Technische Universität München
TUM Campus Straubing für Biotechnologie und Nachhaltigkeit

Bewertung der Umweltbilanzen von Materialien im deutschen Gebäudesektor

Felix Volker Rheude, M.Sc.

Vollständiger Abdruck der vom TUM Campus Straubing für Biotechnologie und Nachhaltigkeit der Technischen Universität München zur Erlangung eines

Doktors der Wirtschafts- und Sozialwissenschaften (Dr. rer.pol.)

genehmigten Dissertation.

Vorsitz: Prof. Dr. Klaus Menrad

Prüfende der Dissertation:

1. Prof. Dr. Hubert Röder
2. Prof. Dr. Magnus Fröhling

Die Dissertation wurde am 17.10.2023 bei der Technischen Universität München eingereicht und durch den TUM Campus Straubing für Biotechnologie und Nachhaltigkeit am 16.04.2024 angenommen.

DANKSAGUNG

Diese Promotion ist eine selbstständig angefertigte, wissenschaftliche Arbeit. Trotzdem wäre sie ohne die Unterstützung und Motivation einiger Personen nicht möglich gewesen.

Ich möchte mich zunächst herzlich bei meinem Doktorvater Herrn Prof. Dr. Hubert Röder bedanken. Sowohl der Austausch im Zuge der Anfertigung dieser Promotionsschrift als auch die Unterstützung und die Schaffung der Möglichkeit, Vorlesungen und Tutorien am Lehrstuhl zu halten, waren für meine fachliche und persönliche Entwicklung in meiner Zeit am TUM Campus Straubing unverzichtbar.

Des Weiteren möchte ich mich bei Herrn Prof. Dr. Magnus Fröhling für die Betreuung meiner Arbeit und das stete Interesse an meinem Fortschritt bedanken.

Frau Veronika Adam hat mich bei jeglichen bürokratischen Hürden, die an der Universität auftreten können, immer mit maximalem Einsatz unterstützt und so viel Kopfzerbrechen meinerseits verhindert hat. Hierfür möchte ich ihr sehr danken, da die Arbeit in dieser Form sonst nicht vorliegen würde.

Außerdem möchte ich Maresa Bussa, Isabel Hertl, Gregor Mager und Andreas Niedermeier für die lustige Zeit und viele entspannte Abende danken.

Ohne meine Eltern und Geschwister wäre ich nicht an dem Punkt an dem ich heute bin und auch Ihnen gilt mein herzlichster Dank für die jahrelange Unterstützung.

Zu guter Letzt geht der größte Dank an meine Frau, Ronja Schmid, die mich in meiner Arbeit immer unterstützt, Freiräume geschaffen und Verständnis gezeigt hat, wenn es mal wieder länger gedauert hat.

ZUSAMMENFASSUNG

Der Bausektor ist einer der größten Emittenten von Treibhausgasen. Deutschland hat das Ziel seine Treibhausgasemissionen im Gebäudesektor zu minimieren. Diskussionen zu diesem Thema finden auf vielen Ebenen statt: Forscher, die sich mit der Entwicklung neuer Materialien und Konzepten befassen, Architekten und Bauingenieure, die versuchen diese Erkenntnisse in ihre Projekte zu integrieren, Handwerker, die diese Ideen in die Praxis umsetzen, sowie Politiker, die versuchen das große Ganze zu steuern. Die Richtung ist klar: Eine ganzheitliche Reduktion der Treibhausgasemissionen bei mindestens gleichbleibender Lebensqualität und möglichst geringer steigender ökonomischer Belastung des Einzelnen zu erreichen. Bei Kommunikation mehrerer Parteien ist es wichtig über eine gemeinsame Grundlage zu verfügen. Hier besteht eine Lücke zwischen Anspruch und Realität: Es wurden in den letzten Jahren Begriffe verwendet, deren Bedeutung nicht eineindeutig ist. Es fehlt ein aktueller Stand über die Entwicklung der Materialität und ihrer ökologischen Bewertung im deutschen Hochbau sowie eine aktuelle Bewertung der ökologischen Folgen eines realen Einfamilienhausabrisses, wie er in den nächsten Jahren durch die Alterung der Bausubstanz vermehrt auftreten wird. Diese identifizierte Lücke als Grundlage für eine gemeinsame Diskussion will die vorliegende Arbeit schließen. Es konnte gezeigt werden, dass eine klare Abgrenzung der verschiedenen Begriffe möglich ist und zukünftig verwendet werden sollte. Ein weiteres Ergebnis war, dass durch die Zunahme biogener Materialien das Bauen leichter und effizienter wird und die Treibhausgasemissionen des Rohbaus im modellierten Zeitraum reduziert wurden. Außerdem konnte gezeigt werden, dass es in Deutschland noch Raum für eine ökologische Optimierung des Abbruchs und der Verwertung von Baurestmassen gibt. Zusammenfassend lässt sich sagen, dass der Hochbausektor in Deutschland immer noch sehr hohe Treibhausgasemissionen aufweist und ein Optimierungspotential im Hinblick auf die Verwendung von Ressourcen sowohl in ökologischer wie ökonomischer Sicht besteht. Das Ziel der Arbeit, eine Grundlage zur aktuellen Diskussion zu schaffen, die von den verschiedenen Akteuren verwendet werden kann, wurde erreicht. Darüber hinaus wurde eine Methode entwickelt, um die jährliche verbaute Materialität des deutschen Hochbausektors fortlaufend zu erfassen und ökologisch zu bewerten.

ABSTRACT

The building sector is one of the largest emitters of greenhouse gases. Germany aims to minimize its greenhouse gas emissions in the building sector. Discussions on this topic are taking place at many levels: Researchers working on the development of new materials and concepts, architects and civil engineers trying to integrate these findings into their projects, craftsmen putting these ideas into practice, and politicians trying to steer the big picture. The direction is clear: to achieve a holistic reduction of greenhouse gas emissions while increasing the quality of life and minimizing the increasing economic burden on the individual. When multiple parties communicate, it is important to have common ground. There is a gap between ambition and reality: In recent years, buzzwords have been invented whose meaning is not unambiguous. There is a lack of an up-to-date status on the development of materiality and its ecological assessment of German building construction in recent years, as well as an up-to-date assessment of the ecological consequences of a real demolition of a single-family house, as will increasingly occur in the next few years due to the building fabric. This identified gap as a basis for a joint discussion is what the present work aims to fill. It could be shown that a clear delimitation of the different terms is possible and should be used in the future. It could also be shown that the increase in biogenic mate-rials makes construction easier and more efficient, and that greenhouse gas emissions from shell construction were reduced over the period modeled. In addition, it could be shown that there is still room for ecological optimization of demolition and recycling of construction waste in Germany. In summary, it can be said that the building construction sector in Germany still has very high greenhouse gas emissions and that there is potential for optimization with regard to the use of resources, both from an ecological and an economic point of view. The aim of the work to create a basis for the current discussion, which can be used by the different actors, was achieved, as well as to develop a method to continuously record and ecologically evaluate the annual used materiality of the German building construction sector.

GLIEDERUNG

ABKÜRZUNGSVERZEICHNIS

a	Jahr
ADPE	Abiotic Depletion Potential, mineral resource elements (abiotisches Abbau-potential, mineralische Elemente)
ADPF	Abiotic Depletion Potential, non renewable fossil energy resources (Abiot-isches Abbaupotential, nicht erneuerbare fossile Energieressourcen)
AP	Acidification Potential (Versauerungspotential)
BREEAM	Building Research Establishment Environmental Assessment Method
CFC-11	Trichlorflourmethan
CO_2	Kohlenstoffdioxid
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DIN	Deutsche Industrie Norm
EP	Eutrophication Potential (Eutrophierungspotential)
FF	Forschungsfrage
FT	Forschungsthema
g	Gramm
GHG	Greenhouse Gas (Treibhausgase)
GWP	Global Warming Potential (Erderwärmungspotenital)
HVAC	Heating, Ventilation and Air Conditioning
HLK-Anlage	Heiz-Lüftung-Klima-Anlage
ISO	International Organisation for Standardization
kg	Kilogramm
km	Kilometer
LEED	Leadership in Energy and Environmental Design
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m^2	Quadratmeter
m^3	Kubikmeter

MFA	Material Flow Analysis (Stoffstromanalyse)
MJ	Megajoule
NMVOC	Non-Methane Volatile Organic Compound (Flüchtige organische Verbindungen ohne Methan)
OPD	Ozon Depletion Potential (Ozon-Abbaupotential)
PO_4	Phosphat
POFP	Photochemical Oxidant Formation Potential (photochemisches Oxidationsmittel-Bildungspotenital)
Sb	Antimon
SDG	Sustainable Development Goal
SLR	Systematic Literature Review (systematische Literaturübersicht)
SO_2	Schwefeldioxid
t	Metrische Tonne
THG	Treibhausgas
WK	Wirkungskategorie
WSF	Water Scarcity Footprint (Wassermangel-Fußabbdruck)
yr	year

TABELLENVERZEICHNIS

ABBILDUNGSVERZEICHNIS

1. EINLEITUNG

In dieser Einleitung soll zunächst die Motivation für die Arbeit beschrieben werden, aus der im Anschluss die Forschungsziele und -fragen hergeleitet werden sollen. Zunächst wird der Klimawandel als grundlegende Motivation für die Arbeit beschrieben und begründet, warum der Bausektor einen großen Einfluss auf die Lösung des Problems haben kann. Aus der Komplexität des Bausektors und den Interaktionen der verschiedenen Akteure wird im Anschluss die Forschungslücke herausgearbeitet.

Die größte Bedrohung für den Wohlstand und die Lebensqualität der Menschheit ist aus globaler Sicht derzeit der Klimawandel (Foley et al., 2005; IPCC, 2022; Leal Filho et al., 2023). Der Klimawandel ist in erster Linie auf die steigenden Treibhausgasemissionen seit Beginn der Industrialisierung zurückzuführen und wird somit wesentlich vom Menschen verursacht. Um Schwellenländern langfristig die Schaffung von Wohlstand zu ermöglichen und in den bereits entwickelten Ländern den Wohlstand zu erhalten, ist es daher notwendig, die Treibhausgasemissionen deutlich zu reduzieren und bereits emittiertes Kohlendioxid durch geeignete Maßnahmen zu binden (Hong et al., 2012; B. B. Lin et al., 2021). Diese Emissionen stehen im Zusammenhang mit der Bereitstellung der für den modernen Lebensstandard und die Produktion von Konsumgütern benötigten Energie einschließlich deren Logistik (International Energy Agency, 2019; Ruske et al., 2010). Dieser Ressourcen- und Energiebedarf der Menschheit ist mit dem rasanten Wachstum von Bevölkerung und Wirtschaft in den letzten Jahrzehnten rapide gestiegen (International Energy Agency, 2019; Population Division, 2019; The World Bank, 2019).

Je nach Berechnungsgrundlage und Abschätzungsmethodik sind Gebäude für 32 -40 % der weltweiten Treibhausgasemissionen, 40 % des weltweiten Stromverbrauchs und weitere negative Umweltauswirkungen verantwortlich (Blom et al., 2010; Doan et al., 2017; Esa et al., 2017; Kim et al., 2019; Röck et al., 2020). Darüber hinaus muss aufgrund des Ersatzes bestehender Gebäude, der allgemeinen globalen Verstädterung und des Anstiegs der Weltbevölkerung in den nächsten 40 Jahren von der Bauindustrie mehr Gebäudefläche errichtet werden als in den letzten 4.000 Jahren erbaut wurde (Eberhardt et al., 2019).

Dies zeigt, dass die Entwicklung sowohl der wirtschaftlichen als auch der ökologischen Tragfähigkeit für die Zukunft wichtig ist und dass Gebäude sowohl die Umwelt als auch den Klimawandel stark beeinflussen (Zuo et al., 2017). Die Bauindustrie kann im Hinblick auf den Klimawandel weder ignoriert noch durch andere Industriezweige substituiert werden, da sie mehrere positive Auswirkungen auf die Gesellschaft hat, wie z. B. die Schaffung von Arbeitsplätzen und die Bereitstellung von Lebensraum für Menschen, und außerdem ein wichtiger Faktor für die wirtschaftliche Entwicklung eines Landes ist (Doan et al., 2017; Zuo & Zhao, 2014). In vielen Industrieländern ist der Bausektor einer der wichtigsten wirtschaftlichen Triebkräfte, ein bedeutender Arbeitgeber und daher oft ein Schwerpunkt für die Einführung einer Kreislaufwirtschaft (Gorecki, 2019).

Der deutsche Bausektor erwirtschaftete im Jahr 2020 einen Umsatz von 387 Milliarden Euro (Bundesministerium für Wirtschaft und Klimaschutz, 2022). Damit hat er einen Anteil am deutschen Bruttoinlandsprodukt von gut 10 % (Bundesministerium für Wirtschaft und Klimaschutz, 2022). Zudem ist die deutsche Bauwirtschaft einer der Wirtschaftszweige mit den meisten sozialversicherungspflichtig Beschäftigten und hat trotz der aktuellen Krisen keinen Rückgang der Produktionskapazitäten oder des Umsatzes zu verzeichnen (Bundesagentur für Arbeit, 2022).

All dies zeigt die Komplexität und den Einfluss der Bauindustrie auf den Alltag der Menschen auf der einen Seite und auf den Klimawandel auf der anderen. Global existieren diverse Initiativen zur Reduktion der Treibhausgasemissionen und zur Verbesserung der Lebensqualität der Menschen in und mit Gebäuden. Diese Initiativen existieren auf (über-)staatlicher wie nicht staatlicher sowie öffentlicher wie privat(-wirtschaftlicher) Ebene. So arbeitet die Forschung intensiv an besseren Baumaterialien (Al Nuaimi et al., 2021; D. F. Lin et al., 2012; Panesar et al., 2017; Zhao et al., 2022), neuen Gebäudekonzepten (Dederich, 2021; Feist et al., 2020; Pomponi et al., 2020) oder der Umnutzung bestehender Gebäude (Jain et al., 2020; Kabirifar et al., 2020; Pantini & Rigamonti, 2020). Nach Ansicht mancher Wissenschaftler wurde durch die Vielzahl an Initiativen der Fokus verloren und es wird mehr an der Entwicklung neuer Instrumente gearbeitet, als an der Nutzung und Verbesserung der bestehenden (Baumann et al., 2002; Bocken et al., 2019). Architekten und Bauingenieure versuchen diese Konzepte in die Realität umzusetzen (Schaefer, 2022), um die individuellen Wünsche ihrer Kunden zu berücksichtigen. Diese haben sich in den letzten Jahren in mehrfacher Hinsicht verändert: Nicht nur, dass die Ansprüche der Kunden an Wohnraumfläche gewachsen sind (Statistisches Bundesamt, 2022), auch die Ansprüche hinsichtlich Ausstattung und Wohnqualität in Verbindung mit einer erhöhten Nachhaltigkeit der Gebäudeeigenschaften fordern aktuell die Bauwirtschaft. Als Gebäudeeigenschaften sind hier sowohl die Materialität der Gebäude zu verstehen als auch die Emissionen während der Nutzungsphase bspw. durch Wärmebedarf.

Während sich der Energiebedarf während der Nutzungsphase in den letzten Jahren aufgrund von Vorschriften und Anreizsystemen bei Neubauten immer mehr minimierte, rücken die Emissionen bei der Herstellung der Baumaterialien in den Fokus. Derzeit macht die Gebäudehülle (je nach Bauart und Energiebedarf) nur einen niedrigen einstelligen Prozentsatz der Gesamtemissionen eines Gebäudes während seines Lebenszyklus aus (Gardner et al., 2020; König, 2017). Je geringer die Emissionen während der Nutzungsphase werden, desto größer werden im Schnitt die Emissionen der Gebäudehülle im Verhältnis zu den Gesamtemissionen (Ramesh et al., 2010). Parallel zur Verbesserung der Energieeffizienz während der Nutzungsphase, z. B. durch effizientere Heizungs-, Lüftungs- und Klimaanlagen und bessere Isolierung von Gebäuden, ist es daher auch wichtig, die Emissionen während der Bauphase zu minimieren.

Dies haben auch die politischen Entscheidungsträger erkannt. So werden neben den bereits erwähnten Anreizsystemen zur Verbesserung der Energieeffizienz (Gesetz zur Einsparung von Energie und zur Nutzung erneuerbarer Energien zur Wärme- und Kälteerzeugung in Gebäuden: Gebäudeenergiegesetz - GEG, 2020), inzwischen auch Anreizsysteme zur Verringerung der Kohlenstoffdioxidemissionen der Materialität angewendet. So hat beispielsweise das deutsche Bundesland Nordrhein-Westfalen einen Zuschuss pro Tonne eingesetzten biogenen Kohlenstoffs eingerichtet (NRW.Bank, 2021; SKHolzbau, 2020). Vergleichbare Programme wurden von den Ländern Berlin und Bayern aufgelegt (Bauen mit Holz, 2019; Bayerisches Staatsministerium für Wohnen, Bau und Verkehr, 2022), und weitere sind in Planung, wie z.B. im Bundesland Baden-Württemberg (Holzbau Offensive, 2020). Dies wird voraussichtlich zu einer Erhöhung der Holzbauquote in Deutschland führen. In diesem Zusammenhang ist darauf hinzuweisen, dass die Umweltminister der Länder eine gemeinsame Erklärung abgegeben haben, dass das Bauen mit biogenen Rohstoffen, insbesondere mit Holz, ausdrücklich klimafreundlich ist und daher besonders gefördert werden soll (Federal Ministry of Finance, 2021; Forstwirtschaft in Deutschland, 2022). Insgesamt zeigt dies, dass die Materialität in den letzten Jahren mehr Aufmerksamkeit erhält und die Umweltauswirkungen reduziert werden sollen.

Für die Nachhaltigkeitsdebatte in Deutschland sind Kenntnisse und Informationen über die im deutschen Gebäudesektor verwendeten Materialien unerlässlich. Wie in den vorherigen Absätzen beschrieben, sind zahlreiche Akteure aus unterschiedlichsten Blickwinkeln mit diversen fachlichen Hintergründen aktuell damit beschäftigt die Nachhaltigkeit im Gebäudesektor zu verbessern. Im Idealfall sollte dabei eine gemeinsame Grundlage für die aktuellen Entwicklungen bestehen. An dieser Stelle zeigt sich ein Unterschied zwischen Anspruch und Realität: In den letzten Jahren wurden diverse Schlüsselwörter geprägt, deren genaue Definition häufig nicht eineindeutig ist und die teilweise als Synonyme verwendet werden. Viele Themen sind nicht eindeutig definiert worden, und die Bewertung von Gebäuden als "grün" ist von Land zu Land und von Interessengruppe zu Interessengruppe sehr unterschiedlich (Mattoni et al., 2018).

Eine unklare Sprache verhindert aber, dass Menschen, gerade mit unterschiedlichem fachlichem Hintergrund, effizient zusammen an Problemen arbeiten können. Neben der Sprache ist auch die allgemeine sachliche Grundlage von entscheidender Bedeutung. Hier zeigt sich, dass keine detaillierten Zahlen über die genaue materielle Entwicklung des Hochbausektors in Deutschland in den letzten Jahren existieren und auch kein Überblick über die Entwicklung der Treibhausgasentwicklungen in der Materialität dieser existiert. Um zu beurteilen, wie klimafreundlich der Gebäudesektor tatsächlich ist bzw. wie klimafreundlich er werden kann und welches die politischen und gesellschaftlichen Hebel sind, um dies zu erreichen ist eine genaue Kenntnis der Materialzusammensetzung notwendig. Um nachhaltige Gebäude zu errichten, müssen sowohl die verwendeten Materialien als auch die Prozesse rund um das Gebäude nachhaltig sein (Rheude et al., 2021). Daraus lässt sich schließen, dass die Materialität im Gebäudesektor nicht vernachlässigt werden darf und daher eine Lücke existiert, die zur Erreichung bereits gesetzter Ziele geschlossen werden muss.

Gleichzeitig ist die deutsche Bausektor vergleichsweise alt: Die meisten Gebäude wurden bis 1970 errichtet und werden damit in den nächsten Jahren das Ende ihrer prognostizierten Lebensdauer erreichen. Viele Gebäude werden daher abgerissen werden. Damit alle Entscheider und Akteure im Bausektor auch hier die aktuelle Ausgangslage kennen, ist es notwendig den Abriss eines Gebäudes zu begleiten, dass prototypisch für den oben genannten Zeitraum ist und nach aktuellem Standard abgerissen wird. Gleichzeitig wurden die Umweltwirkungen erfasst, da diese in der Diskussion wertvolle Erkenntnisse liefern können.

Somit lässt sich folgende Forschungslücke definieren, die diese Arbeit schließen soll: Wie ist der aktuelle Stand der Materialität des deutschen Bausektors mit seinen Umweltwirkungen, um allen beteiligten Akteuren eine gemeinsame Grundlage zur Diskussion und zur Überprüfung der Zielerreichung zu liefern?

2. STRUKTUR DER DISSERTATION

Wie in der Einleitung hergeleitet, muss eine Grundlage für die Entwicklungen im Bausektor geschaffen werden, damit alle Stakeholder eine gemeinsame Basis haben, um die besten Lösungen für bestehende Probleme zu erarbeiten. Wie bereits erläutert besteht diese Grundlage einerseits auf einer beidseits verständlichen Kommunikation, andererseits aber auch aus einer fachlichen Komponente zu ökologischen Entwicklungen in den letzten Jahren.

Zur Lösung dieser Forschungslücke wurde sie in drei Teilbereiche aufgeteilt:

1. Es muss die Kommunikation als elementare Grundlage sichergestellt werden, damit alle Akteure verstehen wovon gesprochen wird. Eine gemeinsame Sprache ist die Grundlage jeder Kooperation. Kooperation ist wiederum notwendig, da sich die komplexen und vielschichtigen Probleme zum Verwirklichen von mehr Nachhaltigkeit im Bausektor nur interdisziplinär erreichen lassen.
2. Momentan existiert kein Überblick über die Entwicklung der Materialität und speziell ihre Umweltwirkungen im Hochbau in den letzten Jahren. Diese Grundlage muss allerdings geschaffen werden, um einen Überblick darüber zu erhalten, wo der Bausektor momentan genau steht und wie er sich in den letzten Jahren entwickelt hat. Gleichzeitig bietet das entwickelte Modell die Möglichkeit in der Zukunft fortgeführt zu werden und damit auch zukünftig zu überprüfen, ob der Hochbausektor die gesteckten Ziele erreicht.
3. Es gab bereits zahlreiche Publikationen zum Abriss von Gebäuden. Allerdings sind die meisten entweder rein theoretischer Natur oder bereits veraltet. Wie in der Einleitung bereits erläutert ist es notwendig den aktuellen Stand zu kennen, um ideale Entscheidungen im Sinne der Nachhaltigkeit zu treffen. Daher wurde der Abriss eines Einfamilienhauses aus den 1950zigern Jahren begleitet und die ökologischen Auswirkungen bewertet, um als Grundlage für Entscheidungsträger zu gelten.

Auf Basis des zweiten und dritten Bereichs wird außerdem eine Szenariokalkulation gerechnet, um die Frage zu beantworten, wie viel Frischbeton eingespart werden könnte, wenn Abfall-Betone aus dem Hochbau auch in diesem – beispielsweise für Fundamente oder Keller von Holzgebäuden – wieder Verwendung finden würden. Diese Szenariokalkulation wird mit den Ergebnissen aus den Berechnungen zur momentanen Materialität des Hochbaus verglichen und Schlussfolgerungen gezogen.

Die abgeleiteten Bereiche wurden wiederum in konkrete Forschungsfragen unterteilt, denen zur Beantwortung eine Methodik zugeordnet wurde (Erläuterungen zu den Methodiken siehe Kapitel Materialien und Methoden). Eine Zusammenfassung der Forschungsthemen auf der einen Seite, den zugeordneten Forschungsfragen auf der anderen und den jeweils gewählten Methodiken bietet Tabelle 1.

Jedem Forschungsthema wurde schließlich eine Publikation zugeordnet, in der die Forschungsfragen beantwortet wurden.

TABELLE 1 FORSCHUNGSTHEMEN UND -FRAGEN DER DISSERTATION

Forschungsthema	Forschungsfragen	Methodik	Publikation
Definition „Nachhaltiges Gebäude“	Wie werden derzeit bestimmte Schlüsselwörter im Zusammenhang mit nachhaltigem und ökologischem Bauen verwendet?	SLR	I
	Sind spezifische Definitionen und Anwendungsfälle für diese Begriffe möglich?	SLR	
Aktueller Stand der materiellen Umweltauswirkungen im deutschen Hochbau	Wie hoch ist der Materialbedarf im deutschen Hochbau?	MFA	II
	Wie hoch ist die materialbasierte Klimawirkung von Gebäuden in Deutschland in den letzten Jahren?	LCA	
Aktueller Stand der Umweltauswirkungen beim Abriss von Gebäuden in Deutschland	Was sind die Umweltauswirkungen von Abbrucharbeiten eines typischen deutschen Einfamilienhauses?	LCA	III
	Welche Auswirkungen auf die THG-Emissionen des Hochbaus kann eine erhöhte Nutzung von Recycling-Beton haben?		Schlussfolgerung aus Publikation II und III

Darüber hinaus ist diese Dissertation zur Beantwortung der Forschungsthemen und -fragen in insgesamt sechs Kapitel unterteilt. Das erste Kapitel beschreibt mit einer Einleitung die Motivation der Arbeit und den aktuellen Forschungsstand und leitet die Forschungslücke her. In Kapitel 2 wird die Struktur dieser Dissertation erläutert sowie die Forschungsthemen und -fragen hergeleitet, gefolgt von Kapitel 3, in dem die verwendeten Methodiken zur Beantwortung der Forschungsfragen dargestellt werden. In Kapitel 4 werden die Forschungsfragen detailliert beantwortet. In Kapitel 5 werden diese Ergebnisse übergreifend diskutiert, bevor auf dieser Basis in Kapitel 6 eine Zusammenfassung der Arbeit inklusive Ausblick beschrieben wird.

3. MATERIALIEN UND METHODEN

In diesem Abschnitt werden die Methoden dargestellt und erläutert, die in dieser Dissertation hauptsächlich verwendet wurden. Kurz gesagt handelt es sich dabei um eine strukturierte Literaturrecherche (SLR), Lebenszyklusanalysen (LCA) und Stoffstromanalyse (MFA). Der Abschnitt fokussiert sich primär auf die Begründung der jeweiligen Methodik zur Beantwortung der jeweiligen Forschungsfrage.

3.1. STRUKTURIERTE LITERATURÜBERSICHT

Für diese Arbeit wurden die Kriterien von Okoli und Schabram (2010) zur Durchführung einer systematischen Literaturübersicht (SLR) verwendet. Diese Methode ermöglicht eine gezielte Analyse der verfügbaren Literatur.

