene in concrete batch 3-6 and 9 in DALY per kg emitted substance for emission to low population density (LPD) and high population density (HPD) regarding carcinogenic (C), non-carcinogenic (NC) effects and the total impact sum

		3.1	3.2	3.3	4.1	4.2	4.3	5.1	5.2	5.3
LPD	**C**	0	9.57E-7	1.46E-7	1.94E-6	1.70E-6	8.69E-7	1.60E-6	1.60E-6	1.60E-6
	NC	0	3.09E-7	4.72E-8	6.28E-7	5.50E-7	2.81E-7	5.17E-7	5.17E-7	5.17E-7
	TOTAL	0	1.27E-6	1.93E-7	2.57E-6	2.25E-6	1.15E-6	2.12E-6	2.12E-6	2.12E-6
HPD	**C**	0	1.84E-6	2.80E-7	3.73E-6	3.27E-6	1.67E-6	3.07E-6	3.07E-6	3.07E-6
	NC	0	5.95E-7	9.09E-8	1.21E-6	1.06E-6	5.41E-7	9.95E-7	9.95E-7	9.95E-7
	TOTAL	0	2.43E-6	3.71E-7	4.94E-6	4.32E-6	2.21E-6	4.06E-6	4.06E-6	4.06E-6

		6.1	6.2	6.3	9.1	9.2	9.3
LPD	**C**	4.82E-7	1.77E-6	9.79E-7	2.95E-6	2.95E-6	2.95E-6
	NC	1.56E-7	5.73E-7	3.16E-7	9.53E-7	9.53E-7	9.53E-7
	TOTAL	6.38E-7	2.35E-6	1.29E-6	3.90E-6	3.90E-6	3.90E-6
HPD	**C**	9.25E-7	3.41E-6	1.88E-6	5.66E-6	5.66E-6	5.66E-6
	NC	3.00E-7	1.10E-6	6.09E-7	1.84E-6	1.84E-6	1.84E-6
	TOTAL	1.23E-6	4.51E-6	2.49E-6	7.50E-6	7.50E-6	7.50E-6

Wood Naphthalene

Appendix table 10 Impact of naphthalene in wood batch 1 and 3 in DALY per kg emitted substance for emission to low population density (LPD) and high population density (HPD) regarding carcinogenic (C), non-carcinogenic (NC) effects and the total impact sum

		1.1	1.2	1.3	3.1	3.2	3.3
LPD	**C**	1.53E-7	1.53E-7	0	3.51E-7	5.40E-7	3.51E-7
	NC	4.96E-8	4.96E-8	0	1.13E-7	1.75E-7	1.13E-7
	TOTAL	2.03E-7	2.03E-7	0	4.64E-7	7.15E-7	4.64E-7
HPD	**C**	2.94E-7	2.94E-7	0	6.73E-7	1.04E-6	6.73E-7
	NC	9.55E-8	9.55E-8	0	2.18E-7	3.36E-7	2.18E-7
	TOTAL	3.90E-7	3.90E-7	0	8.91E-7	1.37E-6	8.91E-7

Clay Benzene

Appendix table 11 Impact of benzene in clay batch 1-3 in DALY per kg emitted substance for emission to low population density (LPD) and high population density (HPD) regarding carcinogenic (C), non-carcinogenic (NC) effects and the total impact sum

		1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
LPD	**C**	1.11E-6	9.81E-7	1.00E-6	8.96E-7	9.91E-7	1.04E-6	1.07E-6	1.08E-6	1.07E-6
	NC	6.61E-8	5.84E-8	5.98E-8	5.33E-8	5.89E-8	6.21E-8	6.37E-8	6.45E-8	6.34E-8
	TOTAL	1.18E-6	1.04E-6	1.06E-6	9.49E-7	1.05E-6	1.11E-6	1.13E-6	1.15E-6	1.13E-6
HPD	**C**	4.39E-6	3.88E-6	3.97E-6	3.54E-6	3.91E-6	4.13E-6	4.23E-6	4.28E-6	4.21E-6
	NC	2.61E-7	2.30E-7	2.36E-7	2.10E-7	2.33E-7	2.45E-7	2.51E-7	2.55E-7	2.50E-7
	TOTAL	4.65E-6	4.11E-6	4.20E-6	3.75E-6	4.15E-6	4.37E-6	4.48E-6	4.54E-6	4.46E-6