Wissenschaftliches Arbeiten muss mehrere Punkte erfüllen. Hierzu zählt, dass die Arbeit transparent sein muss im Sinne, dass Dritte die Ergebnisse mit den vorliegenden Informationen replizieren können. Die Arbeit muss in sich konsistent sein, das heißt Annahmen, die getroffen werden, müssen für alle Fälle innerhalb der Arbeit gelten und dürfen nicht willkürlich gesetzt werden. Darüber hinaus muss die gewählte Methode zur Beantwortung der Frage so genau sein, wie es zur Beantwortung der Forschungsfrage mindestens notwendig ist. Dadurch, dass Wissenschaft mittlerweile global stattfindet sowie viele Fragestellungen interdisziplinär bearbeitet werden müssen, ist es notwendig regelmäßig Zusammenfassungen bestehender wissenschaftlicher Erkenntnisse zu verfassen (sogenannte Literaturübersichten), damit eine allgemeine Übersicht bestehen bleibt. Damit stellen Literaturübersichten ein wichtiges Fundament für wissenschaftliches Arbeiten da. Im Vergleich zu anderen Literaturübersichten, wie beispielsweise bei der Einleitung eines wissenschaftlichen Artikels, steht bei einer strukturierten Literaturübersicht die Literatur und die daraus gezogenen Daten selbst im Vordergrund und legen nicht nur die Grundlage für weitere Forschungen.

In der ersten Publikation soll die Grundlage einer gemeinsamen Kommunikation verschiedener Stakeholder im Hochbausektor gelegt werden. Daher ist es notwendig eine Methode zu wählen, die einerseits die Begriffe identifizieren kann (Forschungsfrage 1), andererseits diesen gefundenen Begriffen dann auch spezifische Bedeutungen zuordnen kann (Forschungsfrage 2). Es steht also die Literatur selbst im Vordergrund, die verwendet werden soll, um aus ihr heraus weitere Erkenntnisse zu schaffen. Daher wurde die Methodik von Okoli und Schabram (2010) verwendet, da sie genau für diesen Zweck entwickelt wurde.

Die Methode findet bei der Erstellung von wissenschaftlichen Literaturübersichten breite Anwendung (Munaro et al., 2020; Roberts et al., 2020; Torres-Carrion et al., 2018). Speziell für Fragen im erweiterten Baubereich wurde die Methode auch schon verwendet, um, wie bei der hier abgeleiteten Forschungsfrage, Definitionen von häufig verwendeten Schlagwörtern abzuleiten (Cocchia, 2014).

In Anbetracht der Forschungsfragen, der Ziele, die damit verbunden sind und der Möglichkeiten welche die Methodik SLR bietet, fiel daher die Wahl auf die Anwendung dieser Methodik zur Beantwortung der Forschungsfragen.

Wie die Methodik im Detail auf die Forschungsfragen angewendet wurde, kann in der Publikation Rheude et al. (2021) nachgelesen werden. Im Folgenden wird eine kurze Zusammenfassung beschrieben, welche in Abbildung 1 dargestellt ist.

Im Zuge der strukturierten Literaturübersicht wurden zwei Reduzierungsschritte vorgenommen, um die geeignete Literatur für die historische Analyse zu finden (erster Schritt) und die Definitionen aus diesen ersten Suchergebnissen abzuleiten (zweiter Schritt). Im ersten Schritt wurden die Ergebnisse nach der Art des Dokuments, der Art des Zugangs, der Art der Quelle und dem Hauptfachgebiet gefiltert. Hinsichtlich des Veröffentlichungsdatums gab es keine Einschränkungen, da die Relevanz der Arbeiten im Hinblick auf ihren Beitrag zum Thema im Vordergrund stand. Im Folgenden wurden die mit den Suchergebnissen verknüpften Schlüsselwörter gescreent. Diese Schlagwörter sollten auf den ersten Blick mit Gebäuden/Bau und Nachhaltigkeit assoziiert werden und zudem vage sein. Insgesamt wurden elf Schlagworte ausgewählt. Die Schlagwörter wurden in drei Gruppen zusammengefasst, wobei jede Gruppe eine umfassendere Kategorie und zwei bis fünf Schlagwörter repräsentiert. Die Gruppen und die zugehörigen Schlagwörter sowie ein Überblick über den Auswahlprozess sind in Abbildung 1 zu sehen.

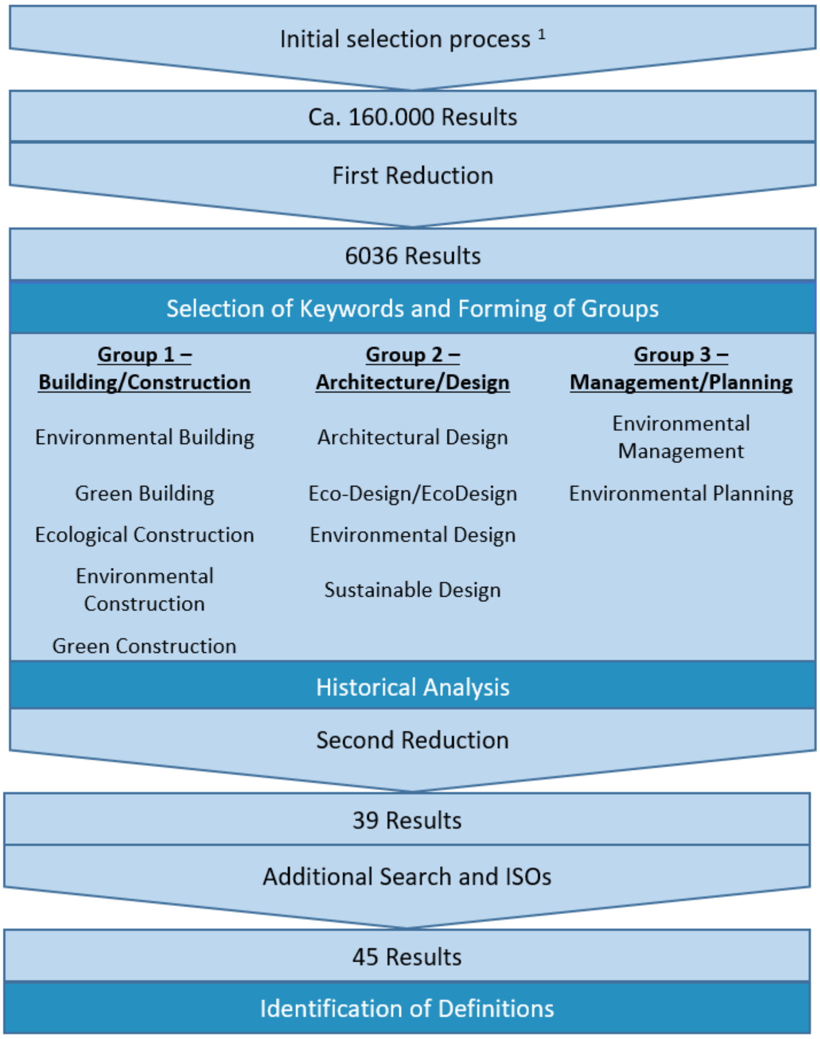

ABBILDUNG 1 AUSWAHLPROZESS FÜR DIE LITERATURRECHERCHE (RHEUDE ET AL., 2021)

3.2. STOFFSTROMANALYSE

In Kapitel 2 wurden aus der Forschungslücke die verschiedenen Forschungsthemen hergeleitet, aus denen wiederum verschiedene Forschungsfragen abgeleitet wurden. In Publikation II soll das Thema „Aktueller Stand der materiellen Umweltauswirkungen im deutschen Hochbau“ bearbeitet werden (Rheude & Röder, 2022). Dieses wurde in zwei Fragen unterteilt. Während Frage 2 mittels der Methodik LCA beantwortet werden soll, soll Frage 1 mittels der Methodik MFA beantwortet werden. In diesem Kapitel wird die Begründung sowie Literaturbeispiele für letztere geliefert.

In seiner einfachsten Fassung ermöglicht die Stoffstromanalyse „die systematische Bewertung der Stoffströme und -bestände innerhalb eines räumlich und zeitlich definierten Systems" (Brunner & Rechberger, 2016). Dabei findet die Methodik Anwendung in den verschiedensten Bereichen: Abfallmanagement (Allesch & Brunner, 2015), Forstwirtschaft (Gonçalves et al., 2021) oder Gesamtbetrachtung der nationalen Aluminiumproduktion (Li et al., 2021).

Werden diese Definition und Beispiele gegen die Forschungsfrage: „Wie hoch ist der Materialbedarf im deutschen Hochbau?“ gelegt, stellt sich heraus, dass die Methodik sehr gut zur Beantwortung dieser Forschungsfrage passt.

Es werden die Inputs und Outputs mittels Herstellung, Import, Export sowie Verbrauch erfasst und genutzt, um die Stoffströme innerhalb der deutschen Volkswirtschaft zu modellieren. Daher wurde beschlossen, die Methodik der MFA für die Beantwortung dieser Forschungsfrage zu verwenden.

Die genauen verwendeten Systemgrenzen und berücksichtigten Stoffströme sind in Abbildung 2 dargestellt. Die grünen Linien wurden in der Stoffstromanalyse modelliert, die gestrichelten Linien wurden zusätzlich für die Treibhausgasemissionen modelliert. Die Gewinnung von Rohstoffen wurde nicht berücksichtigt, um Doppelzählungen zu vermeiden. Darüber hinaus wurde der Abriss nicht modelliert, da es sich bei den Gebäuden in erster Linie um Neubauten handelt, daher ist die Menge der entstehenden Abfälle vernachlässigbar.

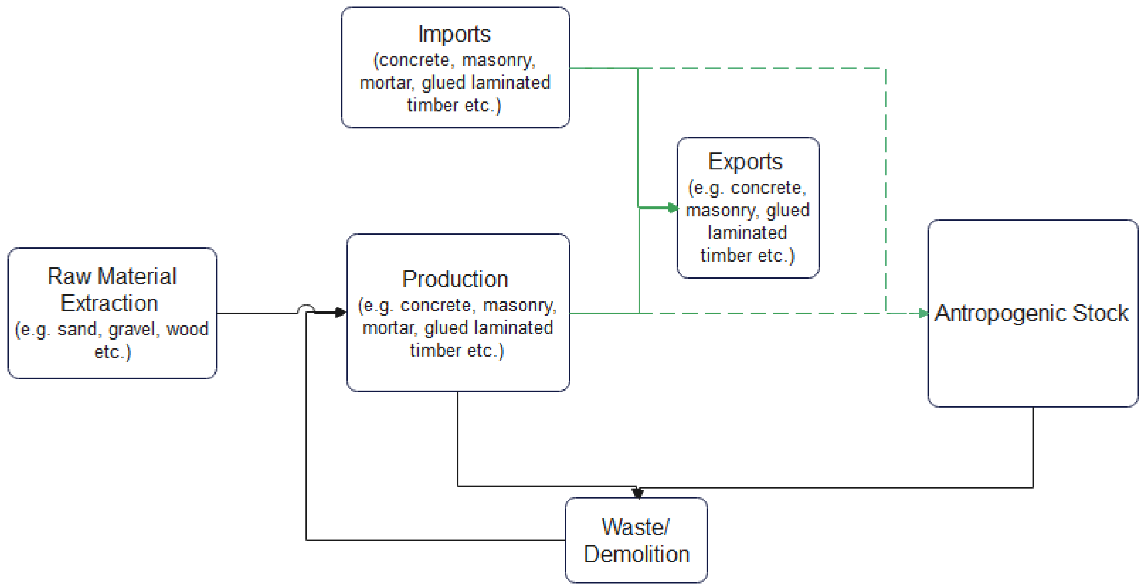

ABBILDUNG 2 SYSTEMGRENZEN DER STOFFSTROMANALYSE (RHEUDE & RÖDER, 2022)

Für die Berechnung der Baumengen wurde ein Top-Down-Ansatz verwendet, der auf dem Ansatz von Schiller et al. (2015) aufbaut und durch weitere Daten ergänzt wurde:

Produktionsstatistiken wurden mit Daten der Außenhandelsstatistik kombiniert, um die Zu- und Abflüsse von Baustoffen in den deutschen Bausektor zu modellieren (Federal Statistical Office, 2022a, 2022b). Die Kombination dieser beiden Statistiken lässt Rückschlüsse auf die inländische Verwendung von Baustoffen in Deutschland zu, da nun die drei Bereiche der inländischen Produktion, der Importe und der Exporte der verschiedenen Güter berücksichtigt werden. Nach Kohler und Yang (2007), neigen Top-down-Ansätze (wie in dieser Studie verwendet) dazu, die tatsächlichen Werte zu überschätzen, während Bottom-up-Ansätze dazu neigen, die Bausubstanz zu unterschätzen.

Es ist zu beachten, dass in dieser Studie nur die für den Endverbraucher relevanten Materialien berücksichtigt wurden (z.B. Betonfertigteile, Holzprodukte und Ziegelsteine, nicht Sand oder Zement). Eine detaillierte Beschreibung der verwendeten Methodik kann der Publikation entnommen werden (Rheude & Röder, 2022).

3.3. BESCHREIBUNG DES GEBÄUDEABRISSES

Der Abriss eines Einfamilienhauses (Baujahr 1954) wurde durch wissenschaftliche Beobachtung begleitet und als Einzelfallstudie ausgewertet (Bucher, 2020). Aufgrund der strukturellen Ähnlichkeiten des aktuellen Wohngebäudebestands in Deutschland ist der Fall typisch für viele Abrisse in den kommenden Jahren (Loga et al., 2015; Metzger et al., 2019). Die Beobachtung in der Fallstudie wurde an den systematischen Ansatz von Weischer und Gehrau (2017) angelehnt und durch Kontrollfragen in einem Beobachtungsprotokoll überprüft.

Die Volumina der Elemente in den Stücklisten wurden während der Beobachtung zweimal überprüft. Einmal, bevor die Fachleute das Gebäude in verschiedenen Schritten abbrachen, und einmal, nachdem die verschiedenen Baustofffraktionen abgebrochen und sortiert worden waren.. Die Datenqualität kann als sehr gut eingestuft werden.

Eine detaillierte Beschreibung der Methodik kann der Publikation entnommen werden (Rheude et al., 2022).

3.4. ÖKOBILANZ

Im Zuge der Arbeit wurden zwei Ökobilanzen in zwei unabhängigen Publikationen durchgeführt. Während eine Ökobilanz nach dem konsequenz-orientierten Ansatz durchgeführt wurde, wurde die andere als attributive Ökobilanz modelliert. Dies liegt daran, dass die Fragestellung in ersterer Studie einen konsequenz-orientierten Ansatz erforderte, wie in Kapitel 3.4.2 erläutert, während die zweite auf EPD-Daten aufbaute und damit einen attributiven Ansatz erforderte. Zunächst wird die Methodik der Publikation für den attributiven Ansatz präsentiert (Publikation II), dann die Methodik für den konsequenz-orientierten Ansatz (Publikation III).

3.4.1. Attributive Ökobilanz

Ziel der Ökobilanz war die Darstellung der THG-Emissionen pro Jahr, die durch die Materialität des Hochbaus verursacht wurden. Nach Curran et al. (2005) beantworten attributive Ökobilanzen die Frage, wie Dinge innerhalb eines festgelegt Zeitfensters verlaufen. Da hier die Emissionen pro Jahr, also einem festgelegten zeitlichen Rahmen erfasst werden sollen, ist die attributive Methodik anzuwenden.

Um die Klimawirkung der Produktion abzuschätzen, wurden die ermittelten Massen mit Informationen aus der Ökobaudat-Datenbank verknüpft (Federal Ministry of Housing, Urban Development and Construction, 2022). Ökobaudat ist eine Datenbank des Bundesministeriums für Wohnen, Stadtentwicklung und Bau, die einheitliche Standards bei der Ökobilanzierung von Gebäuden ermöglichen soll. Ziel der Datenbank ist die Darstellung der Ökobilanzen von Gebäuden (Federal Ministry of Housing, Urban Development and Construction, 2022). Die Datenbank enthält Umweltproduktdeklarationen (EPDs) für verschiedene Produkte und Prozesse, die für das Bauwesen relevant sind (Del Rosario et al., 2021). Die Datenbank ist so strukturiert, dass der Nutzer auf einen Blick erkennen kann, auf welches Produkt sich die EPD bezieht, ob es sich um das spezifische Produkt eines Herstellers oder um generische EPDs handelt, die für eine ganze Produktgruppe repräsentativ sind. Alle EPDs werden in Übereinstimmung mit EN 15804 erstellt (Deutsches Institut für Normung, 2022) sowie unabhängig verifiziert und regelmäßig aktualisiert, so dass der Nutzer auf abgelaufene EPDs zugreifen kann, um z. B. bestimmte Jahre zu modellieren. Die EPDs zeigen nicht einen einzigen absoluten Wert, sondern sind in verschiedene Module unterteilt, wie in Abbildung 3 dargestellt.

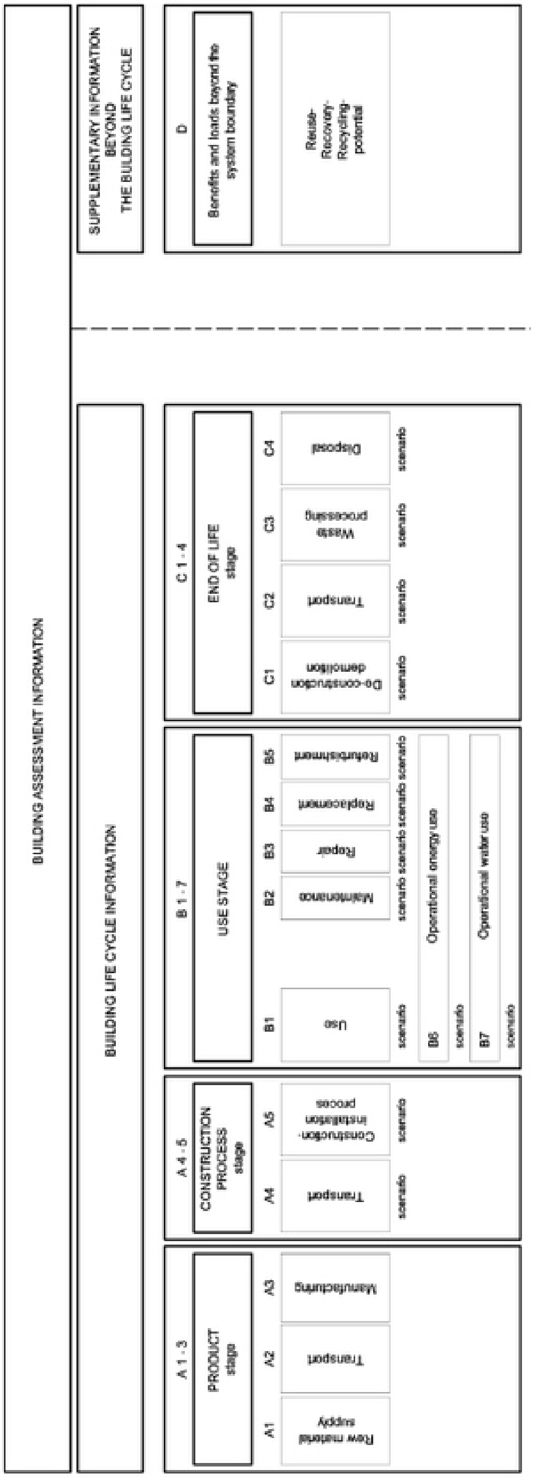

ABBILDUNG 3 LEBENSZYKLUSPHASEN UND MODULE NACH EN 15804 (TRINIUS & GOERKE, 2019)

Zur Berechnung der Treibhausgasemissionen im Zusammenhang mit der Herstellung von Baumaterialien wurden die Daten der Module A1 bis A3 verwendet, sodass sich ein Geltungsbereich von der Wiege bis zum Werkstor (sog. cradle to gate) ergibt. Für die Modellierung in dieser Studie wurden EPDs verwendet, die nicht explizit von einem Unternehmen herausgegeben wurden, sondern eine möglichst große Produktgruppe abdecken. Hintergrund ist, dass EPDs, die spezifisch für ein Produkt eines Unternehmens sind, oft nicht repräsentativ für den gesamten Markt dieser Produkte sind. Daher wurden EPDs von Verbänden und Institutionen wie dem Thünen-Institut oder dem Bundesverband der Deutschen Ziegelindustrie verwendet (Federal Association of the German Brick and Tile Industry e.V., 2015; Thünen Institute for International Forestry and Forest Economics, 2020), die in der Regel Marktdurchschnitte darstellen. Viele zuvor berechnete Produktgruppen lassen sich jedoch nicht einer einzigen EPD zuordnen. Zum Beispiel haben Betone unterschiedlicher Festigkeitsklassen eine gemeinsame Gruppe in der Produktionsstatistik, aber mehrere EPDs. Da dies zu Unsicherheiten führen kann, weil verschiedene EPDs zu unterschiedlichen Ergebnissen kommen können, wurde eine Monte-Carlo-Simulation durchgeführt.

Dazu wurden einer Produktgruppe mehrere EPDs zugewiesen und so die Minimal- und Maximalwerte für die Emissionswerte pro Produktgruppe berechnet. Diese wurden im Folgenden als Extremwerte einer Verteilung verwendet. Als Verteilung für die Monte-Carlo-Simulation wurde die Normalverteilung gewählt. Die Python-Software Brightway2 von Mutel (2017) wurde für die Kalkulation der Monte-Carlo-Simulation verwendet. Auf diese Weise kann eine Verteilung berechnet und damit eine Aussage über die durchschnittlichen Treibhausgasemissionen der im deutschen Bausektor verwendeten Baustoffe von 2012 bis 2020 getroffen werden. Diese Schritte wurden nur für Produktgruppen durchgeführt, denen mehrere EPDs zugeordnet werden konnten. Den meisten Produktgruppen (z.B. Ziegel, Brettschichtholz oder verschiedene Dachziegel) konnte eine einzige EPD zugeordnet werden.

Weitere Details der Methodik können der Publikation Rheude und Röder (2022) entnommen werden.

3.4.2. Konsequenz-orientierte Ökobilanz

Die konsequenz-orientierte Ökobilanzstudie wurde ebenfalls nach DIN 14040 und 14044 durchgeführt. Nach der DIN-Norm muss jede Ökobilanzstudie eine Ziel- und Umfangsdefinition, eine Sachbilanz, eine Wirkungsabschätzung und die Bewertung enthalten (Deutsches Institut für Normung, 2021b, 2021a).

Ziel der Studie ist es, die Umweltauswirkungen des Abrisses eines typischen Einfamilienhauses aus den 1950er Jahren in Deutschland objektiv und systematisch darzustellen. Dies geschieht vor dem Hintergrund eines vergleichsweise alten Gebäudebestandes in Deutschland mit teilweise unbekannter Materialstruktur. Die Ergebnisse sind daher richtungsweisend für die wahrscheinlichen Umweltauswirkungen und Effekte zukünftiger Abbrüche. Die Studie richtet sich in erster Linie an interessierte Wissenschaftler, weniger an Praktiker oder Hauseigentümer.

Die erfassten Mengen wurden genutzt, um eine Ökobilanz des Abbruchs und des Umwelteinflusses der anfallenden Abfälle zu erstellen. Auch wenn viele Ökobilanzen für Gebäude auf der Grundlage des attributiven Ansatzes berechnet werden, wurden hier ein konsequenter Ansatz und Datenbanken verwendet. Die Gründe dafür sind folgende:

1. Nach Curran et al. (2005) sollen mit attributiven und konsequenz-orientierten Ökobilanzen unterschiedliche Arten von Fragen beantwortet werden. Während ein attributiver Ansatz fragt: "How are things flowing within the chosen temporal window?" (Curran et al., 2005, p. 856), beantwortet ein konsequenz-orientierter Ansatz die Frage: "How will flows change in response to decisions?" (Curran et al., 2005, S. 856). Da das Ziel darin besteht, zu beurteilen, ob die geltenden Rechtsvorschriften der Europäischen Union und Deutschlands in der Praxis angewandt werden und ob Entscheidungen zur Verringerung von Bauabfällen und zur Verbesserung der Wiederverwendung getroffen werden müssen, erscheint letzteres angemessen.
2. Ferner weisen Weidema et al. (2018) darauf hin, dass die konsequenz-orientierten Lebenszyklen die Komponente "Auswirkung" der Einflusssphäre messen. Sie beschreiben Produktlebenszyklen auch als konsequenz-orientierte Lebenszyklen, was hier anwendbar ist.
3. Schließlich stellen Weidema et al. (2018) fest, dass alle Paradigmen der sozialen Verantwortung letztlich eine konsequenz-orientierte Perspektive beinhalten. Der Bausektor

hatte schon immer erhebliche soziale und wirtschaftliche Auswirkungen. Wenn man über baurechtliche Maßnahmen nachdenkt, ist es daher notwendig, bei der Suche nach Lösungen auch die soziale Komponente zu berücksichtigen.

4. Auch wenn die meisten verfügbaren Umweltproduktdeklarationen einen attributiven Ansatz verwenden, haben Weidema et al. (2020) festgestellt, dass die Kunden einen konsequenz-orientierten Ansatz stark bevorzugen und dieser daher vermehrt eingesetzt werden sollte. Die Ergebnisse dieser Studie können auch Bauherren als Kunden von Entsorgungsunternehmen als Orientierung dienen, auch wenn sie nicht primäre Zielgruppe sind. Es ist daher sinnvoll, die Ergebnisse aus der Perspektive des zukünftigen Kunden darzustellen.
5. Schließlich stellt das ILCD Handbuch (European Commission, 2010) dar dass, wenn eine Ökobilanz als Entscheidungshilfe verwendet wird, ein Modell der Lebenszyklusauswirkungen (LCI) die Folgen der Entscheidung widerspiegeln sollte.

Aus diesen Gründen wurde ein konsequenz-orientierter Ansatz gewählt. Als LCIA-Methodik zur Berechnung der Ergebnisse wurde die EPD-Methodik (2018) verwendet (EPD International AB, 2021). Diese ist für die Verwendung in Umweltproduktdeklarationen bestimmt, die im Bausektor weit verbreitet sind. Die Methode umfasst die Modellierung von insgesamt acht Wirkungskategorien. Weitere Informationen zu den Wirkungskategorien stehen auf der Website von EPD International AB (2021).

Die Systemgrenzen sind in der folgenden Abbildung im Detail zu sehen.

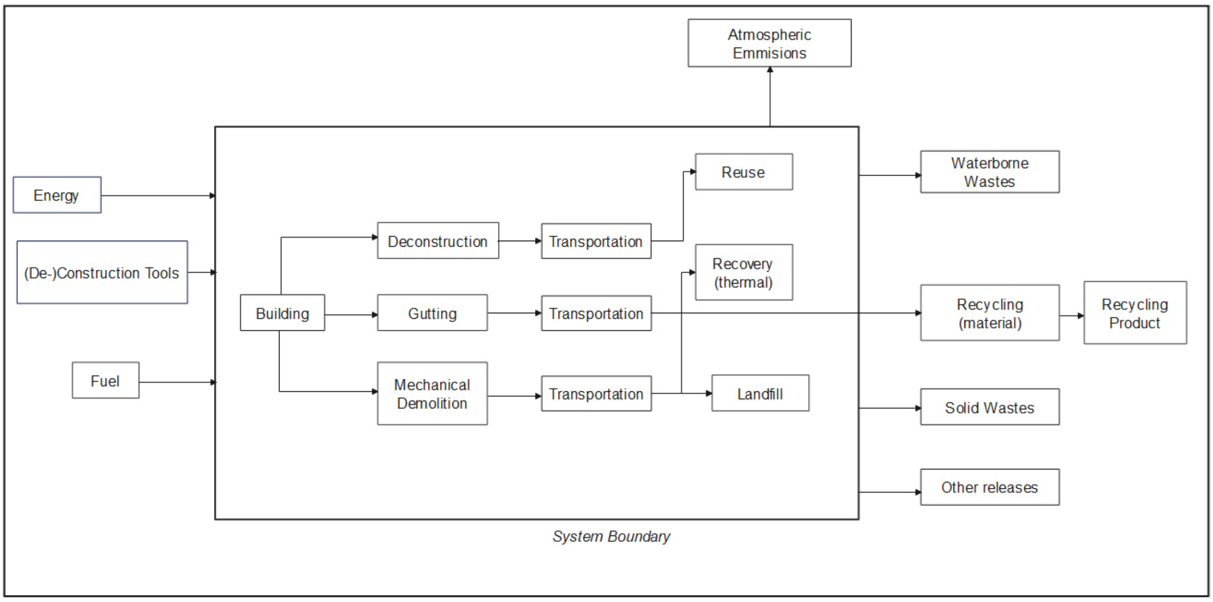

ABBILDUNG 4 SYSTEMGRENZEN DER KONSEQUENZ-ORIENTIERTEN ÖKOBILANZ-STUDIE (RHEUDE ET AL., 2022)

Eine detaillierte Beschreibung der Systemgrenzen kann Rheude et al. (2022) entnommen werden.

Die Datenqualität der Studie kann als sehr gut eingestuft werden: Die verwendeten Daten entsprechen damit dem höchstmöglichen Standard für Ökobilanzen. Es wurde die Ecoinvent 3.6 consequential - unit processes Datenbank vom Dezember 2019 verwendet, da sie eine der größten verfügbaren LCI-Datenbanken ist und sich in Ökobilanzen bereits gut etabliert hat (Ecoinvent, 2019). Im ersten Schritt der Berechnungen wurde das Hintergrundsystem mit SimaPro Version 9.0.1.7 aufgebaut (PRé, 2020). Die Ergebnisse wurden in eine CSV-Datei exportiert und mit Python-Code auf der Grundlage von Brightway2 verarbeitet, einschließlich einer Monte-Carlo-Simulation (Mutel, 2017). Hauschild et al. (2017) zeigen, dass die Monte-Carlo-Simulation eine praktikable Methode ist, um die Unsicherheiten von Ökobilanzen abzuschätzen.

Nach der Festlegung der Systemgrenzen ist die richtige Wahl einer funktionellen Einheit sehr wichtig (Deutsches Institut für Normung, 2021a, 2021b) . In dieser Fallstudie sind je nach der internationalen Norm verschiedene Wahlmöglichkeiten gegeben. Es wurde jedoch die funktionale Einheit von einem Quadratmeter Bruttoaußenfläche gewählt, um Vergleiche mit zukünftigen Abrissen zu ermöglichen (Hafner & Rüter, 2018).

Es ist ersichtlich, dass der gesamte Abbruch des Gebäudes und der Transport der Abbruchmaterialien in der Ökobilanz modelliert wurden. Die anschließende Wiederverwendung der recycelten Materialien wurde nicht simuliert. Die Bau- und Nutzungsphase des Gebäudes wurde nicht modelliert, da in dieser Fallstudie nur die Folgen des Abbruchs von Interesse sind.

Eine detaillierte Beschreibung der Methodik kann Rheude et al. (2022) entnommen werden.

4. ERGEBNISSE

Im Folgenden werden die Ergebnisse der Dissertation in Form der Zusammenfassung der wissenschaftlichen Artikel, die in diesem Rahmen erstellt wurden, dargestellt. Die Reihenfolge der Vorstellung richtet sich nach dem Zeitpunkt, an welchem die Artikel das erste Mal bei wissenschaftlichen peer-review Journalen eingereicht wurden. Im Anschluss an die Präsentation der publizierten Arbeiten werden die Forschungsfragen detailliert beantwortet. Eine Zusammenfassung der Forschungsergebnisse schließt das Kapitel ab.

4.1. REVIEW OF THE TERMINOLOGY IN THE SUSTAINABLE BUILDING SECTOR

In den letzten zehn Jahren hat sich die Forschung im Bereich der Nachhaltigkeit im Bauwesen entwickelt. Es wurden viele Lösungsansätze entwickelt, um die Umweltauswirkungen von Gebäuden zu verringern und ihren sozialen Wert zu erhöhen und gleichzeitig die wirtschaftliche Machbarkeit zu erreichen. Mit der Vielfalt der neuen Instrumente und Modelle stieg jedoch auch die Zahl der neuen, spezifischen Begriffe zur Beschreibung neuer Ansätze und Entwicklungen. Dies führt teilweise zu Missverständnissen und Verwirrung in der wissenschaftlichen Gemeinschaft, bei Unternehmen und Behörden, die an der Planung, Genehmigung und Errichtung von Gebäuden beteiligt sind. In diesem Beitrag wird daher ein Überblick über verschiedene Begriffe gegeben, deren Definitionen - soweit möglich - herausgearbeitet und die Begriffe in Beziehung zueinander gesetzt. Die Literaturrecherche wurde mit Hilfe der Datenbank Scopus und der systematischen Literaturrecherche durchgeführt, um die verschiedenen Schlagwörter zu ermitteln. Insgesamt wurden 11 Schlagworte aus den Bereichen Bau, Konstruktion, Design, Management und Planung identifiziert. Anschließend wurde ein Pool von Artikeln ausgewählt und für jedes dieser Schlüsselwörter analysiert, um eine genaue Definition für jedes von ihnen zu finden. Die Ergebnisse zeigten, dass klare Definitionen für die meisten Schlüsselwörter möglich sind. Einige der derzeit verwendeten Schlüsselwörter sollten nicht im Zusammenhang mit Nachhaltigkeit und Gebäuden oder Bauwesen verwendet werden, um weitere Verwirrungen zu vermeiden. Die Studie trägt dazu bei, die Kommunikation zwischen Wissenschaftlern verschiedener Disziplinen zu verbessern und so eine effiziente Weiterentwicklung der Nachhaltigkeit im Bausektor zu ermöglichen, indem auf dem bereits vorhandenen Know-how aufgebaut wird.

Die Ergebnisse sind in Tabelle 2 dargestellt. Die Definitionen wurden aus dem englischen Original der Publikation zum Zwecke dieser Dissertation ins Deutsche übersetzt. [1]

[1] Rheude F., Kondrasch J., Röder H., Fröhling M. (2021): Review of the terminology in the sustainable building sector. In: Journal of Cleaner Production. DOI: 10.1016/j.jclepro.2020.125445

TABELLE 2 ERGEBNISSE DER DEFINITIONEN FÜR NACHHALTIGE GEBÄUDE (RHEUDE ET AL., 2021)

Thema	Ökologisch	Umweltfreundlich	Grün	Nachhaltig
Gebäude	Außerhalb des Untersuchungsbereichs	Berücksichtigt Umweltaspekte für Gebäudematerialien und -prozesse	Berücksichtigt ökologische- und soziale Aspekte über den kompletten Lebenszyklus	Berücksichtigt ökologische-, ökonomische und soziale Aspekte über den kompletten Lebenszyklus
Konstruktion	Sollte nicht in diesem Kontext verwendet werden	Berücksichtigt Umweltaspekte für Baumaterialien und -prozesse	Berücksichtigt ökologische- und soziale Aspekte über den kompletten Lebenszyklus	Berücksichtigt ökologische-, ökonomische und soziale Aspekte über den kompletten Lebenszyklus
Design	Berücksichtigt Umweltaspekte über den kompletten Lebenszyklus von Gebäuden und Strukturen	Reduziert THG-Emissionen, erhöht die nachhaltige Verwendung von Boden und Ressourcen und berücksichtigt soziale Aspekte	Außerhalb des Untersuchungsbereichs	Beinhaltet ökologische, ökonomische und soziale Kriterien über den ganzen Designprozess
Management	Außerhalb des Untersuchungsbereichs	Management von Umweltaspekten, Verpflichtungen zur Einhaltung von Vorschriften und Umgang mit Risiken und Chancen	Außerhalb des Untersuchungsbereichs	Außerhalb des Untersuchungsbereichs
Planung	Außerhalb des Untersuchungsbereichs	Planung mit Fokus auf Nachhaltigkeit und die weltweite Umwelt	Außerhalb des Untersuchungsbereichs	Außerhalb des Untersuchungsbereichs

Leistungsbeiträge des Autors:

- Konzeption der Forschungsfrage
- Entwicklung der Methodik des Literature-Reviews, Visualisierung und Beschreibung der Ergebnisse
- Federführende Ausarbeitung und Verfassen der Publikation
- Federführend verantwortlich für den Review-Prozess

4.2. ESTIMATING THE USE OF MATERIALS AND THEIR GHG EMISSIONS IN THE GERMAN BUILDING SECTOR

Das Ziel der wissenschaftlichen Arbeit war die Abschätzung der Treibhausgasemissionen, die die Materialität des Hochbausektors in Deutschland in den Jahren 2012 bis 2020 verursacht haben.

Der Bau- und Gebäudesektor ist einer der größten Emittenten von Treibhausgasen. In dieser Studie wurde der Materialeinsatz im Rohbau des deutschen Bausektors von 2012 bis 2020 mittels Stoffstromanalyse berechnet. Anschließend wurden die jährlichen Treibhausgasemissionen im deutschen Gebäudesektor mit den Umweltproduktdeklarationen aus der Ökobaudat-Datenbank und den modellierten Materialien simuliert. Es konnte gezeigt werden, dass der Anteil biogener Materialien an der Wertschöpfung immer größer wird und überproportional wächst. Es konnte ebenfalls gezeigt werden, dass durch die Zunahme biogener Materialien das Bauen leichter und effizienter wird und die Treibhausgasemissionen des Rohbaus in diesem Zeitraum reduziert werden. Zusammenfassend lässt sich sagen, dass der Hochbausektor in Deutschland immer noch sehr hohe Treibhausgasemissionen von rund 26 Millionen Tonnen CO_2-Äq. aufweist. Dennoch steht er insgesamt besser da als zu Beginn des Untersuchungszeitraums, was der effizienten Nutzung der vorhandenen Ressourcen zu verdanken ist. [2]

[2] Rheude F., Röder H. (2022): Estimating the use of materials and their GHG emissions in the German building sector. In: Cleaner Environmental Systems. DOI: 10.1016/j.cesys.2022.100095

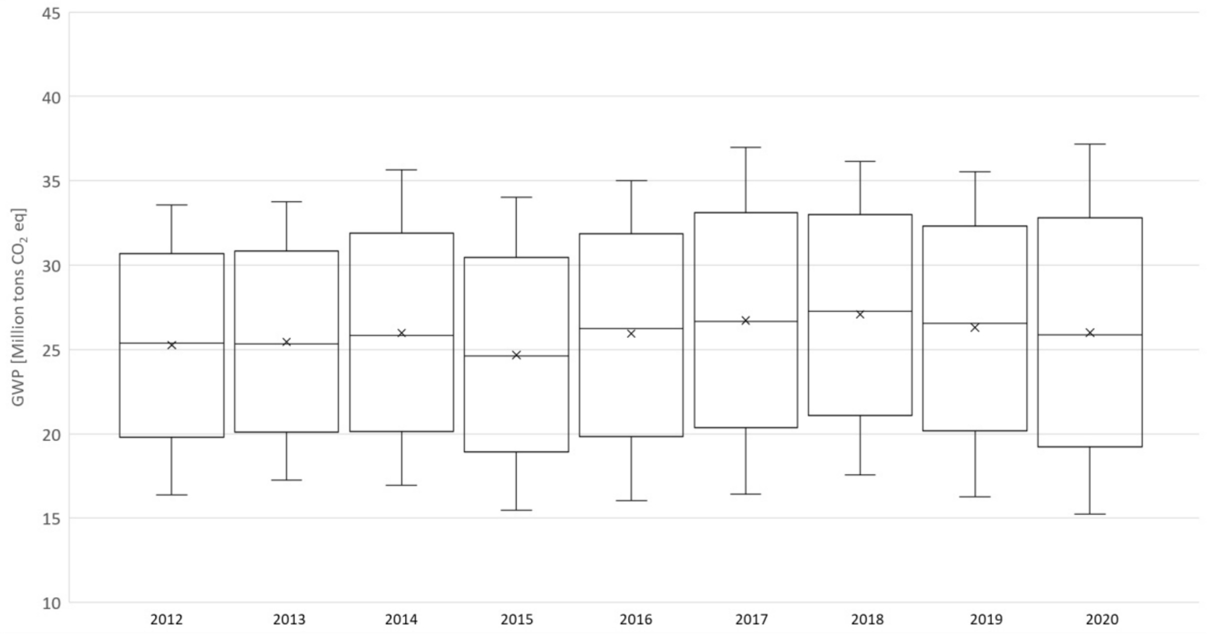

ABBILDUNG 5 TREIBHAUSGASEMISSIONEN VON 2012 BIS 2020 IN MILLIONEN TONNEN PRO JAHR (RHEUDE & RÖDER, 2022)

Leistungsbeiträge des Autors:

- Konzeption der Forschungsfrage
- Entwicklung der Methodik, Visualisierung und Beschreibung der Ergebnisse
- Federführende Ausarbeitung und Verfassen der Publikation
- Federführend verantwortlich für den Review-Prozess

4.3. RESIDENTIAL DEMOLITION AND RECYCLING - AN ECOBALANCING CASE STUDY

Das Ziel der wissenschaftlichen Arbeit war eine Abschätzung der Emissionen, die durch den Abriss von Wohngebäuden in Deutschland entstehen. Hierzu wurde ein typisches Wohngebäude der 50ziger Jahre ausgewählt, welche noch einen großen Anteil aller Wohngebäude in Deutschland stellen.

Aufgrund ihrer Struktur und ihres Alters werden in Deutschland in den kommenden Jahren viele Gebäude abgerissen werden. In dieser Fallstudie wird der Abriss eines typischen Einfamilienhauses aus den 1950er Jahren in Süddeutschland untersucht. Unter Berücksichtigung der gesetzlichen Vorgaben wurde eine Ökobilanz durchgeführt, um die Umweltauswirkungen des Abrisses zu simulieren und die Einhaltung der gesetzlichen Vorgaben zu überprüfen. Es wurde festgestellt, dass 80,3 % des gesamten Bauvolumens deponiert, 14,4 % thermisch verwertet, 0,6 % recycelt und 4,7 % wiederverwendet wurden. Darüber hinaus wurde das Treibhauspotenzial mit einem Mittelwert von 96,59 kg CO2 eq pro Quadratmeter Bruttoaußenfläche bewertet. Diese Ergebnisse zeigen, dass es in Deutschland noch Raum für eine ökologische Optimierung des Abbruchs und der Verwertung von Baurestmassen gibt. [3]

[3] Rheude F. Bucher A. Röder H. (2022): Residential demolition and waste management – An ecobalancing case study. In: Cleaner Waste Systems. DOI: 10.1016/j.clwas.2022.100056

TABELLE 3 ERGEBNISSE DER KONSEQUENZ-ORIENTIERTEN ÖKOBILANZSTUDIE (RHEUDE ET AL., 2022)

WK	AP	EP	GWP 100	POFP	ADPE	ADPF	WSF	ODP
Einheit	[kg SO_2 eq]	[kg PO_4 eq]	[kg CO_2 eq]	[kg NMVOC]	[kg Sb eq]	[MJ]	[m^3 H_2O]	[kg CFC-11 eq]
Durch-schnitt	0.091	0.024	96.596	0.574	0.001	1886.69	28.732	3.226e-05
Min	0.068	0.020	92.839	0.557	0.001	1838.09	26.702	3.184e-05
25 %	0.068	0.023	95.743	0.570	0.001	1873.21	28.230	3.214e-05
50 %	0.084	0.024	96.605	0.574	0.001	1887.05	28.763	3.225e-05
75 %	0.098	0.024	97.491	0.579	0.001	1898.68	29.264	3.237e-05
Max	0.115	0.027	100.122	0.595	0.001	1937.23	30.944	3.268e-05

Leistungsbeiträge des Autors:

- Konzeption der Forschungsfrage
- Entwicklung der Methodik zur Durchführung der Ökobilanz, Visualisierung und Beschreibung der zentralen Ergebnisse
- Federführende Ausarbeitung und Verfassen der Publikation
- Federführend verantwortlich für den Review-Prozess

4.4 BEANTWORTUNG DER FORSCHUNGSFRAGEN

In diesem Unterkapitel werden die in Kapitel 2 gestellten Forschungsfragen zusammengefasst beantwortet, bevor sie im darauffolgenden Kapitel übergeordnet diskutiert werden.

4.4.1. DEFINITION NACHHALTIGES GEBÄUDE

Forschungsfrage 1: „In welchem Zusammenhang werden derzeit bestimmte Schlüsselwörter im Zusammenhang mit nachhaltigem und ökologischem Bauen verwendet?“

Nach Durchführung der in Kapitel 3.1 beschriebenen Literaturübersicht wurden zur Beantwortung der Forschungsfrage die untersuchten Begriffe sowohl zeitlich nach ihrem Auftreten, als auch geordnet nach den häufigsten wissenschaftlichen Zeitschriften und thematisch nach den zentralen Themen aller wissenschaftlicher Zeitschriften geordnet. Auf Basis dessen und der konkreten Verwendung der jeweiligen Begrifflichkeiten wurden im Anschluss Definitionen herausgearbeitet. Im Folgenden sind zentralen Ergebnisse graphisch dargestellt. Es ist zu berücksichtigen, dass die Ergebnisse für die jeweiligen Suchbegriffe in den wissenschaftlichen Datenbanken so gering war, dass nicht für jeden Begriff eine graphische Darstellung möglich war. Exemplarisch wird dies im Folgenden für die Begriffe, die sich direkt mit dem Gebäudebereich beschäftigt haben, gezeigt. Für die weiteren Begrifflichkeiten wird auf die Publikation verwiesen (Rheude et al., 2021).

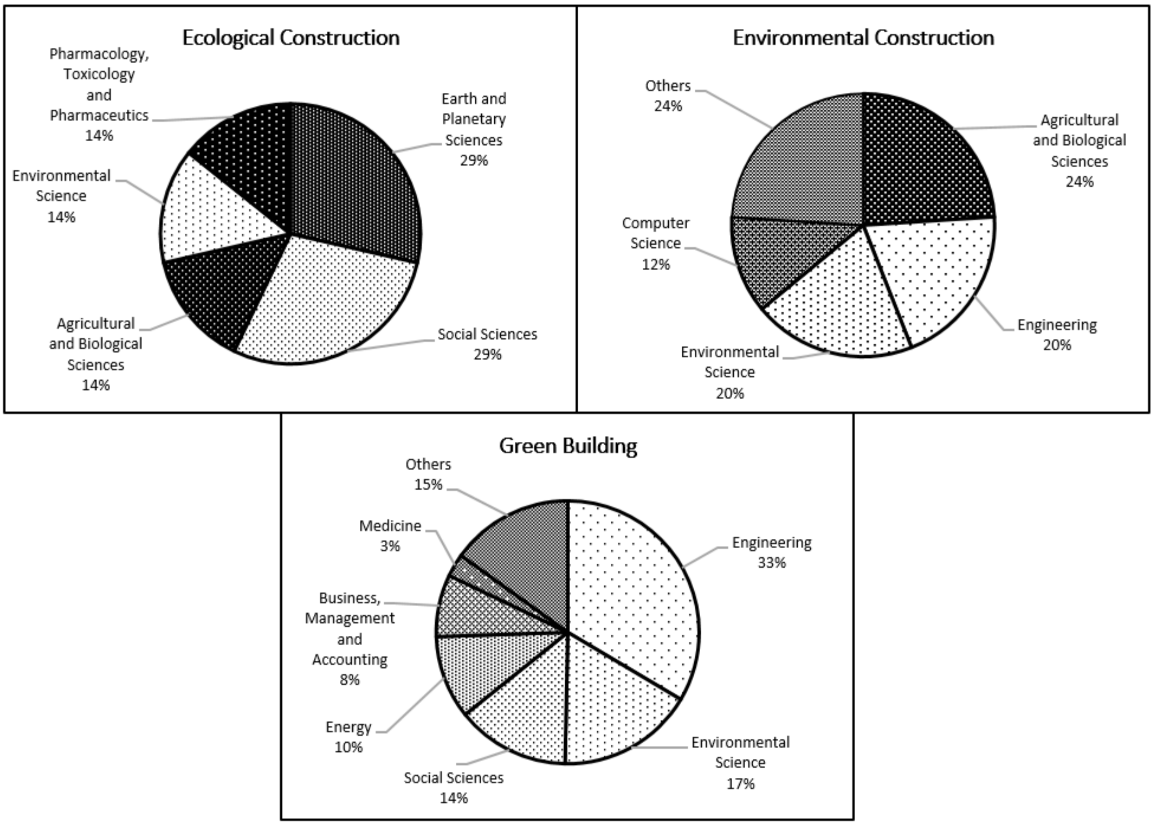

ABBILDUNG 6 PROZENTUALER ANTEIL DER VERSCHIEDENEN THEMENBEREICHE, DIE MIT DEN VERSCHIEDENEN STICHWÖRTERN VERBUNDEN SIND (RHEUDE ET AL., 2021)

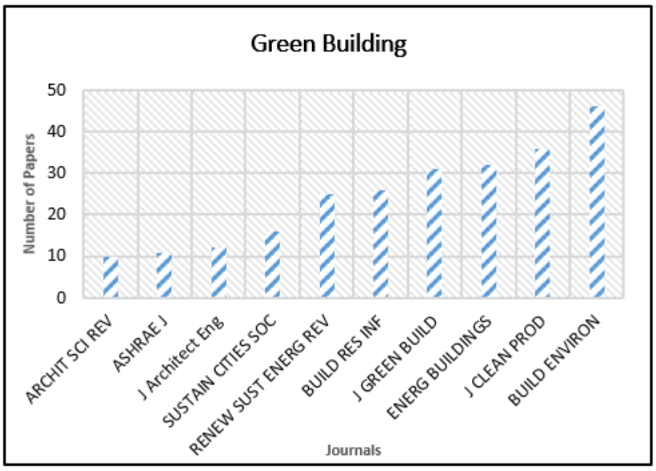

ABBILDUNG 7 ANZAHL DER PUBLIKATIONEN, DIE MIT DEM STICHWORT "GREEN BUILDING" IN VERBINDUNG STEHEN (RHEUDE ET AL., 2021)

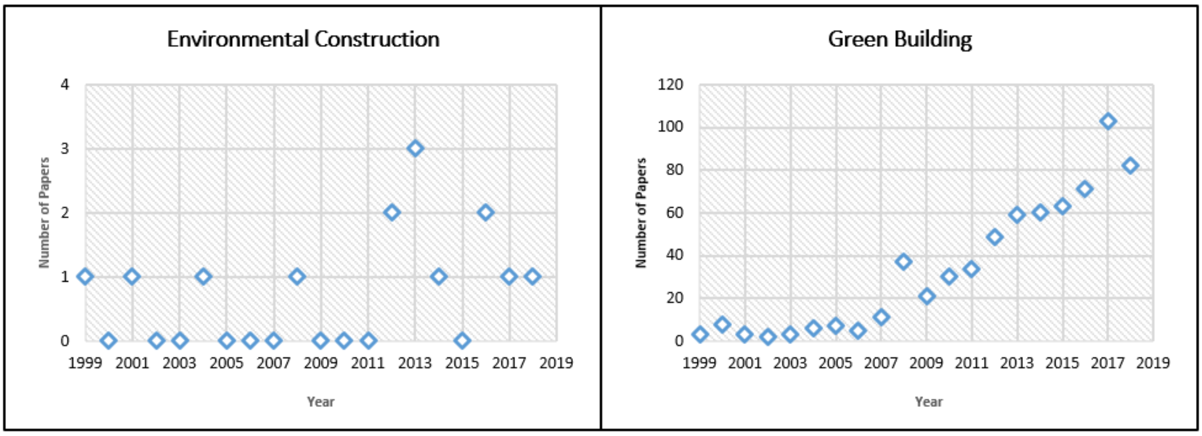

ABBILDUNG 8 ANZAHL DER ASSOZIIERTEN PUBLIKATIONEN IM ZEITRAUM VON 1999 BIS 2018 (RHEUDE ET AL., 2021)

Forschungsfrage 2: „Sind spezifische Definitionen und Anwendungsfälle für diese Begriffe möglich?“

Es konnte herausgearbeitet werden, dass für jedes Schlagwort eine Definition und ein Anwendungsfall möglich ist. Im Folgenden wird dies wieder am Beispiel der gebäudespezifischen Schlagworte dargestellt. Einen Überblick über alle untersuchten Begriffe bietet Tabelle 2.

Für das Herausarbeiten der Definitionen wurde die Literatur, in der das Schlagwort verwendet wurde, gelesen und sortiert (Vergleiche Abbildung 1).

Es wurden dann folgende Definitionen für die Begriffe herausgearbeitet:

Green Building: "Ein grünes Gebäude ist die Schaffung von Strukturen, die während des gesamten Lebenszyklus eines Gebäudes umweltverträglich [, sozialverträglich] und ressourceneffizient sind.“

Environmental Building: "Ein Gebäude, dessen Konstruktion [sowohl die verwendeten Materialien als auch die für den Bau erforderlichen Prozesse] auf Umweltfreundlichkeit ausgerichtet sind.“

Environmental Construction: „Eine Struktur (bspw. Straße, Damm oder Tunnel), dessen Konstruktion [sowohl die verwendeten Materialien als auch die für den Bau erforderlichen Prozesse] auf Umweltfreundlichkeit ausgerichtet sind.“

Sustainable Building; „Ein Gebäude, bei dessen Errichtung, Betrieb und Abriss ökonomische, ökologische und soziale Aspekte zu gleichen Teilen berücksichtigt werden.“

Desweiteren konnte folgende Begriffe klar voneinander abgetrennt werden:

1. Der Begriff "Gebäude" (engl. Building) sollte nur verwendet werden, wenn er sich auf oberirdische Bauwerke bezieht, während sich der Begriff "Bauwerke" (engl. Construction) auf alle anderen von Menschenhand errichteten Bauwerke wie Straßen, Tunnel oder Dämme bezieht.
2. Der Begriff "grün" (engl. green) bezieht sich auf den gesamten Lebenszyklus eines Gebäudes oder einer Konstruktion, nicht nur auf die verwendeten Materialien, während sich der Begriff "umweltfreundlich" (engl. Environmental) hauptsächlich auf die Materialien und Verfahren zum Bau der Strukturen bezieht.
3. Die Begriffe "ökologisch" (engl. ecological) und "umweltfreundlich" (engl. environmental) sind keine Synonyme und sollten daher mit Bedacht verwendet werden; der Begriff "ökologisch" sollte im Zusammenhang mit Gebäuden und Bauwerken nicht verwendet werden, um Verwechslungen zu vermeiden.