Straw Naphthalene

Appendix table 12 Impact of naphthalene in straw batch 1-3 in DALY per kg emitted substance for emission to low population density (LPD) and high population density (HPD) regarding carcinogenic (C), non-carcinogenic (NC) effects and the total impact sum

		1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
LPD	**C**	0	0	6.28E-7	0	0	1.96E-6	1.61E-7	0	0
	NC	0	0	2.03E-7	0	0	6.35E-7	5.19E-8	0	0
	TOTAL	0	0	8.31E-7	0	0	2.60E-6	2.13E-7	0	0
HPD	**C**	0	0	1.21E-6	0	0	3.77E-6	3.08E-7	0	0
	NC	0	0	3.91E-7	0	0	1.22E-6	1.00E-7	0	0
	TOTAL	0	0	1.60E-6	0	0	4.99E-6	4.08E-7	0	0

Wood fibreboard Furan

Appendix table 13 Impact of furan in wood fibreboard batch 1 and 3 in DALY per kg emitted substance for emission to low population density (LPD) and high population density (HPD) regarding carcinogenic (C), non-carcinogenic (NC) effects and the total impact sum

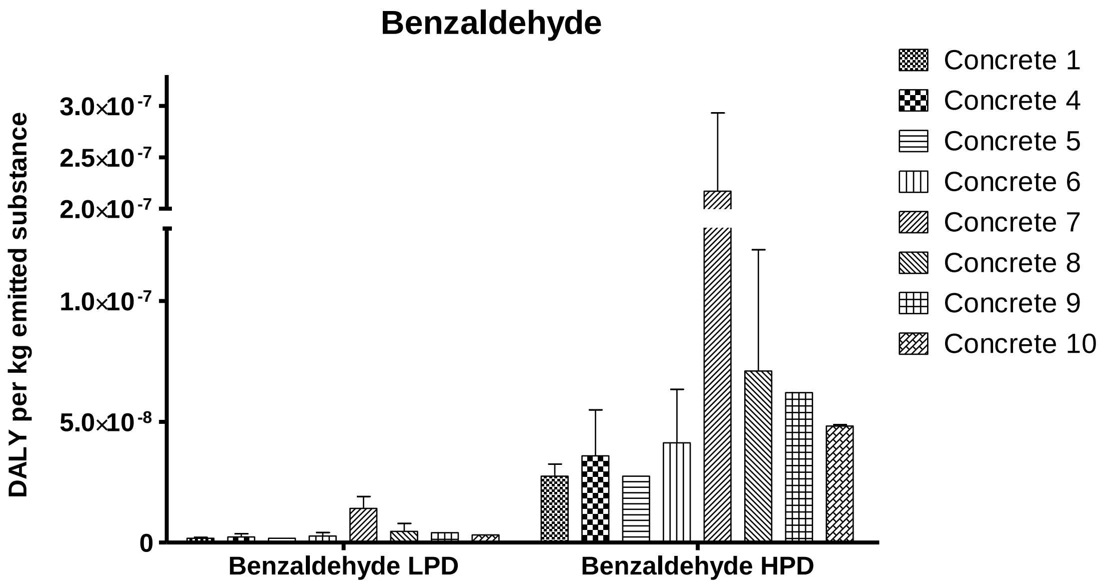
		1.1	1.2	1.3	3.1	3.2	3.3
LPD	**C**	9.81E-6	9.81E-6	9.19E-6	1.11E-5	9.32E-6	9.81E-6
	NC	2.55E-7	2.55E-7	2.39E-7	2.90E-7	2.42E-7	2.55E-7
	TOTAL	1.01E-5	1.01E-5	9.43E-6	1.14E-5	9.56E-6	1.01E-5
HPD	**C**	2.27E-4	2.27E-4	2.12E-4	2.57E-4	2.15E-4	2.27E-4
	NC	5.93E-6	5.93E-6	5.56E-6	6.74E-6	5.64E-6	5.93E-6
	TOTAL	2.33E-4	2.33E-4	2.18E-4	2.64E-4	2.21E-4	2.33E-4

Wood fibreboard Pyridine

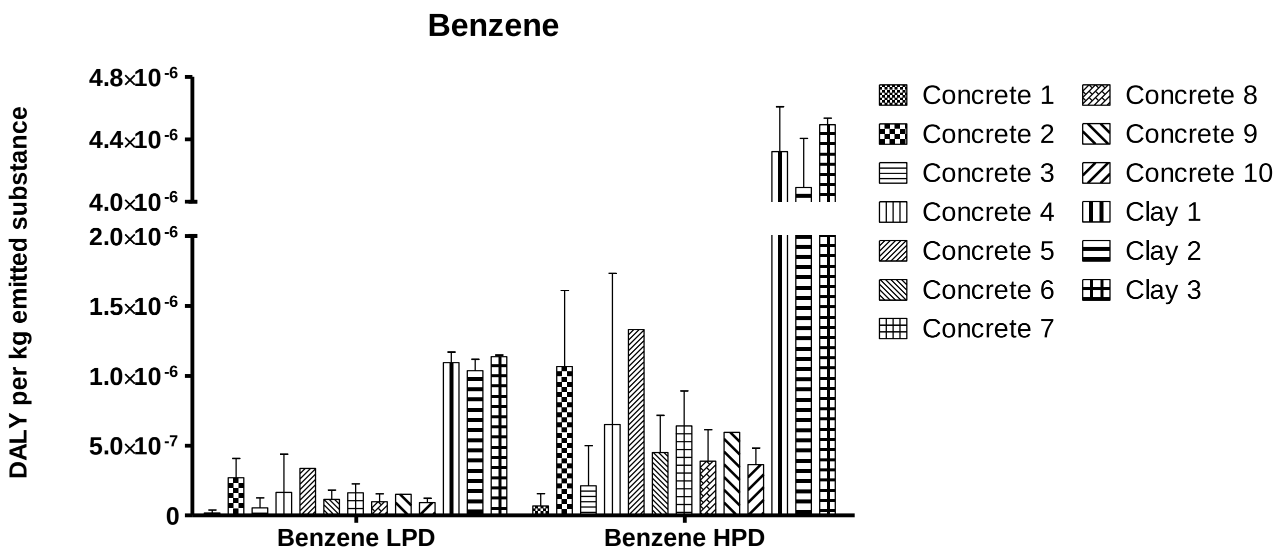
Appendix table 14 Impact of pyridine in wood fibreboard batch 2 in DALY per kg emitted substance for emission to low population density (LPD) and high population density (HPD) regarding carcinogenic (C), non-carcinogenic (NC) effects and the total impact sum

		2.1	2.2	2.3
LPD	**C**	2.27E-6	7.52E-7	1.43E-6
	NC	1.62E-6	5.36E-7	1.02E-6
	TOTAL	3.88E-6	1.29E-6	2.45E-6
HPD	**C**	1.07E-5	3.56E-6	6.76E-6
	NC	7.66E-6	2.54E-6	4.83E-6
	TOTAL	1.84E-5	6.10E-6	1.16E-5