4.4.2. Aktueller Stand der materiellen Nachhaltigkeit im deutschen Hochbau

Forschungsfrage 3: „Wie hoch ist der Materialbedarf im deutschen Hochbau?“

Zur Beantwortung dieser Frage wurde für den Zeitraum von 2012 bis 2020 eine Materialanalyse vorgenommen. Dabei konnte in Publikation II folgende Abbildung für den untersuchten Zeitraum herausgearbeitet werden (Rheude & Röder, 2022). Die untersuchten Baustoffe wurden für eine übersichtlichere Darstellung in die drei Kategorien „biogen“, „mineralisch / fossil“ und „metallisch“ unterteilt.

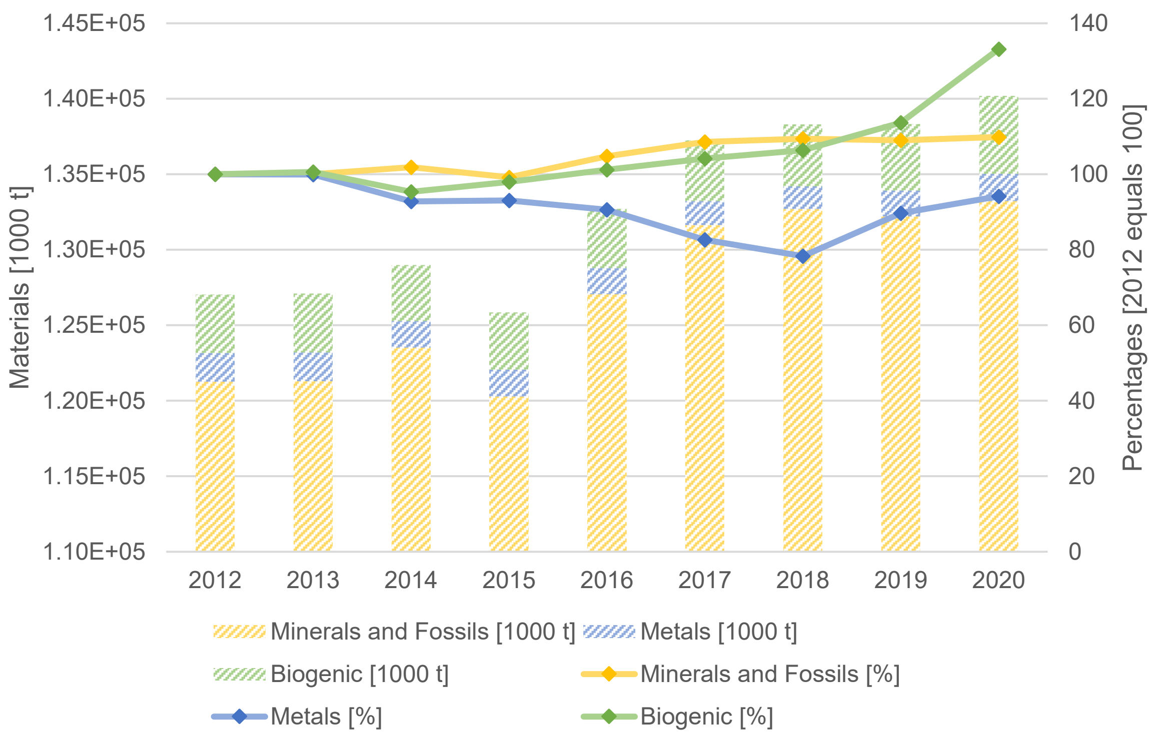

ABBILDUNG 9 JÄHRLICHER MATERIALVERBRAUCH IM DEUTSCHEN HOCHBAU VON 2012 BIS 2020 (RHEUDE & RÖDER, 2022)

Abbildung 9 zeigt, wie sich zum einen das Verhältnis von mineralischen und fossilen zu metallischen und biogenen Rohstoffen im Rohbausektor in den letzten Jahren verändert hat. Andererseits hat sich aber auch das Verhältnis der absoluten Massen verändert. Hier zeigt sich, dass es in den Jahren 2012 bis 2015 nur geringe Veränderungen des Materialeinsatzes im deutschen Bausektor gab, wobei 2015 das Jahr mit dem geringsten Einsatz im gesamten Modellzeitraum war. Von 2015 bis 2017 ist im Folgenden ein deutlicher Anstieg des Materialeinsatzes zu erkennen, der sich bis 2020 abschwächt. In den Gesamtzahlen sind die Schwankungen und der letztendliche Anstieg vor allem auf den Einsatz von mineralischen und fossilen Baustoffen zurückzuführen. Insgesamt ist im modellierten Zeitraum ein Wachstum des Sektors zu erkennen. Auffällig ist, dass die meisten Baustoffe nach wie vor mineralischen Ursprungs sind, aber der größte prozentuale Zuwachs im Betrachtungszeitraum in den letzten Jahren bei den biogenen Baustoffen zu verzeichnen ist. Dieser Zuwachs ist ab 2014 zu beobachten, findet aber hauptsächlich in den Jahren 2018 bis 2020 statt. Insgesamt wurden im Jahr 2020 fast 33,2 % mehr biogene Baustoffe eingesetzt als im Jahr 2012. Damit konnte die oben gestellte Forschungsfrage beantwortet werden.

Forschungsfrage 4: „Wie hoch ist die materialbasierte Klimawirkung von Gebäuden in Deutschland in den letzten Jahren?“

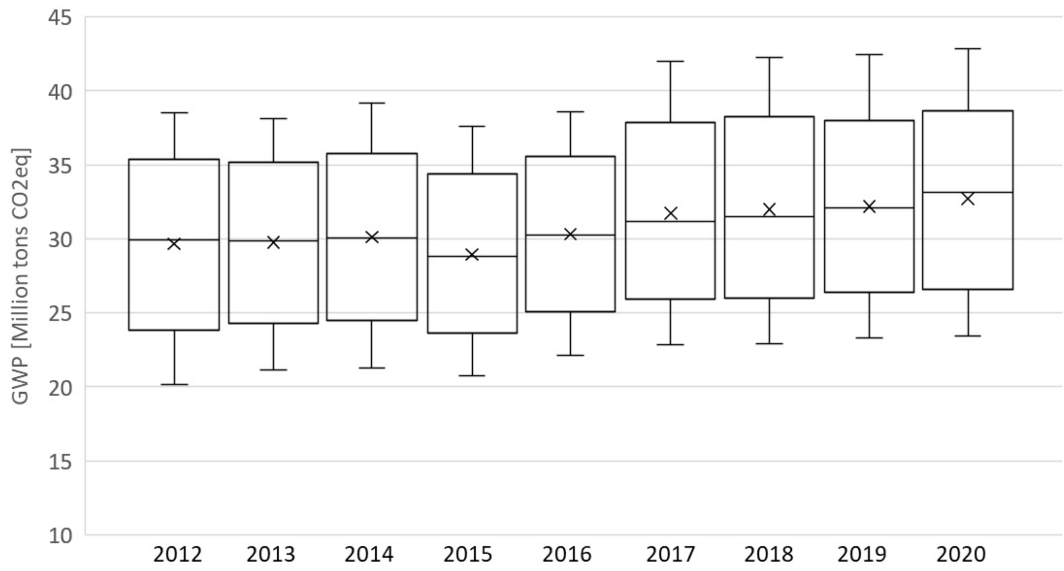

ABBILDUNG 10 THG-EMISSIONEN DER MINERALISCHE UND METALLISCHEN BAUSTOFFE VON 2012 BIS 2020 (RHEUDE & RÖDER, 2022)

Abbildung 10 zeigt die Treibhausgasemissionen der mineralischen und metallischen Baustoffe für den Hochbau über die simulierten Jahre. Ergänzend sei auf Abbildung 5 verwiesen, welche die Gesamtemissionen aufzeigt. Grundlage für die Simulation waren die Zahlen aus Abbildung 9 sowie die Ökobaudat. Aufgrund der großen Unsicherheit, die durch die Verwendung von EPDs bei der Zusammensetzung einiger Produktarten entsteht, gibt es eine große Streuung bei den Ergebnissen. Daher unterscheiden sich die verschiedenen Jahre nicht signifikant voneinander. Auch hier hat 2015 einen niedrigeren Durchschnittswert von 24,593 Millionen Tonnen CO_2 eq. Das Jahr mit den höchsten durchschnittlichen Emissionen ist dagegen 2018 mit 27,259 Millionen Tonnen CO_2 eq. Insgesamt sind die durchschnittlichen Emissionen für den modellierten Zeitraum leicht angestiegen, wenn auch nicht signifikant.

Für die Jahre 2018 bis 2020 ist sogar ein leichter durchschnittlicher Rückgang der THG-Emissionen zu erkennen, obwohl der Materialverbrauch im gleichen Zeitraum insgesamt um etwa 3% gestiegen ist. Dies ist vor allem auf die vermehrte Nutzung der biogenen Baustoffe zurückzuführen, wie Abbildung 11 zeigt.

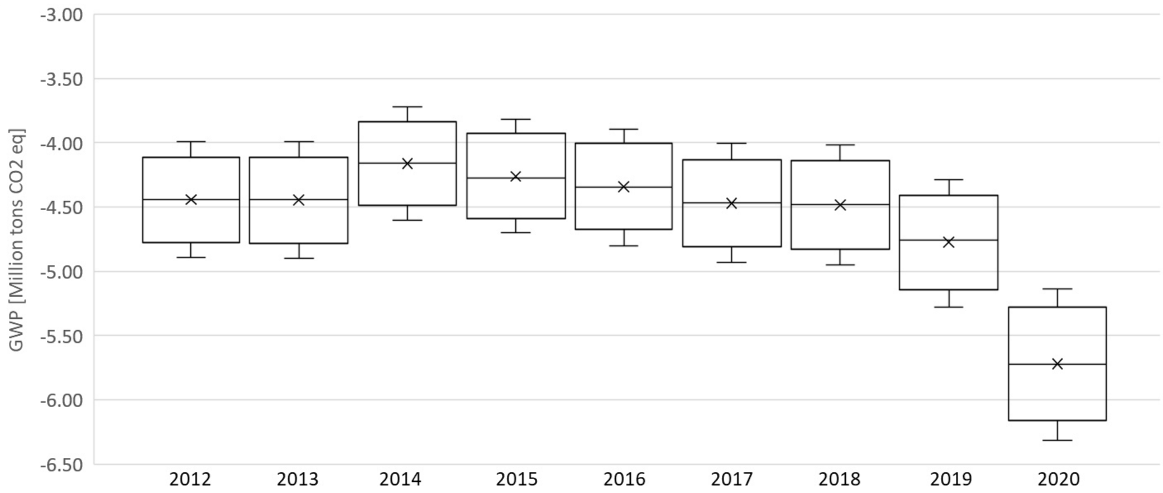

ABBILDUNG 11 THG-EMISSIONEN VON 2012 BIS 2020 FÜR DIE GRUPPE DER BIOGENEN BAUSTOFFE (RHEUDE & RÖDER, 2022)

In Abbildung 11 ist deutlich zu erkennen, dass die Einsparungen (negative GWP [Millionen Tonnen CO_2 eq]) seit dem Jahr 2015 immer weiter zugenommen haben, bevor im Jahr 2020 die gesamten Bau-THG-Emissionen aus biogenen Materialien ein vorläufiges Minimum erreicht haben.

Die berechneten Gesamtemissionen können auch in CO_2 eq/ Quadratmeter Fläche umgerechnet werden. Für die vorliegende Studie kann ein Durchschnittswert von 404 kg CO2 eq/m2 über alle Jahre berechnet werden, wobei der größte Wert im Jahr 2012 bei 438 kg CO2 eq/m2 und der kleinste Wert im Jahr 2020 bei 377 kg CO2 eq/m2 liegt (Rheude & Röder, 2022).

Damit konnte auch Forschungsfrage 4 erfolgreich beantwortet werden.

4.4.3. Aktueller Stand der Umweltauswirkungen beim Abriss von Gebäuden in Deutschland

Forschungsfrage 5: „Was sind die Umweltauswirkungen von Abbrucharbeiten eines typischen deutschen Einfamilienhauses?“

Zur Beantwortung dieser Forschungsfrage wurde eine Fallstudie durchgeführt. Das untersuchte Gebäude war 9 m breit und 8,6 m lang und stand nicht unter Denkmalschutz. Demnach beträgt die Bruttoaußenfläche 77,4 m², die Firsthöhe 5,8 m und der Bruttorauminhalt einschließlich der 10,5 m² großen Anbauten 606,5 m³. Es handelt sich um ein mehrstöckiges Gebäude in Massivbauweise mit einem Keller. Die Fundamente und tragenden Wände sind betoniert, das Innere besteht aus Ziegelmauerwerk, der Dachstuhl ist eine Holzkonstruktion.

Folgende Massen wurden im Rahmen der Studie identifiziert:

TABELLE 4 SORTIERRATEN FÜR GEBÄUDEABBRUCH, (RHEUDE ET AL., 2022)

Material-gruppe	BV [m^3]	D [m^3]	D [%]	G [m^3]	G [%]	M [m^3]	M [%]	SQ [%]
Holz	19,697	2,522	12,8	4,869	24,7	10,573	53,7	91,2
Metall	10,059	7,9	78,5	0,31	3,1	0,68	8,6	88,4
Bitumen-gemisch	0.828			0,577	69,7			69,7
Plastik	7,999			3,167	63,4			63,4
Dämmma-terial	39,364			11,19	28,4	10,05	25,5	53,9
Betone	179,289	2,702	1,5			60,251[1] 27,0722[2]	48,4	49,9
Glas	0,225	0,073	32,4					32,4
Plaster-steine		0,485						0
Ziegel-steine	32,503							0
Keramik	0,884							0
Kork	0,192			0,192	100			100
Komposit-baustoffe	3,949	0,68	17,2	1,995	50,5			67.7
Granit	1,925					0,788	40,9	40,9
Marmor	0,13							0
Disper-sionsfarbe	0,83							0
Tapeten	0,187							0
Mischabfall				1,035		21,839		
Sonstige Bauabfälle						127,082		
Total	295,546	13,877	4,7	23,335	7,9	258,334	87,4	

Die Abkürzungen in der Tabelle stehen für BV: Gesamtbauvolumen, D: Rückbau zur Wiederverwendung, G: Entkernung, M: mechanischer Abbruch, SQ: Sortierrate, [1]: Beton (60 m^3) mit Anstrich in Dispersionsfarbe, [2]: Beton ohne Anstrich.

Die höchste Homogenitätsrate für die zehn Materialgruppen wurde für Holz mit einer Sortierrate von 91,2 % festgestellt. Insgesamt wurden 2,522 m^3 Holz für die Wiederverwendung entnommen, was 12,8 % des gesamten verwendeten Holzes entspricht. 4,869 m^3 Holz wurden durch Entkernung aus dem Gebäude entfernt (24,7 %), und 10,573 m^3 wurden durch mechanischen Abbruch als sortenrein erfasst (53,7 %). Die restlichen 8,8 % des Holzes waren Teil des gemischten Abfalls. Metalle erreichten mit 88,4 % die zweithöchste Sortierquote. Der Rest, der als Bauabfall erfasst wurde, besteht aus Gussrohren, Heizungsrohren, Fenstergittern, Geländerstützen und metallbewehrtem Beton. An dritter Stelle rangiert die Sortierquote von bituminösem Mischgut mit 69,7 %. Dies entspricht dem Anteil des getrennten Estrichs aus Gussasphalt. Die bituminöse Beschichtung der Kelleraußenwand (0,141 m^3) wurde nicht von der Wand getrennt und die verklebte Dachpappe wurde als Mischabfall erfasst.

Die Sortierquote für den gesamten Gebäudeabbruch beträgt:

1. 92,3 %, wenn nur der gemischte Abfall als unsortiertes Material betrachtet wird
2. 49,3 %, wenn gemischte Abfälle und Bauabfälle als unsortiertes Material betrachtet werden
3. 40,1 %, wenn zusätzlich die Kellerwand mit Bitumenbeschichtung als unsortiertes Material betrachtet wird
4. 19,7 %, wenn zusätzlich der Beton mit einem Anstrich aus Dispersionsfarbe als unsortiertes Material angesehen wird

Mithilfe dieser Daten sowie der Transportdistanzen, die zurückgelegt wurden, konnte zunächst ein LCI erstellt werden, welches dann Ausgangsbasis für ein LCA war. Die Ergebnisse sind in Tabelle 3 zusehen. Außerdem wurden die Ergebnisse nach Quadratmeter Brutto-Außenfläche und den betrachteten Modulen nach DIN 15978 geordnet. Dabei entstand folgende Tabelle zu den Umweltwirkungen:

TABELLE 5 WIRKUNGSABSCHÄTZUNG NACH DEN VERSCHIEDENEN MODULEN GEMÄß DIN 15978 PRO QUADRATMETER BRUTTO-AUßENFLÄCHE (RHEUDE ET AL., 2022)

Wirkungskategorie	Einheit	Modul C1	Modul C2	Modul C3	Modul C4
AP	kg SO_2 eq	0.0380	0.3501	-0.2863	-0.0099
GP	kg PO_4--- eq	0.0067	0.0836	-0.2211	0.1547
GWP100	kg CO_2 eq	4.3095	104.5759	-20.2698	8.0023
POFP	kg NMVOC	0.0303	0.4522	-0.1239	0.2160
ADPE	kg Sb eq	2.1629E-05	0.0006	-1.233E-05	0.0004
ADPF	MJ	457.0993	1604.4150	-405.3344	231.3127
WSF	m^3 eq	0.1385	5.5148	-12.0466	35.0662
ODP	kg CFC-11 eq	5.8801E-06	1.9432E-05	2.7584E-10	6.9475E-06

Es fällt auf, dass Modul C3, Abfallbehandlung zur Verwertung, Recycling und energetische Verwertung, ausschließlich negative Werte aufweist. Dies ist auf zwei Gründe zurückzuführen: 1. das Modul ist nicht vollständig, da die Schritte für die stoffliche Verwertung nicht simuliert werden konnten, da diese zum Zeitpunkt der Studie noch nicht bekannt waren und 2. da es sich um eine konsequenz-orientierte LCA handelt, gibt es Nettoeinsparungen durch die Verbrennung des Holzes im deutschen Energiemix, da alternativ Kohle für die energetische Verwertung verbrannt werden würde. Insgesamt hat Modul C2 den größten Einfluss auf die Umweltauswirkungen. Dies ist darauf zurückzuführen, dass der Abfall über längere Strecken mit Lastwagen mit Verbrennungsmotoren transportiert werden muss. Dies verursacht bei weitem die größten Umweltauswirkungen. Modul C1 enthält dagegen nur den Kraftstoffverbrauch des Baggers auf der Baustelle. Eine Umstellung auf Elektro-Baustellenfahrzeuge könnte die Klimabilanz des Abbruchs insgesamt deutlich verbessern.

Damit konnte auch diese Forschungsfrage beantwortet werden.

Forschungsfrage 6: „Welche Auswirkungen auf die THG-Emissionen des Hochbaus kann eine erhöhte Nutzung von Recycling-Beton haben?“

Wie aus Tabelle 4 hervorgeht wurde nur ein geringer Prozentsatz des verbauten Betons wieder verwendet. Der größte Teil des Betons wurde in einer Deponie gelagert und für das Verfüllen von Löchern verwendet. Dies entspricht nicht dem klassischen Recycling. Zur Beantwortung dieser Forschungsfrage werden Erkenntnisse aus Forschungsthema II und III miteinander verknüpft und um weitere Daten und Annahmen ergänzt, um ein mögliches zukünftiges Szenario aufzuspannen.

Grundüberlegung ist, dass zukünftig weniger mineralische und metallische Baustoffe eingesetzt werden sollen, um den Hochbau ökologisch verträglicher zu machen. Dazu soll die Recyclingquote von Beton verbessert werden. Auch wenn mit diesem Recycling-Beton aus statischen Gründen kein Hochhausbau mehr möglich ist, so ist es doch möglich mit ihm Strukturen zu bauen, die mit biogenen Rohstoffen aktuell nicht möglich sind. So werden sowohl Keller als auch Fundamente in naher Zukunft zumindest zum überwiegenden Teil weiterhin aus mineralischen Baustoffen gefertigt werden müssen. Sollten die Gebäude aus den 50ziger und 60ziger Jahren, die in den nächsten Jahren abgerissen werden, zu einem höheren Anteil der mineralischen Baustoffe recycelt werden, dann ließen sich in Verbindung mit einem Gebäude, das ansonsten in weiteren Teilen aus biogenen Baumaterialien besteht, netto Einsparungen realisieren.

Wie in Abbildung 9 bereits gezeigt, werden biogene Baustoffe immer relevanter. Laut Destatis (2022) werden rund 5.000 Wohngebäude pro Jahr abgerissen, davon über 80 % Einfamilienhäuser. Für das folgende Szenario werden folgende Annahmen getroffen:

Die Einfamilienhäuser werden zum überwiegenden Teil im Alter von ca. 60 Jahren abgerissen. Damit wären die meisten Abbrüche in den nächsten Jahren ungefähr im Alter des untersuchten Gebäudes aus Publikation III (Rheude et al., 2022).

Die Bausubstanz der Einfamilienhäuser unterscheidet sich nicht signifikant von dem Gebäude, das in Publikation III (Rheude et al., 2022) untersucht wurde

Es wird angenommen, dass durch effektives Recycling der Anteil des Betons, der für Strukturen im Hochbau (bspw. Keller oder Fundament) verwendet werden kann, auf 80 % erhöht werden kann. Theoretisch wären noch höhere Prozente möglich, es wird aber angenommen, dass Farben, Bitume oder weitere Beimischungen zu diesen alten Baumaterialien eine noch höhere effektive Recyclingquote verhindern.

Es werden nur Einfamilienhäuser betrachtet. Einerseits liegen keine verlässlichen Daten für Mehrfamilienhäuser vor, andererseits wird angenommen, dass sich der gewonnene Recyclingbeton zwar für Strukturen wie Keller oder Fundament eignet, wenn oben drauf ein niedriger Leichtbau aus biogenen Materialien gebaut wird, allerdings aufgrund fehlender statischer Stabilität kein neues Mehrfamilienhaus gebaut werden kann.

Unter Einbeziehung der GWP-Emissionen für Transportfrischbeton und Recyclingbeton ergibt sich eine Netto-Einsparung von rund 2.000 Tonnen CO_2 eq pro Jahr in Deutschland. Diese Zahl lässt sich damit erklären, dass aktuell rund 88 % der THG-Emissionen, die bei der Betonherstellung entstehen, durch das Brennen des Zements entstehen. Diese Emissionen entstehen unabhängig davon, ob der Beton recycelt wird oder nicht.

Daher ist es – ohne signifikante Innovationen im Bereich der Zementherstellung – nicht möglich mit dem Recycling von Beton den Bausektor klimaneutraler zu entwickeln.

Echte Einsparungen sind nur mit einer gesteigerten Verwendung von biogenen Kohlenstoffen notwendig. Hierzu sind entsprechende politische Förderungen in der Breite notwendig.

Würde hingegen die Frage beantworttet werden wollen, wie hoch der Holzeinsatz im deutschen Hochbau sein müsste, um die eingesetzten mineralischen und metallischen Baustoffe zu kompensieren, den Hochbau also klimaneutral zu machen, kann folgende Rechnung auf Basis der erzielten Ergebnisse herangezogen werden:

In Publikation II wurde dargelegt, dass im Jahr 2020 ca. 5,164 Millionen Tonnen Holz eingesetzt wurden, welche Emissionen von ca. 5,7 Millionen Tonnen CO_2 eq vermieden. Gleichzeitig entstehen durch mineralische und metallische Baustoffe Emissionen in Höhe von ca. 31 Millionen Tonnen. Somit wären ca. 28 Millionen Tonnen Holz zusätzlich notwendig, um die Emissionen aus mineralischen und metallischen Baustoffen zu kompensieren. Die folgende Berechnung legt dies dar:

$$\frac{31\ Mio.Tonnen}{5{,}7\ Mio\ Tonnen} \times 5{,}164\ Millionen\ Tonnen = 28\ Millionen\ Tonnen$$

Wird nun die durchschnittliche Dichte von Konstruktionsvollholz berücksichtigt (Holzforschung Austria, 2022), ergibt dies ein Volumen von ca. 60 Millionen Kubikmeter Nadelholz welches, im Baubereich verwendet, ausreichen würde, die Emissionen von mineralischen und metallischen Baustoffen zu kompensieren. Wie in Publikation II dargelegt, ist es unmöglich komplett auf mineralische und metallische Baustoffe zu verzichten, da sie beispielsweise für Keller und Fundamente weiterhin benötigt werden. Ein vermehrter Holzeinsatz könnte aber zur Kompensation bspw. durch Aufstockungen oder variable und flexible Wohnkonzepte beitragen.

Ergänzt kann diese Aussage dadurch werden, dass im Jahr 2020 62,2 Millionen Kubikmeter Nadelholz eingeschlagen wurden (Statistisches Bundesamt, 2021).

4.5. ZUSAMMENFASSUNG DER FORSCHUNGSERGEBNISSE

Wie in den vorherigen Kapiteln dargelegt, sind in der Materialität des Hochbaus immer noch signifikante THG-Emissionen vorhanden. Damit der Hochbau nachhaltig wird, ist auch ein Umstieg bei den verwendeten Baumaterialien und deren Herstellung notwendig. Ansonsten ist ein ökologischer Hochbau mit nur geringem oder keinem THG-Fußabdruck nicht möglich. Hier haben die vorausgehenden Arbeiten gezeigt, dass eine reale Einsparung von THG-Emissionen nur mit einer gesteigerten Verwendungen von biogenen Baustoffen möglich ist und vor allem mineralische Baustoffe auf ein Minimum reduziert werden sollten. Gerade bei Betonen, die noch den größten Anteil ausmachen, ist durch die notwendigen Brennverfahren bei Zement aktuell keine relevante Einsparung von THG-Emissionen zu erwarten.

5. DISKUSSION

5.4. METHODISCHE DISKUSSION

Für die Beantwortung der Forschungsfragen aus Kapitel 2 wurden im Rahmen dieser Arbeit insgesamt vier Methoden angewendet. Dabei wurden von der Methodik Ökobilanz zwei verschiedene Varianten benutzt, um jeweils die Forschungsfragen korrekt beantworten zu können. Im Folgenden werden die verschiedenen Methoden diskutiert und am Ende die methodische Weiterentwicklung im Rahmen dieser Promotionsarbeit herausgearbeitet.