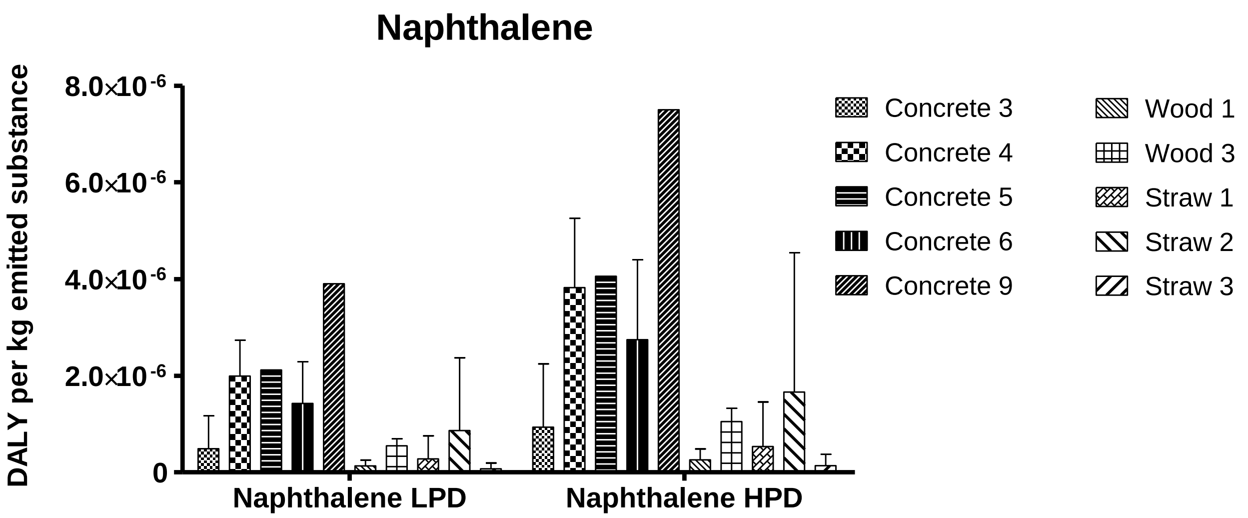
Appendix E Visualisation of Impact from Emitted Substance



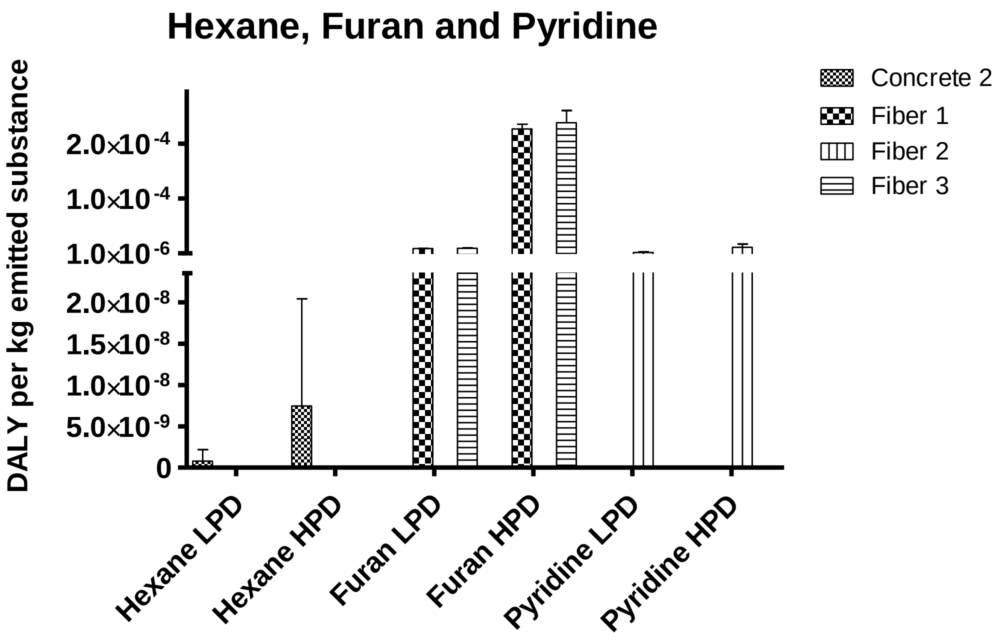
Appendix figure LL Visualisation of the impact [DALY per kg emitted substance] of benzaldehyde being emitted in rural (LPD) or urban area (HPD). There is a factor 10 difference between emitting the chemical in LPD and HPD areas caused by a larger fraction of the population being exposed to the chemical.