Die korrekte Verwendung verschiedener Begriffe ist wichtig für die Verständigung zwischen Personen, insbesondere wenn sie einen unterschiedlichen wissenschaftlichen Hintergrund haben. Zu Beantwortung der ersten Forschungsfragen wurde eine systematische Literaturübersicht nach Okoli und Schabram (2010) durchgeführt. Die systematische Literaturübersicht ermöglicht es, große Mengen an Literatur nach festgelegten Kriterien zu bearbeiten und daraus Schlussfolgerungen zu ziehen. Der Vorteil liegt in der Systematik, die es ermöglicht, die Erkenntnisse von Unabhängigen nachzuvollziehen und die aus wissenschaftlicher Sicht wichtige Transparenz und Vollständigkeit in die Literaturübersicht einzubringen. Literaturübersichten wie sie für die Einleitungen wissenschaftlicher Aufsätze durchgeführt werden, basieren häufig entweder auf dem Prinzip des „Snowballing“ oder den Kenntnissen über die Literatur der Autoren (Nußholz et al., 2023). Damit existiert ein starker Flaschenhals, der eine vollständige Übersicht und Einordnung des aktuellen Kenntnisstandes verhindert.

Es konnte gezeigt werden, dass in der Literatur mehrere unterschiedliche Definitionen für die untersuchten Schlagworte existieren. Die meisten Schlagwörter konnten nach der systematischen Literaturrecherche genau definiert werden und es wurden Vorschläge für die zukünftige Verwendung gemacht. Da im Rahmen der Weiterentwicklung der Nachhaltigkeitskonzepte in Zukunft neue Schlagwörter etablieren werden, um diese zu beschreiben, sollte ihre Einordnung in die vorgeschlagene Systematik erfolgen, um Missverständnisse unter den Anwendern zu vermeiden.

Die Methode der systematischen Literaturübersicht konnte also erfolgreich angewendet werden, um die Beantwortung der Forschungsfragen zu erreichen und eine Systematik herauszuarbeiten, um zukünftige Begriffe direkt einordnen und einschätzen zu können. Damit wurde eine Kommunikationsgrundlage für Diskussionen im Bereich des nachhaltigen Bauens gelegt.

Ökobilanzen sind eine etablierte Methodik, um mit einem systematischen Prozess die vielschichtigen Emissionen von Produkten oder Dienstleistungen über den ganzen Lebensweg zu modellieren. Häufig werden Ökobilanzstudien verwendet, um ein Produkt oder einen Prozess als nachhaltig zu deklarieren und damit zu suggerieren, dass das Paris-Abkommen eingehalten wird. Hier ist aber wichtig zu berücksichtigen, dass Ökobilanzen nur die relative, nicht aber die absolute, Nachhaltigkeit von Produkten oder Prozessen darstellen können. Dies bedeutet, dass ein Produkt oder Prozess mittels der Ökobilanzen als nachhaltiger in Bezug auf die Ökologie als ein anderes dargestellt werden kann. Immer unter der Voraussetzung, das vergleichbare Systemgrenzen, Emissionsfaktoren und funktionelle Einheiten verwendet werden.

Daraus kann aber nicht geschlossen werden, dass ersteres nachhaltig ist. Es kann die planetaren Grenzen immer noch überschreiten, dann nur weniger stark als das zweite Produkt. Es wird zwar daran gearbeitet, diese planetaren Grenzen zu quantifizieren und diese in Ökobilanzen zu integrieren, allerdings steht diese Forschung noch am Anfang (Baabou et al., 2022; Bjørn et al., 2016; Steffen et al., 2015).

Eine weitere Schwäche liegt in der Methodik selbst: So ist sowohl die Anwendung des attributiven Ansatzes als auch des konsequenz-orientierten Ansatz konform mit der ISO-Norm, kann allerdings höchst unterschiedliche Ergebnisse hervorbringen, die nicht miteinander vergleichbar sind. Die Entscheidung hierfür liegt beim Studienkoordinator und ist damit eine häufig subjektive Wahl (Weidema et al., 2018, 2020). Damit ergibt sich für den Anwender der Ökobilanz-Ergebnisse das Problem, dass die Systematik und Methodik im Detail verstanden werden müssen, um die Ergebnisse korrekt anwenden und vergleichen zu können.

Schließlich haben Ökobilanzen durch die kontinuierliche Weiterentwicklung und die damit einhergehenden neuen Erkenntnisse gerade in Bezug auf die Charakterisierungsfaktoren und Wirkungskategorien das Problem, dass sie nicht konstant sind. So zeigt beispielsweise Albertí et al. (2019) , dass die Ökobilanz einer Bushaltestelle 20 Jahre später zu anderen Ergebnissen führt als bei der ersten Anwendung. Damit können auch einmal durchgeführte Ökobilanzen, die sich in Systemgrenzen und funktioneller Einheit entsprechen, trotzdem nicht miteinander verglichen werden, wenn sich der zeitliche Horizont zu weit unterscheidet. Desweiteren gibt es auch Weiterentwicklungen im Bereich der ISO-Normen. So existieren auf Basis der 1040/14044 die ISO-Normen 14067 für Produkte (International Organization for Standardization, 2019) und 14083 für Transportprozesse (International Organization for Standardization, 2022), die richtig angewendet, jeweils großen Einfluss auf die Ergebnisse haben können und einen Vergleich mit anderen Ökobilanz-Studien, gerade wenn der Leser kein Experte ist, erschweren oder sogar verhindern. Deswegen wurde bei der entwickelten Methodik darauf geachtet mit der Ökobaudat einen Standard für Ökobilanzdaten zu verwenden, der unabhängig geprüft, regelmäßig aktualisiert und auf vergleichbare Systemgrenzen achtet.

Die entwickelte Methodik, die auf einer Stoffstromanalyse aufbaut, ermöglicht in Verbindung mit der Ökobilanz die jahresgenaue, volkswirtschaftliche Bewertung der ökologischen Auswirkungen der Materialität im Hochbau in Deutschland. Während im Rahmen der Publikation (Rheude & Röder, 2022) nur die Jahre 2012 bis 2020 ausgewertet wurden, erlaubt das methodische Vorgehen eine Weiterführung in die Zukunft. Je nach Fragestellung und Bedarf können auf dieser Grundlage verschiedene Leistungskennzahlen (engl. KPIs) gebildet werden (bspw. Anteil der biogenen Baustoffe, gesamte Kohlenstoffdioxid-Emissionen, Emissionen pro Tonne verbautem Baustoff etc.), die eine durchgehende Überwachung der neuhinzugekommenen Bausubstanz ermöglichen. Diese können Unternehmen, Verbände und Politiker, aber auch Wissenschaftler, für zukünftige Forschungen oder für die Steuerung durch Gesetzesvorhaben und Förderprogrammen verwenden.

Aktuell beruht die Datengrundlage auf (teilweise stark) aggregierten Zahlen bezüglich der verwendeten Baustoffe. Im Rahmen der Arbeit wurde auf Approximationen und Annahmen zurückgegriffen (vgl. (Rheude & Röder, 2022)). Dies sorgt für die hohen Unsicherheiten (vgl. Abbildung 5) in Bezug auf die Treibhausgasemissionen. Abhilfe können hier sogenannte Gebäudematerialpässe schaffen (Honic et al., 2019). Damit soll die Materialität der Gebäude erfasst und gespeichert werden, sodass bei zukünftigen Maßnahmen die Zusammensetzung genau bekannt ist und somit die Kreislaufwirtschaft im Gebäudesektor etabliert werden kann (Atta et al., 2021). Diese Informationen könnten auch in das bestehende Modell integriert werden, die Datenlage damit deutlich verbessern und die bestehenden Unsicherheiten verringern.

Das entwickelte Modell bildet damit nach aktueller Datenbasis den Stand sehr gut ab, kann aber weiter verbessert werden. Wie in Rheude et al. (2022) beschrieben, existiert momentan keine Statistik über die Zusammensetzung des Abraums von Gebäuden, die in ihrem Detailgrad mit den Statistiken zur Produktion vergleichbar wäre. Daher kann das vorliegende Modell, auch wenn grundsätzlich dazu in der Lage, nicht verwendet werden, um den Materialabgang aus dem

Hochbau zu erfassen. Eine systematische Erfassung von Abraum kann nicht nur die Kreislaufwirtschaft allgemein fördern, sondern würde es auch ermöglichen eine Datenbasis zu schaffen, die eine bessere Grundlage für Entscheidungsträger aller Art ermöglicht.

5.5. DISKUSSION DER ERGEBNISSE

Es konnte gezeigt werden, dass sich die verschiedenen Begrifflichkeiten, die momentan zur Beschreibung von Gebäuden mit stärkerer ökologischer Betrachtung existieren, signifikant voneinander unterscheiden. Eine Systematik für die weitere Einordnung von Begriffen wurde entwickelt werden. Es konnte desweiteren gezeigt werden, dass der Hochbau in Deutschland im Jahr 2020 Emissionen von ca. 31 Millionen Tonnen CO_2 eq nur in der Materialität für mineralische und metallische Baustoffe verursacht hat.

Um die Klimaziele sowohl des deutschen Staates als auch der UN zu erreichen und das Sustainable Development Goal 13 zu erfüllen, ist es notwendig, dass die Baupraxis geändert wird. Mit dem bisherigen hohen Materialbedarf, speziell an mineralischen Baustoffen kann der Bausektor nicht klimaneutral werden (vgl. Rheude und Röder (2022)). Das vermehrte Recycling von mineralischen Baustoffen verspricht ebenfalls keine klimatischen Verbesserungen, solange Zement nicht klimaneutral gebrannt werden kann. Die Ergebnisse zeigen daher, dass ein vermehrter Einsatz von biogenen Baustoffen notwendig ist, um wirklich nachhaltige Gebäude errichten zu können (vgl. Abbildung 9). Da zur Nachhaltigkeit aber nicht nur ökologische, sondern auch ökonomische und soziale Aspekte notwendig sind, ist es notwendig, dass die bisher nur freiwilligen Anreizsysteme (DGNB-Zertifikate, Gebäudematerialpässe und andere) politisch verpflichtend werden. Welche Auswirkungen politische Maßnahmen haben können, konnte in Kapitel 4.4.2 gezeigt werden: Wenige Jahre politischer und finanzieller Förderung haben ausgereicht, um die Holzbauquote signifikant zu erhöhen (vgl. Rheude und Röder (2022)). Diese Preiseffekte sollten sich die Politik auch für die sonstige Materialität im Hochbau zu Nutze machen, da bereits gute Instrumente existieren, die aber aktuell noch nicht in ausreichender Menge eingesetzt werden.

Es konnte gezeigt werden, dass das Recycling von Beton zumindest zur Erreichung der Klimaziele beim aktuellen Energiestandard in der Zementherstellung nicht ausreichend ist, allerdings sind auch weitere Sustainable Development Goals für den Bausektor wichtig. Die Gewinnung von Rohstoffen wie beispielsweise für den (Hoch-)Bau geeignetem Sand, hat schon heute großen Einfluss auf die Biodiversität und die Gesundheit unserer Ökosysteme (SDG 14 und 15). Eine Förderung des Recyclings von Beton aus Klimaschutzsicht hat zwar keinen Effekt, ist aber aus Umweltaspekten vorteilhaft. Hier ist allerdings eine entsprechende Kommunikation von Politik und Fachleuten an die Verbraucher und Bauherren notwendig, damit diese die Hintergründe kennen.

Das übergeordnete SDG 11: Sustainable Cities and Communities kann nur erreicht werden, wenn die Politik ihre Maßnahmen, die sowohl aus Verbraucheranreizen wie auch aus Druck auf die Industrie bestehen sollte, zur Förderung der biogenen Baumaterialien weiter erhöht und zielgerichtet einsetzt (vgl. Rheude und Röder (2022)). Nur dann wäre der Begriff "nachhaltig" entsprechend Kapitel 4.1 dieser Arbeit für den Gebäudesektor anwendbar in Hinblick auf einen lebenswerten Planeten für die Menschheit und zur Vermeidung eines dramatischen Klimawandels.

Die Datenlage für die reine Durchführung von Ökobilanzen eines Abrisses eines Gebäudes ist ausreichend, allerdings ist die Datenlage nicht ausreichend, um diese wie bei der Produktion, auf die volkwirtschaftliche Ebene zu skalieren.

6. SCHLUSSFOLGERUNGEN

Zu Beginn der Arbeit wurde als Forschungslücke eine gemeinsame Grundlage über die Umweltauswirkungen des deutschen Hochbaus definiert. In den Kapiteln und wissenschaftlichen Publikationen wurde eine Systematik zur Einordnung von Schlagwörtern erarbeitet (Rheude et al., 2021), eine Methodik zur fortlaufenden Modellierung der Umweltauswirkungen der Materialität von Neubauten auf volkswirtschaftlicher Ebene vorgestellt (Rheude & Röder, 2022) und die Umweltauswirkungen des Abrisses eines Einfamilienhauses nach aktuellem Stand der Technik dargestellt (Rheude et al., 2022). Die identifizierte Forschungslücke kann daher als geschlossen gelten.

Der Zuwachs an biogenen Rohstoffen in der Materialität hat, obwohl er nur einen geringen Anteil an der Gesamtmaterialität ausmacht, dazu beigetragen, dass die Emissionen trotz des zunehmenden Einsatzes von Baumaterialien auf einem stabilen Niveau gehalten werden konnten. Die dabei entwickelte Methodik kann fortgeführt werden, um ein dauerhaftes Monitoring der Baustoffzusammensetzung und ihrer assoziierten Umweltwirkungen zu etablieren.

Die Modellierung der Treibhausgasemissionen für die Gebäudehülle hat gezeigt, dass dieser Sektor etwa 3,5 % der Gesamtemissionen der deutschen Wirtschaft ausmacht, aber noch ein hohes Optimierungspotenzial zur Reduzierung der Treibhausgasemissionen hat. Insbesondere durch den Einsatz biogener Rohstoffe oder den verstärkten Einsatz innovativer Baustoffe könnten die Emissionen noch deutlich gesenkt werden, während die Gesamtemissionen im Lebenszyklus durch eine höhere Energieeffizienz sinken (Busch et al., 2022; Heveran et al., 2020).

Im Gegensatz zu der nachgewiesenen Bedeutung des Bausektors ist eine Kreislaufwirtschaft, die auf einem hochwertigen Recycling von Abbruchabfällen basiert, noch nicht im industriellen Maßstab erreicht worden. Praxisrelevante und datengestützte Aussagen zeigen, dass trotz Einhaltung der Vorgaben zur Sortierung der zehn Abfallfraktionen nach der Gewerbeabfallverordnung die erreichte Verwertungsquote noch weit unter der vom Statistischen Bundesamt geforderten Verwertungsquote und den Vorgaben der Abfallhierarchie in der EU-Abfallrahmenrichtlinie und dem Kreislaufwirtschaftsgesetz liegen (Ordinance on the Management of Commercial Municipal Waste and Certain Construction and Demolition Waste (Verordnung über die Bewirtschaftung von gewerblichen Siedlungsabfällen und von bestimmten Bau- und Abbruchabfällen): (Gewerbeabfallverordnung - GewAbfV), 2017)). Ein Problem könnte unter anderem sein, dass keine aggregierten Abfallbilanzen auf volkswirtschaftlicher Ebene existieren und damit das Potential für die Wiederverwertung einzelner Stoffe nicht erkannt werden kann.

Obwohl es Vorschriften zur Verringerung von Deponiematerialien und deren Umweltauswirkungen gibt, fehlt es den derzeitigen Rechtsvorschriften an praktischer Umsetzbarkeit. Es bedarf weiterer Verbesserungen durch genauere Überwachung und Statistiken (Rheude et al., 2022). Die derzeitige statistische Erfassung der ersten Phase nach dem Abriss anstelle der endgültigen Abfallentsorgung behindert das öffentliche Bewusstsein für die Verbesserung der Baubabfallsituationn hin zu einer kreislauforientierten und umweltfreundlichen Wirtschaft.

Die vorliegende Arbeit konnte zeigen, dass im Bausektor und der Forschung viele Untersuchungen zur Förderung der Reduzierung der ökologischen Umweltwirkungen stattfinden. Allerdings sind viele Aspekte noch nicht ausreichend koordiniert.

Konkret sollten folgende Punkte in naher Zukunft in Angriff genommen werden, um den ökologischen Fußabdruck der verwendeten Baustoffe zu minimieren:

1. *Bereich Forschung:* Es gibt eine Vielzahl von Studien, die sich damit befassen, ob das Holzaufkommen in Deutschland für den kompletten Bausektor ausreichend ist. Diese kommen zu höchst unterschiedlichen Ergebnissen. Hierzu sollten Verbundprojekte aus Materialwissenschaftlern, Förstern und Ökonomen angestrebt werden, die massentaugliche Lösungskonzepte erarbeiten. Mögliche Forschungsfragen, die sich aus vorliegender Arbeit ergeben, sind:
    a. Wie lassen sich Erkenntnisse zur ökologischen Bewertung von Produkten schneller und leichter an Verbraucher kommunizieren?
    b. Welche Möglichkeiten den Wald wirtschaftlich und ökologisch effizienter zu nutzen, bestehen und wie können diese in der Masse verbreitet werden?
    c. Welche technischen Möglichkeiten bestehen, um Zement großindustriell klimaneutral zu erzeugen?
    d. Wie müssen Fortbildungskonzepte für Fachpersonal im Baubereich aussehen, damit diese dann Verbraucher ökologisch beraten können?
2. *Bereich Politik:* In Publikation II und III konnte gezeigt werden, welchen Einfluss politische Entscheidungen auf die Rohstoffverwendung und -aufbereitung haben können. Zur weiteren Erhöhung der Verwendung von biogenen Baustoffen ist eine entsprechende Förderung seitens der Politik unerlässlich. Es konnte gezeigt werden, dass die

Verwendung von mineralischen Recycling-Baustoffen bei der momentanen Zementherstellung nicht zu THG-Einsparungen führt.

3. *Bereich Öffentlichkeitsarbeit:* Es existieren sehr viele Begriffe, Labels, Auszeichnungen und Zertifikate im Baubereich, die auch die Nachhaltigkeit zertifizieren sollen. Für die meisten Personen ohne Fachwissen sind diese nicht mehr verständlich und zu komplex (Niedermeier et al., 2021). Es müssen daher für Verbraucher und Bauherren einfach verständliche Kommunikationsmittel entworfen werden, damit wirklich nachhaltige Produkte direkt als solche erkannt und nachgefragt werden können.
4. *Bereich Fachpersonal:* Im Laufe der Anfertigung der Promotionsarbeit konnte festgestellt werden, dass sehr viel Wissen im akademischen Bereich zu den wichtigsten Fragestellungen bereits vorhanden ist. Dies findet aber aktuell keine breite Kommunikation nach außen. Weder zum Endverbraucher noch beispielsweise zu Handwerkern, die ökologische Baustoffe verbauen sollen. Hier ist eine Förderung notwendig, da diese Fachleute sehr häufig Endverbraucher beraten. Ohne entsprechendes Wissen kann auch keine fachlich-qualifizierte Beratung nach aktuell wissenschaftlichem Standard erfolgen.

Zusammenfassend lässt sich daher abschließend festhalten, dass sich die ökologische Nachhaltigkeit in der Materialität in den letzten Jahren verbesserte. Aktuelle politische und gesamtgesellschaftliche Bestrebungen zur Minimierung der Treibhausgasemissionen zeigen Wirkung, sollten in den nächsten Jahren aber noch weiter intensiviert werden, um die Ziele des Paris Abkommens und der SDGs zu erreichen.

LITERATURVERZEICHNIS

Al Nuaimi, N., Sohail, M. G., Hawileh, R., Abdalla, J. A., & Douier, K. (2021). Durability of Reinforced Concrete Beams Externally Strengthened with CFRP Laminates under Harsh Climatic Conditions. *Journal of Composites for Construction*, *25*(2), 04021005. https://doi.org/10.1061/(ASCE)CC.1943-5614.0001113

Albertí, J., Civancik-Uslu, D., Contessotto, D., Balaguera, A., & Fullana-i-Palmer, P. (2019). Does a life cycle assessment remain valid after 20 years? Scenario analysis with a bus stop study. *Resources, Conservation and Recycling*, *144*, 169–179. https://doi.org/10.1016/j.resconrec.2019.01.041

Allesch, A., & Brunner, P. H. (2015). Material Flow Analysis as a Decision Support Tool for Waste Management: A Literature Review: MFA for Waste Management: A Literature Review. *Journal of Industrial Ecology*, *19*(5), 753–764. https://doi.org/10.1111/jiec.12354

Atta, I., Bakhoum, E. S., & Marzouk, M. M. (2021). Digitizing material passport for sustainable construction projects using BIM. *Journal of Building Engineering*, *43*, 103233. https://doi.org/10.1016/j.jobe.2021.103233

Baabou, W., Bjørn, A., & Bulle, C. (2022). Absolute Environmental Sustainability of Materials Dissipation: Application for Construction Sector. *Resources*, *11*(8), 76. https://doi.org/10.3390/resources11080076

Bauen mit Holz. (2019, Januar 1). *Holzbau-Zentrum: Berlin fördert den urbanen Holzbau*. https://www.bauenmitholz.de/holzbau-zentrum-berlin-foerdert-den-urbanen-holzbau-26032019

Bayerisches Staatsministerium für Wohnen, Bau und Verkehr. (2022, Januar 1). *Holzbauzuschuss: Bayern zahlt Klimaprämie für Holzhäuser*. https://www.stmb.bayern.de/med/aktuell/archiv/2022/220601bayfholz/#:~:text=Die%20Zuwendungsh%C3%B6he%20betr%C3%A4gt%20500%20Euro,sp%C3%A4testens%20Ende%202022%20gestellt%20werden.

Bjørn, A., Margni, M., Roy, P.-O., Bulle, C., & Hauschild, M. Z. (2016). A proposal to measure absolute environmental sustainability in life cycle assessment. *Ecological Indicators*, *63*, 1–13. https://doi.org/10.1016/j.ecolind.2015.11.046

Blom, B., Sunderland, T., & Murdiyarso, D. (2010). *Getting REDD to work locally: Lessons learned from integrated conservation and development projects*. *13*(2), 164–172. https://doi.org/10.1016/j.envsci.2010.01.002

Brunner, P. H., & Rechberger, H. (2016). *Handbook of Material Flow Analysis* (0 Aufl.). CRC Press. https://doi.org/10.1201/9781315313450

Bucher, A. (2020). *Eine empirische Analyse zur Förderung der Kreislaufwirtschaft beim Gebäudeab-bruch.*

Bundesagentur für Arbeit. (2022). *Employees by economic sector (WZ 2008): Beschäftigte nach Wirtschaftszweigen (WZ 2008)*. https://statistik.arbeitsagen-tur.de/SiteGlobals/Forms/Suche/Einzelheftsuche_Formular.html?nn=20898&topic_f=beschaeftigung-sozbe-wz-heft

Bundesministerium für Wirtschaft und Klimaschutz. (2022, Januar 1). *Bauwirtschaft*. https://www.bmwk.de/Redaktion/DE/Artikel/Branchenfokus/Industrie/branchenfokus-bauwirtschaft.html#:~:text=Im%20Jahr%202020%20erzielte%20das,%3A%20Hauptverband%20der%20Deutschen%20Bauindustrie).

Busch, P., Kendall, A., Murphy, C. W., & Miller, S. A. (2022). Literature review on policies to mitigate GHG emissions for cement and concrete. *Resources, Conservation and Recycling*, *182*, 106278. https://doi.org/10.1016/j.resconrec.2022.106278

Cocchia, A. (2014). Smart and Digital City: A Systematic Literature Review. In R. P. Dameri & C. Rosenthal-Sabroux (Hrsg.), *Smart City* (S. 13–43). Springer International Publishing. https://doi.org/10.1007/978-3-319-06160-3_2

Curran, M. A., Mann, M., & Norris, G. (2005). The international workshop on electricity data for life cycle inventories. *Journal of Cleaner Production*, *13*(8), 853–862. https://doi.org/10.1016/j.jclepro.2002.03.001

Dederich, L. (2021). *Holzhauskonzepte* (4.). https://www.fnr.de/fileadmin/allgemein/pdf/broschueren/Broschuere_Holzhauskonzepte_2020_RZ_web.pdf

Del Rosario, P., Palumbo, E., & Traverso, M. (2021). Environmental Product Declarations as Data Source for the Environmental Assessment of Buildings in the Context of Level(s) and DGNB: How Feasible Is Their Adoption? *Sustainability*, *13*(11), 6143. https://doi.org/10.3390/su13116143

Deutsches Institut für Normung. (2021a). *DIN EN ISO 14040:2021-02, Umweltmanagement_- Ökobilanz_- Grundsätze und Rahmenbedingungen (ISO_14040:2006_+ Amd_1:2020);*

Deutsche Fassung EN_ISO_14040:2006_+ A1:2020. Beuth Verlag GmbH. https://doi.org/10.31030/3179655

Deutsches Institut für Normung. (2021b). *DIN EN ISO 14044:2021-02, Umweltmanagement_- Ökobilanz_- Anforderungen und Anleitungen (ISO_14044:2006_+ Amd_1:2017_+ Amd_2:2020); Deutsche Fassung EN_ISO_14044:2006_+ A1:2018_+ A2:2020*. Beuth Verlag GmbH. https://doi.org/10.31030/3179656

Deutsches Institut für Normung. (2022). *DIN EN 15804:2022-03, Nachhaltigkeit von Bauwerken_- Umweltproduktdeklarationen_- Grundregeln für die Produktkategorie Bauprodukte; Deutsche Fassung EN_15804:2012+A2:2019_+ AC:2021*. Beuth Verlag GmbH. https://doi.org/10.31030/3294005

Doan, D. T., GhaffarianHoseini, A., Naismith, N., Zhang, T., & Tookey, J. (2017). A critical comparison of green building rating systems. *Building and Environment*, *123*, 243–260. https://doi.org/10.1016/j.buildenv.2017.07.007

Eberhardt, L. C. M., Birgisdottir, H., & Birkved, M. (2019). Potential of Circular Economy in Sustainable Buildings. *IOP Conference Series: Materials Science and Engineering*, *471*, 092051. https://doi.org/10.1088/1757-899X/471/9/092051

Ecoinvent. (2019, Januar 1). *Ecoinvent database*. https://www.ecoinvent.org/

EPD International AB. (2021, Januar 1). *Method EPD 2018*. https://www.environdec.com/about-us

Esa, M. R., Halog, A., & Rigamonti, L. (2017). Developing strategies for managing construction and demolition wastes in Malaysia based on the concept of circular economy. *Journal of Material Cycles and Waste Management*, *19*(3), 1144–1154. https://doi.org/10.1007/s10163-016-0516-x

European Commission. (2010). *International Reference Life Cycle Data System (ILCD) Handbook—General guide for Life Cycle Assessment—Detailed guidance* (Bd. 24708). Publications Office.