Appendix figure MM Visualisation of the impact [DALY per kg emitted substance] of benzene being emitted in rural (LPD) or urban area (HPD). There is approx. five times greater difference between emitting the chemical in LPD and HPD areas caused by a larger fraction of the population being exposed to the chemical. The graph is not created to compare between materials.



Appendix figure NN Visualisation of the impact [DALY per kg emitted substance] of naphthalene being emitted in rural (LPD) or urban area (HPD). There is approx. two times greater difference between emitting the chemical in LPD and HPD areas caused by a larger fraction of the population being exposed to the chemical. The graph is not created to compare between materials.



Appendix figure OO Visualisation of the impact [DALY per kg emitted substance] of hexane, furan, and pyridine being emitted in rural (LPD) or urban area (HPD). The difference between emitting the hexane and furan in LPD and HPD areas is approx. four times greater for hexane and 100 times greater for furan, which is caused by a larger fraction of the population being exposed to the chemical. The difference between emitting pyridine to LPD and HPD is very low, and the two are more or less similar. The graph is not created to compare between materials.

Appendix F Embodied Toxicity Contribution Impact of each Material

	Non-carcinogenic				Carcinogenic				
Clay	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	Life Cycle Clay	8.45E-08	2.28E-07	100.00%	Life Cycle Clay	1.18E-08	1.36E-07	3.47E-07
	13.38%	Clay production	1.13E-08	3.05E-08	21.36%	Clay production	2.52E-09	2.9E-08	5.96E-08
	86.33%	Clay transport	7.30E-08	1.97E-07	78.02%	Clay transport	9.22E-09	1.06E-07	3.03E-07
	0.29%	Clay disposal	2.46E-10	6.65E-10	0.62%	Clay disposal	7.35E-11	8.45E-10	1.51E-09
Concrete	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	Life Cycle Concrete	1.23E-08	3.33E-08	100.00%	Life Cycle Concrete	1.48E-09	1.7E-08	5.03E-08
	89.10%	Concrete production - DK	9.34E-09	2.52E-08	75.66%	Concrete production - DK	1.32E-09	1.51E-08	4.03E-08
	39.80%	Transport concrete - DK	4.77E-09	1.29E-08	38.67%	Transport concrete - DK	5.88E-10	6.76E-09	1.96E-08
	-28.90%	Disposal flow concrete - DK	-1.77E-09	-4.8E-09	-14.33%	Disposal flow concrete - DK	-4.27E-10	-4.9E-09	-9.68E-09
Straw	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	Life Cycle Straw	-3.35E-06	-9.1E-06	100.00%	Life Cycle Straw	-2.76E-07	-3.2E-06	-1.2E-05
	63.46%	Straw production - LT	-2.13E-06	-5.7E-06	1.19%	Straw production - LT	-3.28E-09	-3.8E-08	-5.78E-06
	-2.13%	Transport of straw - LT	7.16E-08	1.93E-07	-3.20%	Transport of straw - LT	8.82E-09	1.01E-07	2.95E-07
	38.67%	Disposal of straw - DK	-1.30E-06	-3.5E-06	102.01%	Disposal of straw - DK	-2.81E-07	-3.2E-06	-6.73E-06
Wood LT	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	Life Cycle Wood EcoCocon	3.64E-05	9.83E-05	100.00%	Life Cycle Wood EcoCocon	7.28E-06	8.37E-05	1.82E-04
	103.92%	Wood product LT	3.78E-05	1.02E-04	104.35%	Wood product LT	7.59E-06	8.73E-05	1.90E-04
	0.20%	Transport of wood LT	7.16E-08	1.93E-07	0.12%	Transport of wood LT	8.82E-09	1.01E-07	2.95E-07
	-4.12%	Disposal of wood	-1.50E-06	-4.1E-06	-4.47%	Disposal of wood	-3.25E-07	-3.7E-06	-7.79E-06
Wood fiberboard	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	Life Cycle Wood fiberboard	-1.32E-06	-3.6E-06	100.00%	Life Cycle Wood fiberboard	-3.03E-07	-3.5E-06	-7.06E-06
	-14.40%	Wood fibreboard product DK	1.90E-07	5.14E-07	-9.65%	Wood fibreboard product DK	2.93E-08	3.37E-07	8.51E-07
	-4.05%	Transport of wood fiberboard DE	5.35E-08	1.44E-07	-2.23%	Transport of wood fiberboard DE	6.76E-09	7.78E-08	2.22E-07
	118.45%	Disposal of wood fiberboard DK	-1.57E-06	-4.2E-06	111.88%	Disposal of wood fiberboard DK	-3.39E-07	-3.9E-06	-8.13E-06
Wood DK	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	Life Cycle Wood	1.38E-06	3.71E-06	100.00%	Life Cycle Wood	4.33E-07	4.98E-06	8.69E-06
	2750.61%	Wood product DK	3.78E-05	1.02E-04	1754.37%	Wood product DK	7.59E-06	8.73E-05	1.90E-04
	0.35%	Transport of wood DK	4.77E-09	1.29E-08	0.14%	Transport of wood DK	5.88E-10	6.76E-09	1.96E-08
	-2650.96%	Recycling of wood	-3.65E-05	-9.85E-05	-1654.50%	Recycling of wood	-7.16E-06	-8.2E-05	-1.81E-04

Appendix table 15 The impact contribution per life cycle stage for all singular building material in percentages, CTUh and DALY per kg material for carcinogenic and non-carcinogenic effects, and the sum of all human toxicity effects

	Carcinogenic				**Non-carcinogenic**				
Concrete Component	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	Concrete 1 m³ Life Cycle	9.22E-06	1.06E-04	100.00%	Concrete 1 m³ Life Cycle	6.54E-05	1.77E-04	2.83E-04
	75.66%	Concrete production - DK	6.97E-06	7.39E-10	89.10%	Concrete production - DK	5.83E-05	1.57E-04	1.57E-04
	38.67%	Transport concrete - DK	3.56E-06	3.78E-10	39.80%	Transport concrete - DK	2.60E-05	7.03E-05	7.03E-05
	-14.33%	Disposal flow concrete - DK	-1.32E-06	-1.40E-10	-28.90%	Disposal flow concrete - DK	-1.89E-05	-5.10E-05	-5.10E-05
EcoCocon element (Incineration)	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	EcoCocon 1 m³ Life cycle	2.70E-04	3.11E-03	100.00%	EcoCocon 1 m³ Life cycle	1.18E-03	3.19E-03	6.29E-03
	114.55%	Wood product - LT	3.10E-04	3.57E-03	132.67%	Wood product - LT	1.57E-03	4.24E-03	7.80E-03
	-0.12%	Straw production - LT	-3.19E-07	-3.67E-06	-17.56%	Straw production - LT	-2.10E-04	-5.67E-04	-5.71E-04
	0.13%	Transport of wood - LT	3.65E-07	4.20E-06	0.25%	Transport of wood - LT	2.96E-06	8.00E-06	1.22E-05
	0.31%	Transport of straw - LT	8.60E-07	9.89E-06	0.59%	Transport of straw - LT	6.98E-06	1.88E-05	2.87E-05
	-4.91%	Disposal of wood	-1.35E-05	-1.55E-04	-5.26%	Disposal of wood	-6.22E-05	-1.68E-04	-3.23E-04
	-9.98%	Disposal of straw	-2.74E-05	-3.15E-04	-10.70%	Disposal of straw	-1.30E-04	-3.51E-04	-6.66E-04
EcoCocon element (Recycling)	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	EcoCocon 1 m³ Life cycle	-8.58E-06	-9.87E-05	100.00%	EcoCocon 1 m³ Life cycle	-2.70E-04	-3.11E-03	-3.20E-03
	-3664.69%	Wood product LT - LT	3.18E-04	3.66E-03	-586.92%	Wood product - LT	1.57E-03	1.81E-02	2.17E-02
	3.72%	Straw production - LT	-3.19E-07	-3.67E-06	77.66%	Straw production - LT	6.98E-06	-2.42E-03	-2.73E-03
	-4.26%	Transport of wood LT - LT	3.65E-07	4.20E-06	-1.11%	Transport of wood - LT	2.96E-06	3.41E-05	3.83E-05
	-10.01%	Transport of straw - LT	8.60E-07	9.89E-06	-2.61%	Transport of straw - LT	-1.30E-04	8.02E-05	9.01E-05
	3456.08%	Recycling of wood - DK	-3.00E-04	-3.45E-03	565.66%	Recycling of wood - DK	-2.10E-04	-1.74E-02	-2.08E-02
	319.16%	Disposal of straw EcoCocon	-2.74E-05	-3.15E-04	47.32%	Disposal of straw EcoCocon	-1.51E-03	-1.50E-03	-1.50E-03