Federal Association of the German Brick and Tile Industry e.V. (2015, Januar 1). *Mauerziegel*. https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=f98eea66-671c-4014-bfbb-2db1ffba8331&version=00.05.000&stock=OBD_2021_II&lang=de

Federal Ministry of Finance. (2021, Januar 1). *Klimafreundliches Bauen mit Holz*. https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Europa/DARP/Leuchtturm-Projekte/klimafreundliches-bauen-mit-holz.html

Federal Ministry of Housing, Urban Development and Construction. (2022, Januar 1). *Ökobaudat*. https://www.oekobaudat.de/

Federal Statistical Office. (2022a, Januar 1). *Manufacturing industry: Persons employed and turnover of enterprises in the construction industry*. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Bauen/Publikationen/Downloads-Baugewerbe-Struktur/personen-umsatz-baugewerbe-2040510217004.pdf?__blob=publicationFile

Federal Statistical Office. (2022b, Januar 1). *Production value, quantity, weight and enterprises of the Quarterly production survey: Germany, years, List of goods (9-digit): 42131-*

0003. https://www-genesis.destatis.de/genesis//online?operation=table&code=42131-0003&bypass=true&levelindex=0&levelid=1648791359504#abreadcrumb

Feist, W., Pfluger, R., & Hasper, W. (2020). Durability of building fabric components and ventilation systems in passive houses. *Energy Efficiency*, *13*(8), 1543–1559. https://doi.org/10.1007/s12053-019-09781-3

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., & Snyder, P. K. (2005). Global Consequences of Land Use. *Science*, *309*(5734), 570–574. https://doi.org/10.1126/science.1111772

Forstwirtschaft in Deutschland. (2022, Januar 1). *Minister Peter Hauk MdL: „Der verstärkte Einsatz von Holz beim Bauen kann einen wesentlichen Beitrag für mehr Klimaschutz leisten“*. https://www.forstwirtschaft-in-deutschland.de/aktuelles/news-detailansicht/news/minister-peter-hauk-mdl-der-verstaerkte-einsatz-von-holz-beim-bauen-kann-einen-wesentlichen-beitrag/

Gardner, H. M., Hasik, V., Banawi, A., Olinzock, M., & Bilec, M. M. (2020). Whole Building Life Cycle Assessment of a Living Building. *Journal of Architectural Engineering*, *26*(4), 04020039. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000436

Gesetz zur Einsparung von Energie und zur Nutzung erneuerbarer Energien zur Wärme- und Kälteerzeugung in Gebäuden: Gebäudeenergiegesetz—GEG, 2020 Bundesgesetzblatt 1728 (2020). https://www.buzer.de/s1.htm?g=GEG&f=1

Gonçalves, M., Freire, F., & Garcia, R. (2021). Material flow analysis of forest biomass in Portugal to support a circular bioeconomy. *Resources, Conservation and Recycling*, *169*, 105507. https://doi.org/10.1016/j.resconrec.2021.105507

Gorecki, J. (2019). Circular Economy Maturity in Construction Companies. *IOP Conference Series: Materials Science and Engineering*, *471*, 112090. https://doi.org/10.1088/1757-899X/471/11/112090

Hafner, A., & Rüter, S. (2018). *Method for assessing the national implications of environmental impacts from timber buildings-an exemplary study for residential buildings in Germany*. *50*, 139–154. https://doi.org/10.22382/wfs-2018-047

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (Hrsg.). (2017). *Life cycle assessment: Theory and practice*. Springer. http://www.springer.com/de/book/9783319564746

Heveran, C. M., Williams, S. L., Qiu, J., Artier, J., Hubler, M. H., Cook, S. M., Cameron, J. C., & Srubar, W. V. (2020). Biomineralization and Successive Regeneration of Engineered Living Building Materials. *Matter*, *2*(2), 481–494. https://doi.org/10.1016/j.matt.2019.11.016

Holzbau Offensive. (2020, Januar 1). *Aufruf für kommunale Ideen zur Entwicklung innovativer Holzbau- und Hybridprojekte wie Quartiere, eigene Liegenschaften oder zur Kommunikation*. https://www.holzbauoffensivebw.de/de/p/massnahmen-landesregierung/fordermittel-1089.html#:~:text=Im%20Rahmen%20der%20Holzbau%2DOffensive%20des%20Landes%20Baden%2DW%C3%BCrttemberg%20werden,Euro%20zur%20Verf%C3%BCgung.

Hong, T., Ji, C., & Park, H. (2012). *Integrated model for assessing the cost and CO 2 emission (IMACC) for sustainable structural design in ready-mix concrete*. *103*, 1–8. https://doi.org/10.1016/j.jenvman.2012.02.034

Honic, M., Kovacic, I., & Rechberger, H. (2019). Concept for a BIM-based Material Passport for buildings. *IOP Conference Series: Earth and Environmental Science*, *225*, 012073. https://doi.org/10.1088/1755-1315/225/1/012073

International Energy Agency. (2019, Januar 1). *Global Energy and CO2 Status Report: The latest trends in energy and emissions in 2018*. https://www.iea.org/geco/

International Organization for Standardization. (2019). *DIN EN ISO 14067:2019-02, Treibhausgase_- Carbon Footprint von Produkten_- Anforderungen an und Leitlinien für Quantifizierung (ISO_14067:2018); Deutsche und Englische Fassung EN_ISO_14067:2018*. Beuth Verlag GmbH. https://doi.org/10.31030/2851769

International Organization for Standardization. (2022). *DIN EN ISO 14083:2022-03, Treibhausgase_- Quantifizierung und Berichterstattung über Treibhausgasemissionen von Transportvorgängen (ISO/DIS_14083:2022); Deutsche und Englische Fassung prEN_ISO_14083:2022*. Beuth Verlag GmbH. https://doi.org/10.31030/3320884

IPCC. (2022). *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (S. 3056). Cambridge University Press. doi:10.1017/9781009325844.

Jain, S., Singhal, S., & Pandey, S. (2020). Environmental life cycle assessment of construction and demolition waste recycling: A case of urban India. *Resources, Conservation and Recycling*, *155*, 104642. https://doi.org/10.1016/j.resconrec.2019.104642

Kabirifar, K., Mojtahedi, M., Wang, C., & Tam, V. W. Y. (2020). Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review. *Journal of Cleaner Production*, *263*, 121265. https://doi.org/10.1016/j.jclepro.2020.121265

Kim, H., Hong, T., & Kim, J. (2019). *Automatic ventilation control algorithm considering the indoor environmental quality factors and occupant ventilation behavior using a logistic regression model*. *153*, 46–59. https://doi.org/10.1016/j.buildenv.2019.02.032

Kohler, N., & Yang, W. (2007). Long-term management of building stocks. *Building Research & Information*, *35*(4), 351–362. https://doi.org/10.1080/09613210701308962

König, H. (2017). *Projekt: Lebenszuklusanalyse von Wohngebäuden: Lebenszyklusanalyse mit Berechnung der Ökobilanz und Lebenszykluskosten*. https://legep.de/wp-content/uploads/Endbericht-Lebenszyklusanalyse_von_Wohngebaeuden.pdf

Leal Filho, W., Tuladhar, L., Li, C., Balogun, A.-L. B., Kovaleva, M., Abubakar, I. R., Azadi, H., & Donkor, F. K. K. (2023). Climate change and extremes: Implications on city livability and associated health risks across the globe. *International Journal of Climate Change Strategies and Management*, *15*(1), 1–19. https://doi.org/10.1108/IJCCSM-07-2021-0078

Li, Q., Dai, T., Gao, T., Zhong, W., Wen, B., Li, T., & Zhou, Y. (2021). Aluminum material flow analysis for production, consumption, and trade in China from 2008 to 2017. *Journal of Cleaner Production*, *296*, 126444. https://doi.org/10.1016/j.jclepro.2021.126444

Lin, B. B., Ossola, A., Alberti, M., Andersson, E., Bai, X., Dobbs, C., Elmqvist, T., Evans, K. L., Frantzeskaki, N., Fuller, R. A., Gaston, K. J., Haase, D., Jim, C. Y., Konijnendijk, C., Nagendra, H., Niemelä, J., McPhearson, T., Moomaw, W. R., Parnell, S., … Tan, P. Y. (2021). Integrating solutions to adapt cities for climate change. *The Lancet Planetary Health*, *5*(7), e479–e486. https://doi.org/10.1016/S2542-5196(21)00135-2

Lin, D. F., Huang, L. S., Luo, H. L., & Weng, R. S. (2012). *Effects on cement after partial replacement with burned joss paper ash*. *33*(22), 2595–2601. https://doi.org/10.1080/09593330.2012.715803

Loga, T., Stein, B., Diefenbach, N., & Born, R. (2015). *German residential building typology (Deutsche Wohngebäudetypologie): Example measures for improving the energy efficiency of typical residential buildings (Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden)* (2., erw. Aufl.). IWU. http://www.building-typology.eu/downloads/public/docs/brochure/DE_TABULA_TypologyBrochure_IWU.pdf

Mattoni, B., Guattari, C., Evangelisti, L., Bisegna, F., Gori, P., & Asdrubali, F. (2018). *Critical review and methodological approach to evaluate the differences among international green building rating tools*. *82*, 950–960. https://doi.org/10.1016/j.rser.2017.09.105

Metzger, S., Katy, J., & Walikewitz, N. (2019). *Housing and renovation (Wohnen und Sanieren): Empirical residential building data since 2002 (Empirische Wohngebäudedaten seit 2002)*. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-05-23_cc_22-2019_wohnenundsanieren_hintergrundbericht.pdf

Munaro, M. R., Tavares, S. F., & Bragança, L. (2020). Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. *Journal of Cleaner Production*, *260*, 121134. https://doi.org/10.1016/j.jclepro.2020.121134

Mutel, C. (2017). Brightway: An open source framework for Life Cycle Assessment. *The Journal of Open Source Software*, *2*(12), 236. https://doi.org/10.21105/joss.00236

Niedermeier, A., Emberger-Klein, A., & Menrad, K. (2021). Which factors distinguish the different consumer segments of green fast-moving consumer goods in Germany? *Business Strategy and the Environment*, *30*(4), 1823–1838. https://doi.org/10.1002/bse.2718

NRW.Bank. (2021). *Fördermittel des Landes Nordrhein-Westfalen: Die NRW.BANK unterstützt Kommunen und Investoren dabei, bezahlbaren und modernen Wohnraum zu schaffen.* https://www.bauen-mit-holz.nrw/foerdermittel/

Nußholz, J., Çetin, S., Eberhardt, L., De Wolf, C., & Bocken, N. (2023). From circular strategies to actions: 65 European circular building cases and their decarbonisation potential. *Resources, Conservation & Recycling Advances*, *17*, 200130. https://doi.org/10.1016/j.rcradv.2023.200130

Okoli, C., & Schabram, K. (2010). A Guide to Conducting a Systematic Literature Review of Information Systems Research. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.1954824

Ordinance on the Management of Commercial Municipal Waste and Certain Construction and Demolition Waste (Verordnung über die Bewirtschaftung von gewerblichen Siedlungsabfällen und von bestimmten Bau- und Abbruchabfällen): (Gewerbeabfallverordnung—GewAbfV), (2017).

Panesar, D. K., Seto, K. E., & Churchill, C. J. (2017). Impact of the selection of functional unit on the life cycle assessment of green concrete. *The International Journal of Life Cycle Assessment*, *22*(12), 1969–1986. https://doi.org/10.1007/s11367-017-1284-0

Pantini, S., & Rigamonti, L. (2020). Is selective demolition always a sustainable choice? *Waste management (New York, N.Y.)*, *103*, 169–176. https://doi.org/10.1016/j.wasman.2019.12.033

Pomponi, F., Hart, J., Arehart, J. H., & D'Amico, B. (2020). Buildings as a Global Carbon Sink? A Reality Check on Feasibility Limits. *One Earth*, *3*(2), 157–161. https://doi.org/10.1016/j.oneear.2020.07.018

Population Division. (2019, Januar 1). *Entwicklung der Weltbevölkerungszahl von Christi Geburt bis zum Jahr 2020 (in Milliarden)*. https://de.statista.com/statistik/daten/studie/1694/umfrage/entwicklung-der-weltbevoelkerungszahl/

PRé. (2020). *SimaPro*. https://simapro.com/

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, *42*(10), 1592–1600. https://doi.org/10.1016/j.enbuild.2010.05.007

Rheude, F., Bucher, A., & Röder, H. (2022). Residential demolition and waste management—An ecobalancing case study. *Cleaner Waste Systems*, *3*, 100056. https://doi.org/10.1016/j.clwas.2022.100056

Rheude, F., Kondrasch, J., Röder, H., & Fröhling, M. (2021). Review of the terminology in the sustainable building sector. *Journal of Cleaner Production*, *286*, 125445. https://doi.org/10.1016/j.jclepro.2020.125445

Rheude, F., & Röder, H. (2022). Estimating the use of materials and their GHG emissions in the German building sector. *Cleaner Environmental Systems*, *7*, 100095. https://doi.org/10.1016/j.cesys.2022.100095

Roberts, M., Allen, S., & Coley, D. (2020). Life cycle assessment in the building design process – A systematic literature review. *Building and Environment*, *185*, 107274. https://doi.org/10.1016/j.buildenv.2020.107274

Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., & Passer, A. (2020). Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Applied Energy*, *258*, 114107. https://doi.org/10.1016/j.apenergy.2019.114107

Ruske, K.-D., Gracht, H., Kauschke, P., Gnatzy, T., Reuter, J., Darkow, I.-L., & Montgomery, E. (2010). *Transportation & Logistics 2030: Volume 3: Emerging Markets—New hubs, new spokes, new industry leaders?* https://www.pwc.com/gx/en/transportation-logistics/tl2030/emerging-markets/pdf/tl2030_vol3_final.pdf

Schaefer, M. (2022, Dezember 8). Carl dient Experten als gutes Beispiel. *Pforzheimer Zeitung*, 18.

Schiller, G., Ortlepp, R., & Krauß, N. (2015). *Mapping of the Anthropogenic Stockpile in Germany for the Optimization of Secondary Raw Materials Management (Kartierung des Anthropogenen Lagers in Deutschland zur Optimierung der Sekundärrohstoffwirtschaft)*. http://www.umweltbundesamt.de/publikationen/kartierung-des-anthropogenen-lagers-in-deutschland

SKHolzbau. (2020, Januar 1). *NRW-Politik fördert Holzbau mit bis zu 7.500 Euro pro Bauvorhaben*. https://www.skholzbau.de/nrw-foerdert-bauen-mit-holz/#:~:text=NRW%2DPolitik%20f%C3%B6rdert%20Holzbau%20mit,in%20nicht%20unbetr%C3%A4chtlichem%20Ma%C3%9F%20gef%C3%B6rdert.

Statistisches Bundesamt. (2021). *Holzeinschlag erreicht 2020 aufgrund von Waldschäden neuen Rekordwert*. https://www.destatis.de/DE/Presse/Pressemitteilungen/2021/04/PD21_192_413.html#:~:text=WIESBADEN%20%E2%80%93%20Im%20Jahr%202020%20wurden,Holz%20geschlagen%20worden%20als%202020.

Statistisches Bundesamt. (2022). *Living space per inhabitant in dwellings in Germany from 1991 to 2020*. https://www.bbsr.bund.de/BBSR/DE/veroeffen-tlichungen/bbsr-online/2021/bbsr-online-32-2021-dl.pdf;jsessionid=6460D137E1162161E4C7CD972ECAC8E0.live11314?__blob=publicationFile&v=3

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., Vries, W., Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Sustainability. Planetary boundaries: Guiding human development on a changing planet. *Science (New York, N.Y.)*, *347*(6223), 1259855. https://doi.org/10.1126/science.1259855

The World Bank. (2019, Januar 1). *GPD (current US-Dollar) -World*. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?end=2017&locations=1W&start=1960&year_low_desc=false

Thünen Institute for International Forestry and Forest Economics. (2020, Januar 1). *Balkenschichtholz (Durchschnitt DE)*. https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=c253ae30-eb7d-4f9c-8e8c-1df00344d5b2&version=00.00.022&stock=OBD_2021_II&lang=de

Torres-Carrion, P. V., Gonzalez-Gonzalez, C. S., Aciar, S., & Rodriguez-Morales, G. (2018). Methodology for systematic literature review applied to engineering and education. *2018 IEEE Global Engineering Education Conference (EDUCON)*, 1364–1373. https://doi.org/10.1109/EDUCON.2018.8363388

Trinius, W., & Goerke, J. (2019). Declaration of the End-of-Life for Building Products. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012050. https://doi.org/10.1088/1755-1315/323/1/012050

Weidema, B. P., Pizzol, M., Schmidt, J., & Thoma, G. (2018). Attributional or consequential Life Cycle Assessment: A matter of social responsibility. *Journal of Cleaner Production*, *174*, 305–314. https://doi.org/10.1016/j.jclepro.2017.10.340

Weidema, B. P., Simas, M. S., Schmidt, J., Pizzol, M., Løkke, S., & Brancoli, P. L. (2020). Relevance of attributional and consequential information for environmental product labelling. *The International Journal of Life Cycle Assessment*, *25*(5), 900–904. https://doi.org/10.1007/s11367-019-01628-4

Weischer, C., & Gehrau, V. (2017). *Die Beobachtung als Methode in der Soziologie* (Bd. 4866). UVK Verlagsgesellschaft mbH; UVK Lucius.

Zhao, Z., Xiao, J., Duan, Z., Hubert, J., Grigoletto, S., & Courard, L. (2022). Performance and durability of self-compacting mortar with recycled sand from crushed brick. *Journal of Building Engineering*, *57*, 104867. https://doi.org/10.1016/j.jobe.2022.104867

Zuo, J., Pullen, S., Rameezdeen, R., Bennetts, H., Wang, Y., Mao, G., Zhou, Z., Du, H., & Duan, H. (2017). *Green building evaluation from a life-cycle perspective in Australia: A critical review*. *70*, 358–368. https://doi.org/10.1016/j.rser.2016.11.251

Zuo, J., & Zhao, Z.-Y. (2014). Green building research-current status and future agenda: A review. *Renewable and Sustainable Energy Reviews*, *30*, 271–281. https://doi.org/10.1016/j.rser.2013.10.021

APPENDIX

FULL PAPER: REVIEW OF THE TERMINOLOGY IN THE SUSTAINABLE BUILDING SECTOR

Dear Felix Rheude

We hereby grant you permission to reprint the material below at no charge in your thesis subject to the following conditions:

RE: Review of the terminology in the sustainable building sector, Journal of Cleaner Production, Volume 286, 2021, Rheude et al.

1. If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgment to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies.

2. Suitable acknowledgment to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"This article was published in Publication title, Vol number, Author(s), Title of article, Page Nos, Copyright Elsevier (or appropriate Society name) (Year)."

3. Your thesis may be submitted to your institution in either print or electronic form.

4. Reproduction of this material is confined to the purpose for which permission is hereby given.

5. This permission is granted for non-exclusive world English rights only. For other languages please reapply separately for each one required. Permission excludes use in an electronic form other than submission. Should you have a specific electronic project in mind please reapply for permission.

6. As long as the article is embedded in your thesis, you can post/share your thesis in the University repository.

7. Should your thesis be published commercially, please reapply for permission.

8. Posting of the full article/ chapter online is not permitted. You may post an abstract with a link to the Elsevier website www.elsevier.com, or to the article on ScienceDirect if it is available on that platform.

Kind regards,

Roopa Lingayath
Senior Copyrights Specialist
ELSEVIER | HCM - Health Content Management

Visit Elsevier Permissions

Journal of Cleaner Production 286 (2021) 125445

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Review of the terminology in the sustainable building sector

Felix Rheude [a], Johanna Kondrasch [a], Hubert Röder [a, *], Magnus Fröhling [b]

[a] *Chair of Sustainable Business Economics, TUM Campus Straubing for Biotechnology and Sustainability, Weihenstephan-Triesdorf University of Applied Sciences, Petersgasse 18, D-94315, Straubing, Germany*
[b] *Chair of Circular Economy, TUM Campus Straubing for Biotechnology and Sustainability, Technical University of Munich, Petersgasse 18, D-94315, Straubing, Germany*

A R T I C L E I N F O

Article history:
Received 20 April 2020
Received in revised form
12 November 2020
Accepted 6 December 2020
Available online 15 December 2020

Handling Editor: Prof. Jiri Jaromir Klemeš

Keywords:
Ecodesign
Green building terms
Environmental design
Environmental management

A B S T R A C T

Over the last decade, research focusing on sustainability in construction has emerged. Many solution approaches were developed with the aim to reduce the environmental impact of buildings and increase their social value, while achieving economic feasibility. However, with the variety of new tools and models increased the number of specific terms to describe the upcoming approaches and developments. This leads partly to misunderstandings and confusion in the scientific community, by companies and authorities, which are involved in planning, permission and construction of buildings. So this paper gives an overview of different terms, work out their definitions - as far as possible - and interrelate the terms with one another. The literature research was conducted using the Scopus database and the systematic literature review to determine the various terms. In total 11 terms have been identified from the fields of building, construction, design, management and planning. Afterwards, a pool of articles was selected and analyzed for each of these terms in order to find an accurate definition for each of them. The findings showed that clear definitions for most of the terms are possible. Some terms currently used should not be used in the context of sustainability and buildings or construction to avoid further confusions. As a result this study helps to improve the communication between scientists from different disciplines and thus enable an efficient further development of sustainability in the building sector by building on the already existing know-how.

© 2020 Elsevier Ltd. All rights reserved.

Contents

* Corresponding author. Weihenstephan-Triesdorf University of Applied Sciences, Petersgasse 18, D-94315, Straubing, Germany.
E-mail address: hubert.roeder@hswt.de (H. Röder).

https://doi.org/10.1016/j.jclepro.2020.125445
0959-6526/© 2020 Elsevier Ltd. All rights reserved.

1. Introduction

The anthropogenic climate change is affecting the world with various impacts and is mainly occurring due to the rising greenhouse gas emissions during the last decades. These emissions are connected to the production of consumer goods and the provision of the required energy for the modern standard of living including its logistics (International Energy Agency, 2019; Ruske et al., 2010). With a rapid growth in both the economy and population, the energy and resources that humanity demands has grown rapidly as well (International Energy Agency, 2019; Population Division, 2019; The World Bank, 2019). According to the United Nations Environment Program, buildings account for 40% of the electric global energy and 30% of the global .GHG emissions and additional negative environmental side effects (United Nations Environmental Programme, 2009). On top of that, due to the increase of global population, urbanization and the replacement of existing buildings, the construction industry will have to build more urban space in the next 40 years than it did in the last 4000 (Eberhardt et al., 2019).

This shows that buildings strongly affect both the environment and climate change and that the development of both economic and environmental viability are important for the future (Jian Zuo et al., 2017). As the construction industry has several positive impacts on society such as providing facilities for human beings, provide them employment opportunities and is an important factor for the economic development of any country (Doan et al., 2017; J. Zuo and Zhao, 2014), it cannot be ignored in terms of climate change nor substituted by other industries.

For this reason the sustainability idea has to be incorporated into the construction sector (Ortiz et al., 2009) creating a big task for the scientists for its implementation. In the literature, sustainable buildings are often described as requiring less virgin building materials and energy, while generating less pollution and waste than conventional buildings (Brejnrod et al., 2017; Zanni et al., 2014). At this point it should be noticed, that even the term sustainability is much debated and has several definitions (Barbosa, Drach, and Corbella, 2014). However, the authors believe that true sustainability can only be achieved when the triple bottom line, which includes environmental, economic and social aspects in equal shares, is considered (Illankoon et al., 2017). This is underpinned by Mensah and Enu-Kwesi (2019) as well as Barbosa, Drach, and Corbella (2014). Therefore, in this paper, a sustainable building has to consider each of the mentioned aspects in equal shares and not only environmental aspects.

Several tools have been developed to measure and reduce the environmental impact of buildings (BREEAM, 2018; BREEAM, 2018; LEED, 2019). These rating systems are considered as an appropriate scale to rate buildings as environmentally friendly. However, it is indicated that many specialists are more interested in the development of new tools than using and improving the existing ones (Baumann et al., 2002; Bocken et al., 2019). Furthermore, several topics have not been defined at a global scale and the assessment of buildings as "green" differs a lot among countries and stakeholders (Mattoni et al., 2018). It has to be considered, that the specific materials and processes used during a building's lifecycle differ according to the local climatic and geographical conditions, however, when using a certain keyword the overall system boundaries in consideration should be distinct.

Even terms used in the international literature, such as green building and sustainable building, are used interchangeably by several authors, even though they do not have the same meaning (Doan et al., 2017). Using scientific terms correctly is becoming increasingly important, as scientists all over the world are working on comparable problems and using the same expressions (Arnaudov et al., 2005; Baranyiovà, 2013). Applying the same terms but having different definitions in mind will become a hurdle when collaborating, especially when working in modern, interdisciplinary teams, which is nowadays not only in the scientific community common, but as well in the construction industry and politics. To overcome this hurdle this paper aims to analyze often used terms in the context of sustainable buildings and point out their differences through specific definitions for correct future use. This paper therefore focuses on the following research questions:

1. In which context are specific keywords associated with sustainable building and environmental construction currently used and how were they used in the past?
2. Are specific definitions and use cases for these terms possible?

In the following paragraph the importance of distinct definitions for scientific discourses will be described, followed by the explanation of the method how the literature review was conducted. Afterwards the results are presented and in an additional paragraph summarized. The paper is concluded by a discussion of the results and a conclusion.

2. Importance of definitions in scientific discourses

According to the theory of meaning by Locke and Winkler (1996) words are subjective, however academic language has the goal of being as precise and concise as possible (Townsend et al., 2018; Williams, 2013), to help scientists to learn from one another experiences and contribute to the scientific body of knowledge (Gee, 2015; Norris and Jones, 2005). Being at the same time abstract and technical (Norris and Jones, 2005), knowing the precise meaning of scientific vocabulary is important to participate in scientific discourses (Townsend et al., 2018). However, according to Reeves (2005), three problems occur when using scientific terminology:

1. Using incongruous terms in academic language;

2. Using unclear terms resulting in several definitions by different scientists and
3. Defining of the same term in multiple ways by scientists from different sub-fields.

Especially the last problem was also identified by Tenopir and King (2004) and Hyland and Tse (2007), when concluding that terminology is used inconsistently by scientists across different scientific disciplines. Even though words have different meanings in different disciplines (Nagy and Townsend, 2012), it is important, that scientists working on the same tasks understand each other, by meaning the same when using the same words. Especially in the area of sustainability it becomes increasingly important, as the interdisciplinary field incorporates scientists from various disciplines. Glavič and Lukman (2007) have already stated, that "not enough critical attention has been given to the definitions and their semantic meanings" (Glavič and Lukman, 2007:p.1875), when emphasizing, that new terms have emerged in the field of sustainability. As most of the words are not general academic words, they do not include dictionary entries (Nagy and Townsend, 2012; Glavič and Lukman, 2007). However, in comparison to this study, Glavič and Luk man (2007) did not focus on the building sector, but sustainability in general, which is why most of their derived definitions have only little significance for this study. A first study on the definitions and concepts in the building and construction sector was conducted by Zabihi et al. (2012) defining the keywords of "Sustainable Construction" and "Sustainable Building". However, the number of terms has increased over the past years and these terms need precise definitions in order to support clear communication among scientists from different fields (Williams, 2013). Therefore, this review was conducted to establish definitions for keywords in the field of sustainable building and construction to enable scientists from different fields of knowledge to efficiently communicate with one another.

3. Materials and methods

For this review, the criteria of Okoli and Schabram (2010a,b) were used to conduct a systematic literature review (SLR). This method allows analyzing the available literature deliberately. The journal database Scopus.com was analyzed to select the most suitable literature. As sustainable building and environmental construction are interdisciplinary research topics with various subject areas being involved in achieving the reduction of the environmental impact of buildings, Scopus seems to be a suitable database for finding the appropriate literature. Due to the vast number of available literature and to avoid possible double counting in the later analysis, no further databases (e.g. Google Scholar or Web of Science) were used. For some figures, journal abbreviations were made to achieve more clarity. The ISO 4 standard was used to phrase the abbreviations (ISO 4, 1997—12).

3.1. Screening criteria

The search terms in Scopus were ("environmental" OR "sustainable") AND ("building" OR "construction") for the title or abstract of the journal articles. Other terms were not searched for to limit the number of results and avoid the search for terms to be analyzed later. Searching for terms such as for example "Green Building" would result in a large number of results and so move the historical analysis of the keywords in favor of "Green Building" in comparison to the others. The results for "Environmental Building" and "Environmental Construction" were comparatively so few that they had no significant influence on overall results (see Table 1). Approximately 160,000 articles were found. Overall, two reduction steps were taken to find the appropriate literature for the historical analysis (first step) and to derive the definitions from these initial search results (second step). During the first step, the results were filtered by the type of document (only published, peer-reviewed articles), access type (many open access journals were excluded due to the poor quality of many journals), source type (only journal articles) and main subject area (only journals which have a main subject area related to building and construction). No restrictions were given regarding publication date, as priority was given to the relevance of the papers in terms of their contribution to the topic. In the following, the keywords associated with the search results were screened with a focus on the most often used terms that could easily be considered as interchangeable. These keywords should at first sight be associated with buildings/construction and sustainability and additionally vague (e.g.: "Green Building": The building has obviously not to be coloured green, but what does "green" in this sense then specifically mean?).

In total, eleven keywords were selected. These criteria limited the amount of papers used for the historical analysis to 6036 papers. The keywords were aggregated into three groups, each group representing a broader category and two to five keywords. The groups and associated keywords as well as an overview of the selection process can be seen in Fig. 1.

As mentioned above several terms have emerged in the scientific community to describe different kinds of environmentally friendly or sustainable buildings or constructions. However, not all those words can be covered in this article. Out of scope are for example: low carbon building (Kesidou and Sovacool, 2019), net zero energy building (Purbantoro and Siregar, 2019) and nearly zero-energy buildings (J. Li et al., 2019). These and others have been excluded as their number of results was a lot lower or none compared to the studied terms using the search algorithm.

3.2. Analysis

First, the historical development of each keyword will be shown. For the definition of the keywords, the results were screened again and papers that were either too specific in their topic (e.g. engineering papers focusing on specific components or construction parts) (e.g. Kilkis (2006)) or too specific in terms of their geographical focus were sorted out (e.g. Abas et al. (2018), N. Abrantes, Alves, and V. Abrantes (2015) and Kayode et al. (2008)). These papers were sorted out because experience has shown that these types of papers focus more on specific technical subjects or specific geographical characteristics rather than the overview necessary to compile the globally unique definitions. Furthermore, many papers had the keyword in their list, but did not mention the keyword afterwards in the paper. As a definition cannot be derived under such circumstances, these papers were excluded as well. Additionally, most papers take the meaning of the terms for granted and do not provide any kind of definition or explanation for them. These papers were also excluded. Overall, 39 papers were left to infer the definitions. An overview of the method used in the search for the papers is illustrated in Fig. 1.

Selection process for the papers used to define the keywords, [1] for the initial selection process the search phrases ("environmental" OR "sustainable") AND ("building" OR "construction") were entered into Scopus.

The tools provided by Scopus were used for the historical analysis. The search results per keyword were grouped into lists and analyzed. Graphs were made for the documents published per year, per source and per subject area. The goal was to ascertain whether specific terms were used more often during certain periods, in specific subject areas or journals. Any of these results could help future authors to use the correct term when writing a paper for

Table 1
Number of papers used for the historical comparison and the number of papers used for compiling the definitions; in brackets: number of papers or ISOs listed, which were used for additional information.

Group	Keyword	Comparison	Definitions
Building/Construction	Ecological Construction	4	4
	Environmental Building	6	3
	Environmental Construction	14	- (3)
	Green Building	710	5
	Green Construction	6	3
Design/Architecture	Architectural Design	1665	6
	Ecodesign/Eco-design	170	3 (2)
	Environmental Design	113	5
	Sustainable Design	209	4
Management	Environmental Management	2565	3 (1)
	Environmental Planning	574	3

publication or communicating to other specialists. A specific screening regarding the geographical area of the examined papers was not conducted, as the goal was to derive globally unique definitions for the keywords. The only exception was “Ecological Construction”, which will be explained in 4.1.2.

4. Results

The following table shows the final number of papers per keywords used to define the words. It has to be noted that the meaning of the terms is taken for granted in most papers. This explains why the number of papers used to compile the definitions are, in most cases, much lower than the number of papers used for historical comparisons. Furthermore, additional papers are listed in brackets, used when less than three papers in the initial search were found. These papers were found by searching for publications without the searching phrase (“environmental” OR “sustainable”) AND (“building” OR “construction”) and filtering the results according to the same rules as applied above. They were found by directly searching for the search phrase in the keywords (e.g. KEY “Environmental Construction”). Furthermore, ISOs were identified and cited in two cases.

Number of papers used for the historical comparison and the number of papers used for compiling the definitions; in brackets: number of papers or ISOs listed, which were used for additional information.

4.1. Group 1 - building and construction

4.1.1. Historical analysis

Number of papers associated with the keywords over the period from 1999 to 2018”

Fig. 2 shows the number of papers associated with the keywords over a period of 20 years with the results per year. Only the results for “Environmental Construction” and “Green Building” are shown, as the number of results for both “Green Construction” and “Environmental Building” had only six results within the observed period and thus also significantly less than the others and do not allow conclusions. However, both “Environmental Building” and “Green Construction” had their results within the past 10 years and none before that period, indicating that they got more relevant during this period.

“Green Building” has the highest quantity of results and is the only keyword in this group where a constant development over the years can be seen. Since 2007, a constant rise in the number of papers with the keyword “Green Building” can be observed. This indicates, that within the last decade the research interest in “Green Building” has risen constantly. For the other keywords no significant development during the observed period can be derived.

Number of papers associated with the keyword “Green Building”; listed are a maximum of 10 papers sorted by the highest amount.

“Ecological Construction”, “Environmental Building” and “Green Construction” have less than 10 results over the observed period and are additionally equally distributed throughout the journals, which is why the figures of these keywords are not shown here. The journal “Energy and Buildings” had twice the keyword “Environmental Building” and therefore more results than any other journal of those keywords (Castellano et al., 2015; García- Sanz-Calcedo et al., 2014). The keyword “Environmental Construction” is also not shown here, as the results are completely equally distributed over the different journals as well. A keyword focus of for specific journals is therefore not visible. The highest number of papers with the key word “Green Building” had “Building and Environment” with over 45 papers and therefore more than the other keywords combined. Overall “Green Building” had 710 article results using our search mechanism, resulting in more than 10 different journals publishing articles with the keyword “Green Building”. In total, 160 journals published at least one paper with the keyword “Green Building” within the observed time period and search area. To keep an overview, Fig. 3 only shows the 10 most important journals citing “Green Building” in their keywords. However, the results indicate, that journals without specific focus on architecture, but more technical features of buildings (e.g. Building Environment, Journal of Cleaner Production or Energy and Building) are using this keyword more frequently. This is underpinned by the following results.

Percentage of the different subject areas associated with the different keywords; the six largest subject areas are shown; Number of papers for each keyword (every papers has several subject areas) Ecological Construction: N = 4, Environmental Construction: N = 14, Green Building: N = 710.

Fig. 4 shows the distributions of the subject areas associated with the different keywords in percentages. Due to the few number of results, the figures for both “Green Construction” and “Environmental Building” are not shown here, but will be discussed.

It can be seen that most of the papers are published in subject areas associated with “Engineering”, except for “Ecological Construction” which was most present in “Earth and Planetary Sciences” as well as “Social Sciences”. “Ecological Construction” is mentioned on second place in papers associated with “Environmental Sciences” (as well as Agricultural and Biological Sciences) equally to the subject area of “Environmental Building” and “Green Building”.

In comparison, the term “Green Construction” is not presented

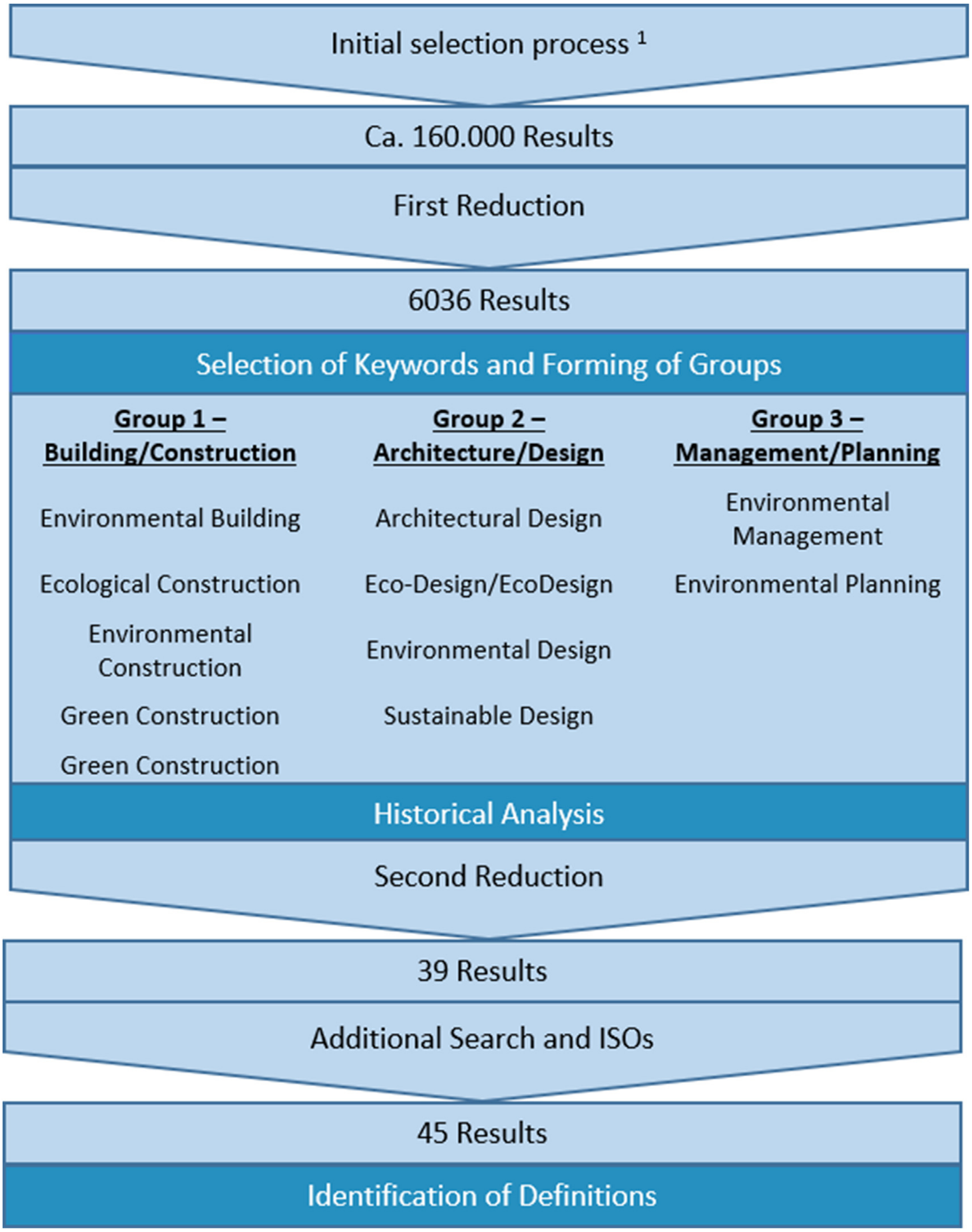

Fig. 1. Selection process for the papers used to define the keywords,[1] for the initial selection process the search phrases ("environmental" OR "sustainable") AND ("building" OR "construction") were entered into Scopus.

in this subject area. The keyword "Green Building" is most often mentioned in the subject areas of "Engineering" (32%) and "Environmental Science" (17%), both subject areas of the journal "Building and Environment". It can be seen that there are also subject areas, which may not be expected at first thought, e.g. medicine (3%) for "Green Building". This is because journals are still represented in this historical analysis, like for example the "Journal of Green Building", which also covers subjects areas such as "Public Health" and "Environmental and Occupational Health" both subcategories of "Medicine". The papers represented here are therefore no major health journals, such as the "New England Journal of Medicine", for example, but papers covering medicine as well as part of their subject-specific areas.

4.1.2. Definitions

Ecological Construction. As the number of papers generated for the keyword "Ecological Construction" was very low and any useful results for the definition of this term could not be achieved with this keyword, further research was conducted. Hallberg and Tarandi (2011) described that in 2007, the Chinese government

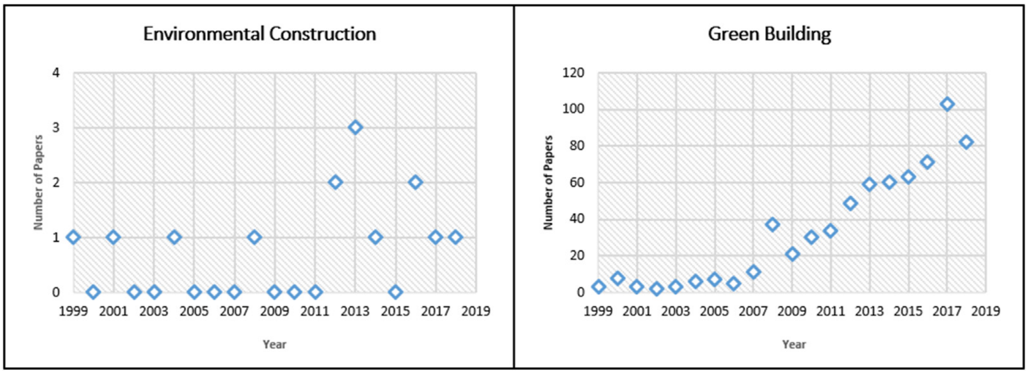

Fig. 2. Number of Papers associated with the keywords over the period from 1999 to 2018.

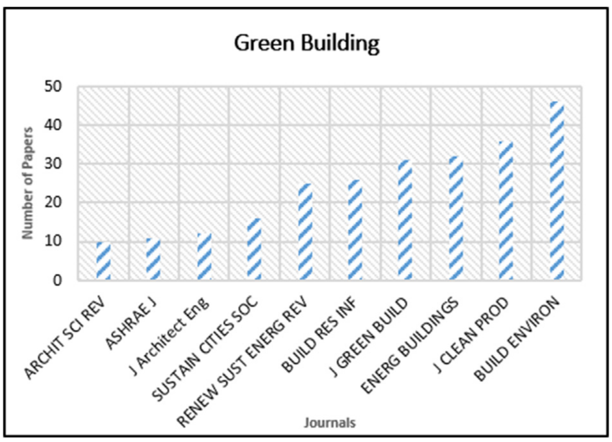

Fig. 3. Number of papers associated with the keyword "Green Building"; listed are the 10 papers with the highest amount. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

announced a new strategy on "Ecological Construction" with its sub-parts green economy, green society and green environment. The sub-parts are described below:

1. Green economy: Save energy, reduction of emissions and improve economic development through increased funding in science and technology.
2. Green society: Save energy and water in the living departments, while increasing investments in education and health.
3. Green environment: The investments in infrastructure should increase in order to achieve an environmentally friendly country within the next decade.

Because of the importance and interdisciplinary nature of this strategy, it is not surprising that most journal articles with the keyword "Ecological Construction" found on Scopus are written by Chinese researchers and cover Chinese geographical, social or political issues (e.g.Liu Xusheng, Li Xianwen, and Sun Tao (2017); Xia and Yan Li (2018) G. Xu et al. (2018); J. Yang, Song, and Xing (2019)). Yunfeng Hu et al. (2019) described "Ecological Construction" as improving and sustaining the vegetation and natural environment of certain areas through human activities. Liu et al. (2018) also describe "Ecological Construction" as preservation and restoration of land against human activities and influences. In comparison, Hisseine et al. (2019) describe "Ecological Construction" as using more eco-efficient building materials, meaning building materials with a lower water and carbon footprint. A similar approach was taken by Suresh and Anand (2017) when they described the use of rammed earth in building construction as "Ecological Construction".

Environmental Building . Spinks (2015) described "Environmental Building" as constructions fulfilling the quality criteria of the sustainable building rating system BREEAM. However, as BREEAM is just a building assessment method, Spinks (2015) does not mention which BREEAM quality criteria a building has to achieve in order to be classified either as sustainable or environmental. In comparison, Herbert (1998) described an "environmentally advanced building" as one requiring "less energy than the current best practice while providing the occupants with a comfortable, healthy and controllable working environment" (Herbert, 1998:p. 87). This building has achieved the highest available rating in BREEAM and uses recycling materials in construction. According to Herbert (1998) it can be considered as a model for modern 21st century buildings and is thus an example for "Environmental Building(s)". Indirectly, Castellano et al. (2015) described an "Environmental Building" in their article as focused on the environmental part of construction. This fits the descriptions of Spinks (2015) and Herbert (1998) as BREEAM also incorporates mainly environmental criteria and less so economic and no social sustainability criteria.

Environmental Construction . The selected literature took the definition of "Environmental Construction" for granted. Therefore, additional literature was searched and screened to identify a suitable definition for the keyword. According to S. Li, H. Xu, and Shen (2013) urban "Environmental Construction" should be the high interaction between people and their environment. This means incorporating economic development, social progress and environmental protection with a focus on a stable, coordinated and sustainable urban development. A comparable description was used by Baranova et al. (2017) as they described "Environmental Construction" with the example of how financial, logistical and human resources are required to cope with the reduction of the thickness of loess to ensure a safe development of the buildings in the investigated area. Švajlenka, Kozlovská, and Pošivaáková (2018) described "Environmental Construction" as one part of "Sustainable Construction", as sustainability incorporates the three pillars, namely economic, environmental and social matters. Therefore, in their point of view, "Environmental Construction" is a construction focused primarily on ecological sustainability, but that does not necessarily consider economic or social matters.

Green Building. "Green Building" as a term is widely used, as the previous results in the historical analysis indicate. However, "Green Building" as a term has several uses in the literature. For example,Y. Li et al. (2019) wrote "[…] green buildings are characterized by highly environmental performance, such as improved energy and

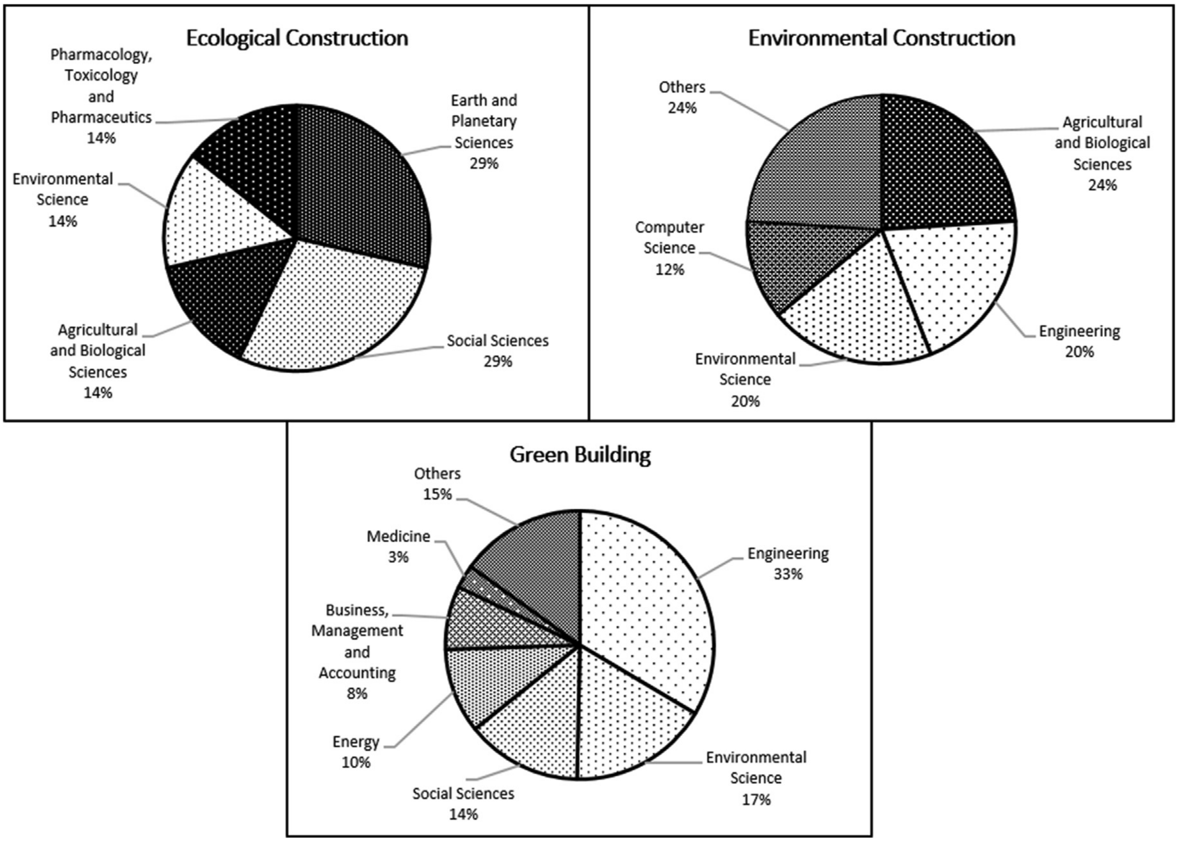

Fig. 4. Percentage of the different subject areas associated with the different keywords; the six largest subject areas are shown; Number of papers for each keyword (every papers has several subject areas) Ecological Construction: N = 4, Environmental Construction: N = 14, Green Building: N = 710.

water efficiency, enhanced air quality of indoor environment, and reduced air pollution" (Y. Li et al., 2019:p. 183). In comparison, Kats (2003) described a green building as "[…] sensitive to environment, resource and energy consumption, impact on people (quality and healthiness of work environment), financial impact (cost-effectiveness from a full financial cost-return perspective) [and] the world at large […]" (Kats, 2003:p. 1). Ahmad, Aibinu, and Stephan (2019) defined a "Green Building" simply as "their emphasis on environmental and social aspects" (Ahmad et al., 2019:p.83) in comparison to conventional buildings. In his paper, Paumgartten (2003a,b) described a "Green Building" as "any building that meets the high standards set forth in the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) Green Building Rating System, the pre-eminent metric system by which new buildings are judged to be environmentally conscious" (Paumgartten, 2003a,b:p.26). However, Paumgartten did not mention the quality level of LEED he is referring to in his definition. As the quality level strongly influences the sustainability of a building, it is not clear what a specific "Green Building" is in his opinion (LEED, 2019). Finally, Hwang et al. (2017) defined a "Green Building" as "the creation of structures that are environmentally-responsible and resource-efficient throughout a building's life-cycle" (Hwang et al., 2017:p.2).

Green Construction. According to Hamid et al. (2012) "Green Construction" can be described as "the creation and responsible maintenance of a healthy built environment based on ecological principles and by means of an efficient use of resources" (Hamid et al., 2012:p.56). In comparison, Tan, Yu, and C. L. Yang (2013) described the key measures for "Green Construction" as material saving, energy saving, land saving and water saving during the building phase as well as guaranteeing professional health and the protection of the environment. According to Kibert (1994) "Green Construction" can be used interchangeably with "Sustainable Construction". Kibert defined six principles for sustainable (green) construction: the minimization of resource consumption, the maximization of resource reuse, the increasing use of renewable or recyclable resources, the protection of the natural environment while creating a healthy, non-toxic environment and achieving a high quality in the built environment.

4.1.3. Suggesting definitions

Green Building. In their definitions, the seven examined papers of "Green Building" mention the environmental performance of the building as very important. Additionally, in two articles, the other fields of sustainability (economic and social performances) were mentioned and considered as well. Moreover, Hwang et al. (2017) emphasized the importance of the "Green Building" responsibility throughout the whole building lifecycle. Rating systems (e.g. LEED) were mentioned as a suitable methodology to assess "Green Buildings", unfortunately without specifying the degree of their fulfilment required to have a "green" building. Since the early 2000s, the term "Green Building" has been used more often in publications focusing on the fields of Engineering and Environmental Sciences. Considering this and the scope of the journals publishing most of the articles which had the keyword "Green Building", the authors suggested to extend the definition of Hwang et al. (2017) when speaking in the future about "Green Building" and to separate it from the other discussed terms.

The definition suggested for "Green Building" should be: "A green building is the creation of structures that are environmentally-responsible [, socially-friendly] and resource-efficient throughout a building's lifecycle".

This is underpinned by Fig. 4 showing that the keyword "Green Building" is mainly published in the three subject areas of "Engineering", "Environmental Science" and "Social Sciences", which cover all aspects of the suggested definition. Additionally, "Green Building" has been mainly used in journals focusing not on architecture, but technical aspects, which is supported by the suggested definition.

Environmental Building. Even though "Environmental Building" had only a few results in the screened literature, the term is widely used. Like "Green Building" the term has its main published subject area in the field of Engineering but was not as popular as "Green Building" in recent years. Comparing the screened literature and the context with the other terms, the authors suggest to use a slight adaptation of the definition used by Castellano et al. (2015) for the definition of "Environmental Building": "A building, whose construction [both used materials and processes required for the construction] focuses on being environmentally-friendly."

A focus is given on the construction of the building, not its overall lifetime efficiency regarding water use, heating and indoor air quality or its later deconstruction. These are the main differences to the definition of "Green Building" and rating systems such as BREEAM or LEED, which (among others) consider these aspects.

Environmental Construction. As both "Environmental Construction" and "Ecological Construction" are examined in this paper, first "environmental" and "ecological" shall be distinguished, as they are often used as substitutes. The term ecology was first defined by Ernst Haeckel in his book "Generelle Morphologie der Organismen" from 1866 as a branch of biology, which deals with the relations between organisms as well as with their surroundings. The term environment, on the other hand, is much broader and includes the interdisciplinary work of biologists, chemists and other fields of knowledge to study humans influence on its surrounding (Moffatt, 1982).

"Environmental Construction" was mentioned more often in the recent literature compared to the previous "Environmental Building". However, the number of papers still mentioning the term in the searched area never exceeded three mentions per year. Furthermore, the journals were equally distributed without any accumulation to a specific journal. According to the literature related to "Environmental Construction" and in contrast to the other keywords described and defined in this article, the authors suggest to use the term "Environmental Construction" when writing about all human-made constructions except buildings. This is in accordance with the definition of Švajlenka, Kozlovskáá, and Pošiváková (2018) having a focus on environmentally-friendly materials and construction methods. Those constructions could be embankments, roads or tunnels, for example. Fig. 4 shows that the main subject areas of the journals publishing the keyword "Environmental Construction" are, in descending order, "Agricultural and Biological Science", "Engineering" and "Environmental Science" showing that considering agricultural and biological as well as environmental areas are important for the keyword. The suggested definition is furthermore underpinned by the fact that "Engineering" is the second largest subject area.