Appendix table 16 The impact contribution per life cycle stage for building components in percentages, CTUh and DALY per m³ building component for carcinogenic and non-carcinogenic effects, and the sum of all human toxicity effects

	Carcinogenic				Non-carcinogenic				
EcoCocon Outer Wall Part (Incineration)	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	EcoCocon Life Cycle	1.80E-04	2.07E-03	100.00%	EcoCocon Life Cycle	7.67E-04	2.13E-03	4.15E-03
	118.27%	EcoCocon Product	2.13E-04	2.45E-03	119.11%	EcoCocon Product	9.13E-04	2.47E-03	4.92E-03
	0.51%	EcoCocon Transport	9.07E-07	1.04E-05	0.95%	EcoCocon Transport	7.33E-06	1.97E-05	3.01E-05
	-0.01%	EcoCocon Use	-1.46E-08	-1.68E-07	-0.01%	EcoCocon Use	-4.38E-08	-1.20E-07	-2.86E-07
	-18.77%	EcoCocon EOL	-3.33E-05	-3.83E-04	-20.06%	EcoCocon EOL	-1.53E-04	-4.13E-04	-8.00E-04
Concrete Outer Wall Part	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	Concrete Wall Life Cycle	-4.65E-05	-5.35E-04	100.00%	Concrete Wall Life Cycle	-2.13E-04	-5.73E-04	-1.11E-03
	-358.25%	Concrete Wall Product	1.67E-04	1.92E-03	-402.26%	Concrete Wall Product	8.47E-04	2.29E-03	4.20E-03
	-0.98%	Concrete Wall Transport	4.55E-07	5.23E-06	-1.73%	Concrete Wall Transport	3.64E-06	9.87E-06	1.51E-05
	0.10%	Concrete Wall Use	-4.65E-08	-5.35E-07	0.08%	Concrete Wall Use	-1.76E-07	-4.73E-07	-1.01E-06
	459.13%	Concrete Wall EOL	-2.13E-04	-2.45E-03	503.91%	Concrete Wall EOL	-1.06E-03	-2.86E-03	-5.31E-03
EcoCocon Outer Wall Part (Recycling)	Contribution	Process	CTUh	DALY	Contribution	Process	CTUh	DALY	TOTAL DALY
	100.00%	EcoCocon Life Cycle Recycling	-1.12E-05	-1.29E-04	100.00%	EcoCocon Life Cycle Recycling	-2.00E-04	-2.30E-03	-2.43E-03
	-1869.78%	EcoCocon Product	2.13E-04	2.45E-03	-459.13%	EcoCocon Product	9.13E-04	1.05E-02	1.30E-02
	-8.05%	EcoCocon Transport	9.04E-07	1.04E-05	-3.68%	EcoCocon Transport	7.32E-06	8.42E-05	9.46E-05
	0.13%	EcoCocon Use	-1.46E-08	-1.68E-07	0.02%	EcoCocon Use	-4.38E-08	-5.03E-07	-6.71E-07
	1977.70%	EcoCocon EOL	-2.20E-04	-2.53E-03	562.79%	EcoCocon EOL	-1.12E-03	-1.29E-02	-1.54E-02

Appendix table 17 The impact contribution per life cycle stage for external wall systems in percentages, CTUh and DALY per m^3 complete external wall system for carcinogenic and non-carcinogenic effects, and the sum of all human toxicity effects