Ecological Construction. In comparison to the previous terms, "Ecological Construction" does not have the subject area "Engineering" as a major subject (see Fig. 4). The subject areas are more equally subdivided than for the previous terms and cover many different areas. Whereas the previous terms had been published in global journals, the term "Ecological Construction" seems to be published mainly in journals with a focus on Chinese territory. This is in accordance to the fact that the Chinese governmental strategy on "Ecological Construction". The authors therefore suggest not to use the term "Ecological Construction" in terms of buildings to avoid the possibility of confusion with the broad and dominant Chinese strategy. Even though only a few papers have been published in the searched area, it can be seen in Fig. 4 that a large subject area is covered.

Green Construction. The term "Green Construction" has a focus on "Engineering" when comparing the different subject areas, which is in accordance with the published journals, most of them also having "engineering" in their title. The term was mainly used in previous years because lifecycle thinking gained prominence only in recent years. The authors therefore suggest to use the definition provided by Tan, Yu, and C. L. Yang (2013) as human-made constructions except buildings, which have an environmental focus not only on the required materials, but also throughout their lifecycle. The alignment of "Green Construction" with "Sustainable Construction" by Kibert (1994) is misleading because the other two pillars of sustainability are not mentioned to be an aspect of "Green Construction" concept.

Following these definitions, the subsequent general statements can be made:

1. The term "building" should be used only when referring to above-ground construction, whereas the term constructions refer to all other human-made constructions such as roads, tunnels or embankments.
2. The term "green" refers to the whole lifecycle of either a building or construction, not only the used materials, whereas the term environmental focuses mainly on the materials and processes to build the structures.
3. The terms "ecological" and "environmental" are not synonyms and authors should therefore be cautious when using them. The term "ecological" should not be used in the context of buildings and constructions to avoid the possibility of confusion.

4.2. Group 2 - design/architecture

4.2.1. Historical analysis

Number of papers over the period from 1999 to 2018 for the second group associated with design.

The second group, keywords belonging to the topic of design and architecture, has overall more research results than the first group. It can be seen that since around 2006 "Architectural Design" had a steady annual increase to nearly 350 publications in 2018. "Ecodesign" as keyword experienced strong growth in mentions in the keywords since 2014. Before that year, only individual results have been found for both keywords. This development shows, how the research interests and studies about these keywords have increased within the observed period.

The third keyword, "Environmental Design" has, in total, fewer results than "Ecodesign". The maximum was achieved in 2015 and remained on a lower, but steady level for the following three years. Between 1999 and 2014, "Environmental Design" had also only few mentions and a sharp increase after that. "Sustainable Design" started in 2006 peaked in 2011. Since then, a decline in papers with "Sustainable Design" in their keywords can be observed, which indicates, that this keyword is nowadays less interesting for the academic research than in 2011. A reason for this may be the ecodesign directive from 2009 (Parliament and Council, 2009) and the first version of the ISO from 2011 (14006, 7.2011), which may be the origin for the decline of sustainable design.

Number of papers associated with the keywords of design per journal; listed are the 10 journals with the most published papers.

Fig. 5 shows the 10 journals having the highest number of papers with the associated keywords. Both "Architectural Design" and

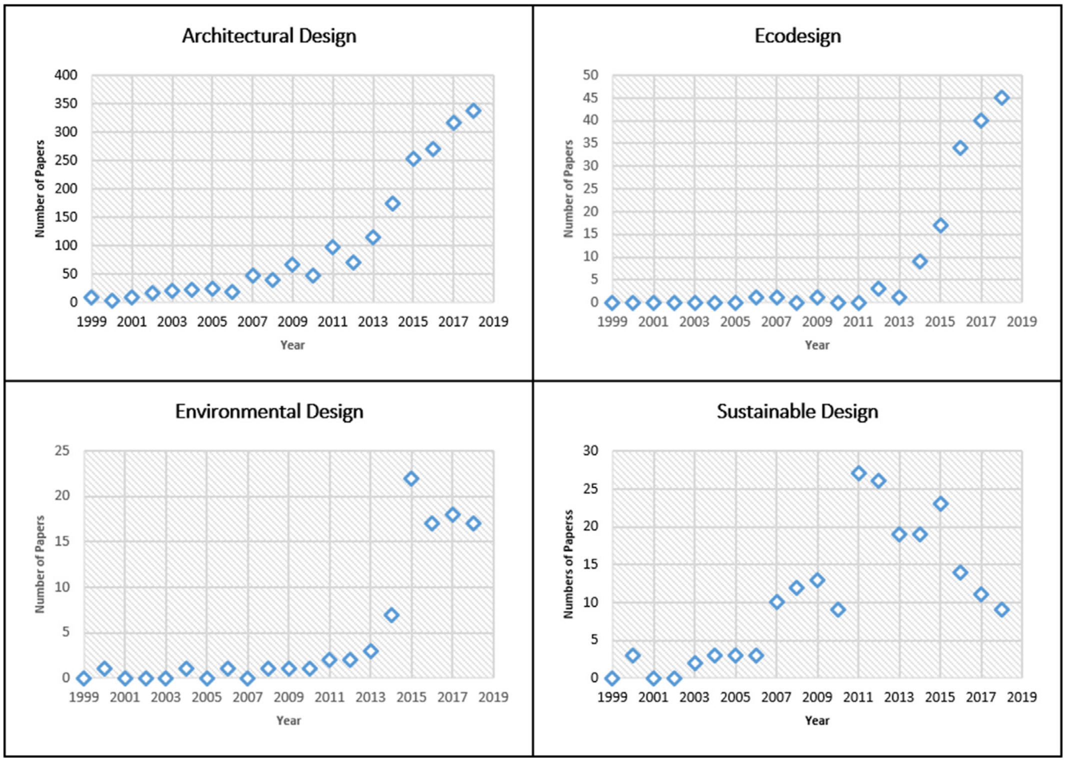

Fig. 5. Number of papers over the period from 1999 to 2018 for the second group associated with design.

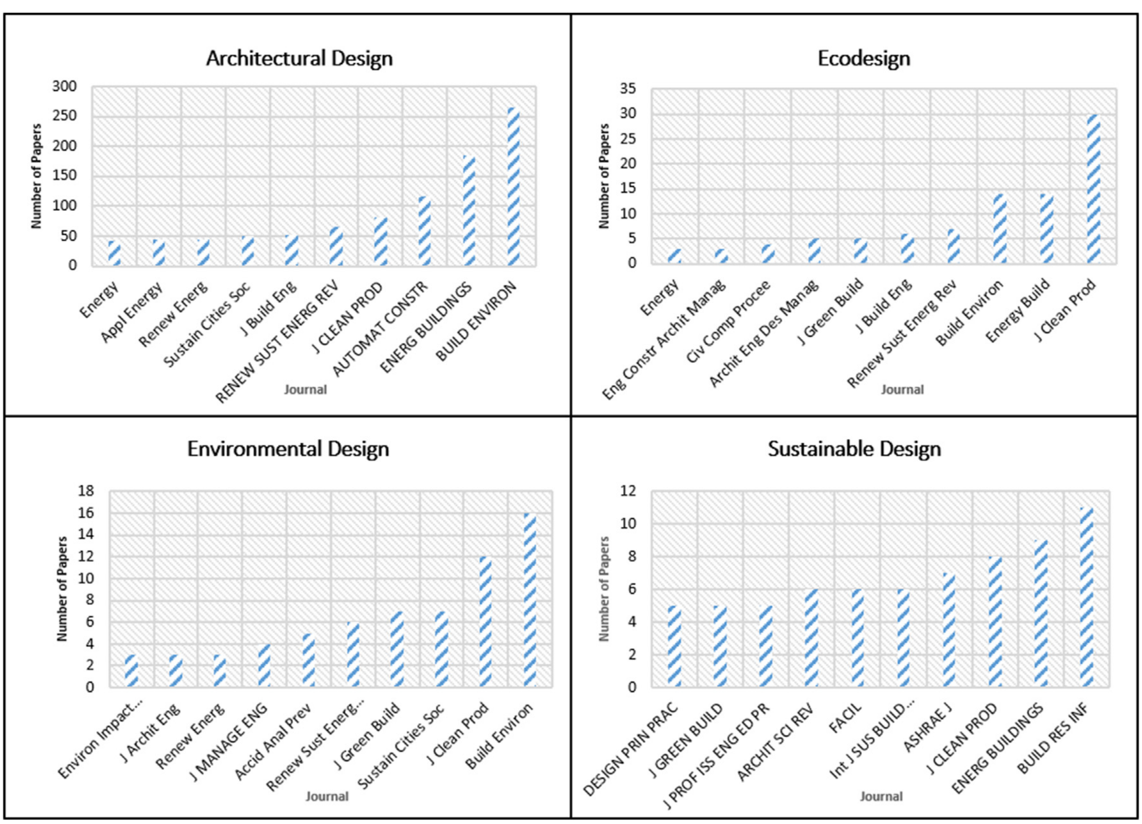

Fig. 6. Number of papers associated with the keywords of design per journal; listed are the 10 journals with the most published papers.

"Environmental Design" are most often mentioned in the journal of "Building and Environment". For the keyword "Ecodesign", "Building and Environment" is the journal with the third highest number of results. In comparison, "Building and Environment" is not among the first 10 journals when searching for the keyword "Sustainable Design". However, the "Journal of Cleaner Production" is the only journal which is in the top 10 of all keywords. "Building and Environment", "Energy and Buildings", "Journal of Green Building" and "Renewable And Sustainable Energy Reviews" are all represented three times in the lists. Noticeable is also the reference to some kinds of architectural journals for all of the three keywords except for "Architectural Design" itself. However, no journal focusing mainly on architecture is within the top 3 of any keyword. This is underpinned by the following figure, showing that architecture is not within the most relevant subject areas (see Fig. 6).

Percentage of the different subject areas associated with the keywords; the six largest subject areas are shown, all other subject areas are combined in "others"; Number of papers for each keyword (every papers has several subject areas) Architectural Design: N = 1665, Ecodesign: N = 170, Environmental Design: N = 113, Sustainable Design: N = 209.

Fig. 7 shows the percentage distribution of the different subject areas per keyword. It can be seen that "Engineering" is the dominant subject area for all keywords, followed by "Environmental Science". Also dominant are the subject areas of "Social Sciences", "Energy" and "Business, Management and Accounting". As in Fig. 4, the subject area "Medicine" is mentioned once again, this time for the keyword "Environmental Design". Comparing it with the field of "Environmental Design" in Fig. 3 shows that the journal "Journal of Green Building" is once more in the top 10 results for the keyword. For "Sustainable Design" with 4%, the subject area "Arts and Humanities" is shown, although the major source here was the journal "Design Principles and Practices" as well as architectural and construction journals.

4.2.2. Current definitions

Architectural Design . "Architectural Design" as pointed out by Farid et al. (2017) is a "[â€¦]cooperation between art and science" (Farid et al., 2017:p.70). The shift to the sustainability aspects in "Architectural Design" are becoming more evident. Form and aesthetics are no longer the dominant factors in architecture. Instead a well-balanced trade-off between traditional architecture and specific building performance is becoming more important (Kwon, 2014; Shi, 2010). However, it is up to an architect on how to interpret building performance as "[In] architectural design, performance is often used as a generic term to describe many design considerations of a building" (Shi, 2010:p.512). Thus, the achievement of the overall benefit in the attributes pursued in the design phase means performance. Structural and environmental performance are the main types regarding sustainability in building design and therefore, nowadays performance-based design has become popular regarding sustainable development in the built environment (Shi, 2010).

According to Feria and Amado (2019) "Architectural Design" is the decision-making process of an architect to achieve a detailed designed building. This method can be adjusted according to the building's requirements. This is underpinned by the descriptions of Ryan (2011) and Lawson (2006).

Ecodesign. In the past 20 years, several "Ecodesign" approaches have been developed and discussed in the literature, but most of

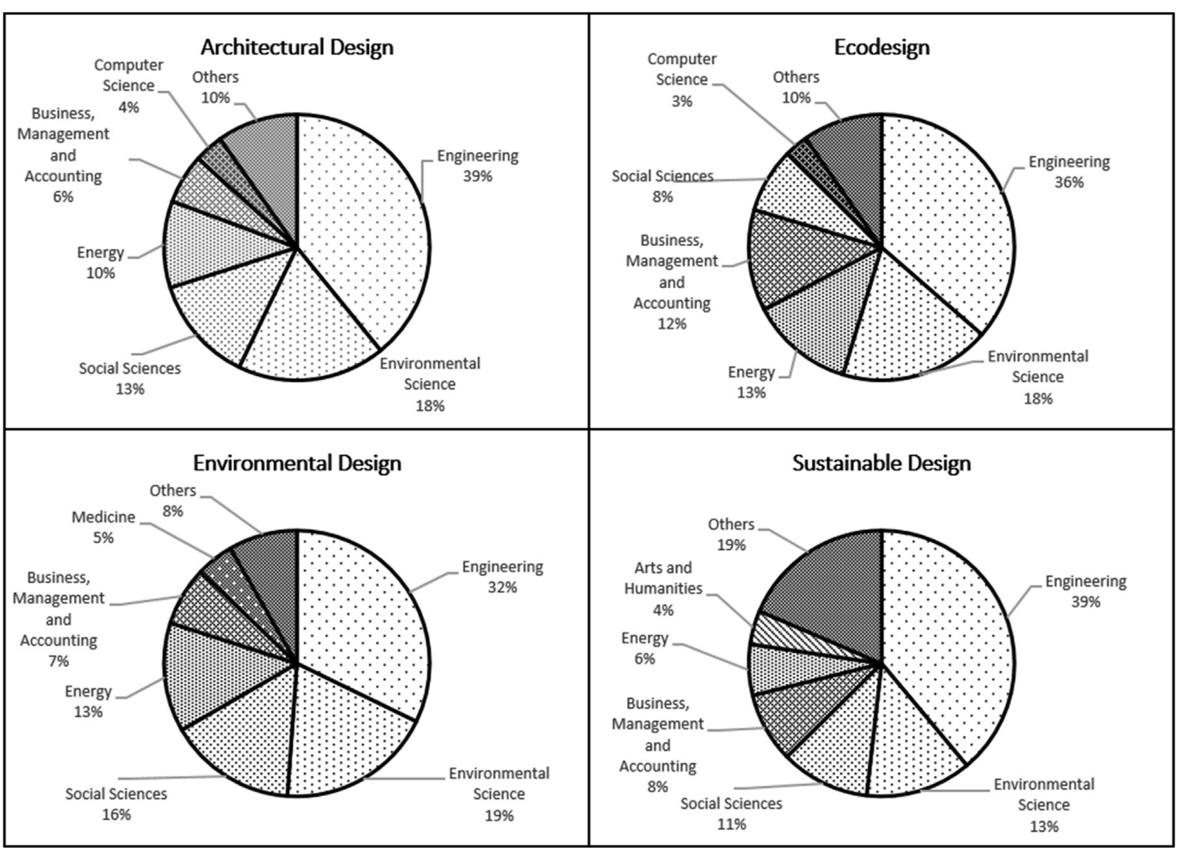

Fig. 7. Percentage of the different subject areas associated with the keywords; the six largest subject areas are shown, all other subject areas are combined in "others"; Number of papers for each keyword (every papers has several subject areas) Architectural Design: N = 1665, Ecodesign: N = 170, Environmental Design: N = 113, Sustainable Design: N = 209.

them have been incomplete in terms of flexibility and specificity (Cicconi et al., 2018). Another definition was developed by Glavič and Lukman (2007) which is focusing on the product development process. However, according to DIN EN ISO 14006:2020–05 (ISO 14006, 5.202), “Ecodesign” is defined as a systematic approach, which takes environmental aspects into account with the goal to reduce adverse environmental aspects over the whole lifecycle of a product. A comparable definition was already written down in DIN EN ISO 14006:2011–10 (ISO 14006, 2011). Charter and Tischner (2010) have defined “Ecodesign” as solutions that minimize negative and maximize positive sustainable impacts from an economic, environmental, social and ethical point of view and throughout its entire lifecycle. McAloone and Pigosso (2017) said, that “Ecodesign” involves the integration of environmental issues into product development.

Environmental Design. Sustainable buildings face several challenges in design and construction due to their complexity and multi-disciplinary processes (Gangemi et al., 2000). Gangemi, Malanga, and Ranzo (2000) described “Environmental Design” as integrating environmental concerns into the design process of a project; in their example, these are sustainable buildings. According to Jalilian (2013) “Environmental Design” can be defined as “the process of addressing surrounding environmental parameters when devising plans, buildings and [â€¦] it can refer to designing due to ecological and sustainability issues.” (Jalilian, 2013:p.195). Bangwal and Tiwari (2019) described “Environmental Design” as connecting people to the natural environment and eliminate the negative environmental impact completely through “Sustainable Design”. D’Ambrosio and Leone (2015) described “Environmental Design” as “advanced strategies that incorporate as added value and growth factor the reduction of CO2 emissions, the sustainable use of soil and resources, in addition to local development and social inclusion objectives” (D’Ambrosio and Leone, 2015:p.134). Critically for D’Ambrosio and Leone is the correlation of “Environmental Design” with both urban and spatial planning considering economic, environmental and social consequences.

Sustainable Design. Farid, Zagloul, and Dewidar (2017) described the term “Sustainable Design” not only as a philosophy but rather as an active contribution driven by designers, which is sustainable and responsible for the future generation. It improves building performance towards a better environmental appearance. Beyond the triple bottom concept of sustainability, developed by Elkington (2002), it should also meet the requirements of human comfort and architectural aesthetics. The authors stated also that “Sustainable Design” is still in the metamorphosis phase, being only at the first transformation stage between discussion and adaptation (McLennan and Berkebile, 2004). Grierson and Moultrie (2011) pointed out that “Sustainable Design” should be recognized as a philosophical, interdisciplinary approach. Besides the functional requirements, social, environmental and economic criteria should ensure the achievement of “Sustainable Design” by incorporating different methodological principles at various stages of the design process. The consideration of environmental aspects together with the issues of cost, schedule, comfort and health of building residents as well as worker/employee security is a characteristic of “Sustainable Design”. Compared to the previous authors, Bashir et al. (2016) do not distinguish between sustainable and green design. The efficiency of such “Sustainable Design” depends generally on five parts: site location, optimization of the energy demand and application of regenerative energy sources, selection of recycled local and nonhazardous materials, water conservation and indoor environmental quality. These fundamental elements were identified by analyzing different rating systems (such as DGNB, LEED-Canada, Green Star, BREEAM and others). From the point of view of Bashir et al., “Sustainable Design” appears as a necessity rather than an alternative (Bashir et al., 2016).

4.2.3. Suggesting definitions

“Architectural Design” had the most publications within the group, followed by “Sustainable Design”, “Ecodesign” and then “Environmental Design”. It can be seen that both “Sustainable Design” and “Architectural Design” had their first publications in the early 2000s, while “Ecodesign” and “Environmental Design” had their first publications in 2014. Since then, “Architectural Design” has especially experienced a rapid development. All of the terms in this group have the most publications in the subject areas of Engineering, with journals such as “Building and Environment”, “Journal of Cleaner Production” and “Energy and Buildings” being those with the most publications. However, the definition and use of the terms and phrases differs.

4.2.3.1. Architectural design. “Architectural Design”, even though often used in the sustainable building context, is not specific and – as recommended by the authors – should not be used in the sustainable building context to avoid confusion as the definitions in the previous section have shown. To distinguish, Feria and Amado (2019) already use the phrase “Sustainable Architectural Design”, but it may be confusing whether the process and method or the product are sustainable. Thus, “Architectural Design” should only be used if specifically defined first by the user group.

4.2.3.2. Ecodesign. Since “Ecodesign” has an ISO (ISO 14006, 5.202), the phrase should be used according to ISO standards, which is supported by the directive of the European Union (Parliament and Council, 2009). This can be underpinned by the fact that the subject areas of the journals publishing the keyword “Ecodesgin” are mainly “Engineering” and “Environmental Science” as well as “Energy” and “Business, Management and Accounting” (Fig. 7). The social component suggested by Charter and Tischner (2010) is therefore not prominent in the published journals and should not be included in the definition.

4.2.3.3. Environmental Design and sustainable design. The definition of “Environmental Design” according to Jalilian (2013) states that a “[â€¦] designing due to ecological and sustainability issues” should be made, even though the ecological issues are already incorporated into sustainability issues, as sustainability can only be achieved when equally considering economic, social and environmental aspects. The definition by Bangwal and Tiwari (2019) cannot be recommended either, as once again an indistinct differentiation between sustainability and environmental aspects is made. Therefore, the authors recommend the definition by D’Ambrosio and Leone (2015) for “Environmental Design”, which incorporates both the reduction of negative environmental effects and increasing social inclusion, but do not equate it with sustainability, as the economic factor is not considered. Therefore, “Sustainable Design” can be seen as “Environmental Design” while considering economic factors in the decision-making process.

4.3. Group 3 - management/planning

4.3.1. Historical analysis

Number of papers associated with the keywords over the period from 1999 to 2018.

Fig. 8 shows the development of the different keywords over time, summarized in the topic “Management/Planning”. It can be seen that especially “Environmental Management” steadily developed over time, going from 27 published papers in 1999 to over 300 in 2018. The result indicates, that the researchers interest in subjects associated with “Environmental Management” has increased

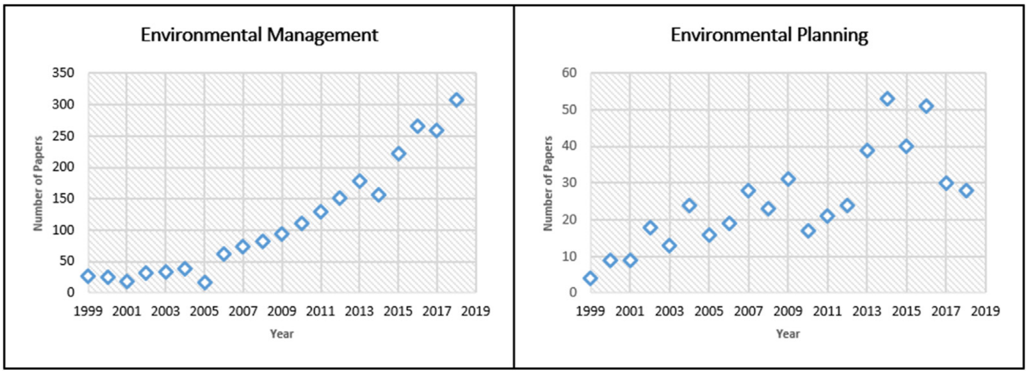

Fig. 8. Number of papers associated with the keywords over the period from 1999 to 2018.

over time. In the observed period and the searched area, "Environmental Planning" had a total number of 497 search results, distributed over time as can be seen in Fig. 8. Until 2014, the number of publications had an overall increase to 53 papers, followed by a decline in papers to 28 in 2018. The results indicate, that after an increase in "Environmental Planning" until 2014, the interest decreased steadily during the observed period as fewer articles were published. However, both keywords still have an high significance and should be distinguished from one another.

Number of papers associated with the keywords per journal; listed are the 10 journals with the most published papers.

Fig. 9 shows the top 10 papers associated with the keywords of group 3. "The Journal of Cleaner Production" has published the most papers with the keyword "Environmental Management", overall more than the second and third place combined. However, the "Journal of Cleaner Production" is not within the top 10 of "Environmental Planning". The top journal for "Environmental Planning" is the "Environmental Management" journal. This journal is not within the top 10 of "Environmental Management" which might be for avoiding double counting within the journal's title and its keywords.

Percentage of the different subject areas associated with the keywords; the six largest subject areas are shown, all other subject areas are combined in "others"; Number of papers for each keyword (every papers has several subject areas) Environmental Management: N = 2565, Environmental Planning: N = 574.

Fig. 10 shows the distribution of the keywords per subject area. In these figures, only the top six subject areas are shown, smaller subject areas were combined in the term "Others". It can be seen that in both keywords, the dominant subject area is "Environmental Science". "Engineering" is the second largest subject area for "Environmental Management", but only the sixth largest for the keyword "Environmental Planning". The second largest subject area of "Environmental Planning" is, in comparison, "Social Sciences". All other subject areas for the keyword "Environmental Planning" are each below 10%. "Environmental Management" has 10% of its results in the subject area of "Energy", the other subject areas are also each below 10%.

4.3.2. Current definitions

Environmental Management. Sandewall and Nilsson (2001) already pointed out that there is a lack in separating planning and management from each other, especially between different cultures and political systems. The task of management is described by Forrester (1958) as "to interrelate the flows of information, materials, manpower, money and capital equipment so as to achieve a higher standard of living, stability of employment, profit to the owners and rewards appropriate to the success of the managers" (Forrester, 1958:p. 38). Planning itself is, on the other hand, according to Vahs and Schäfer-Kunz (2012), defined as "a systematic process, which should enable to describe both goal and the path to these goals as well as identifying and solving problems which may arise" (Vahs and Schäfer-Kunz, 2012:p. 349, translated from German). According to 14001 (10.2015), "Environmental Management" is defined as "part of the management (system) used to manage environmental aspects, fulfill compliance obligations, and address risks and opportunities" (14001, 10.2015:p.23). However, according to Mirski et al. (2017), "[â€¦] environmental management involves managing the oceans, freshwater systems, land and atmosphere, according to sustainability principles" (Mirski

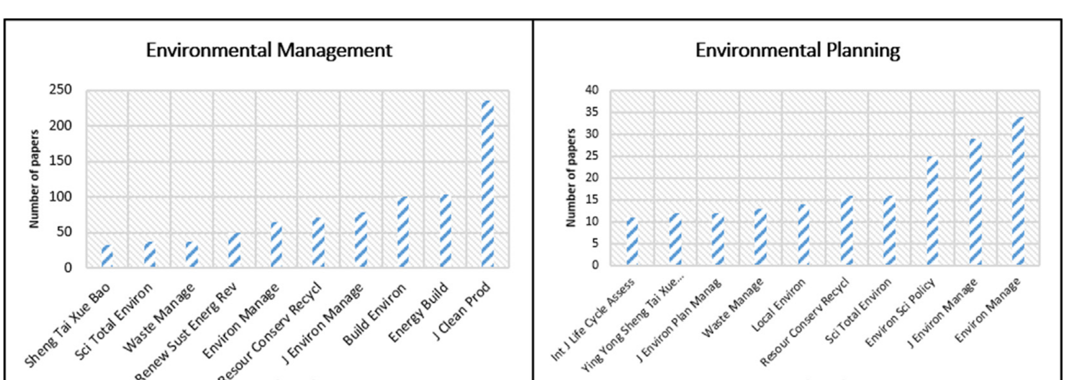

Fig. 9. Number of papers associated with the keywords per journal; listed are the 10 journals with the most published papers.

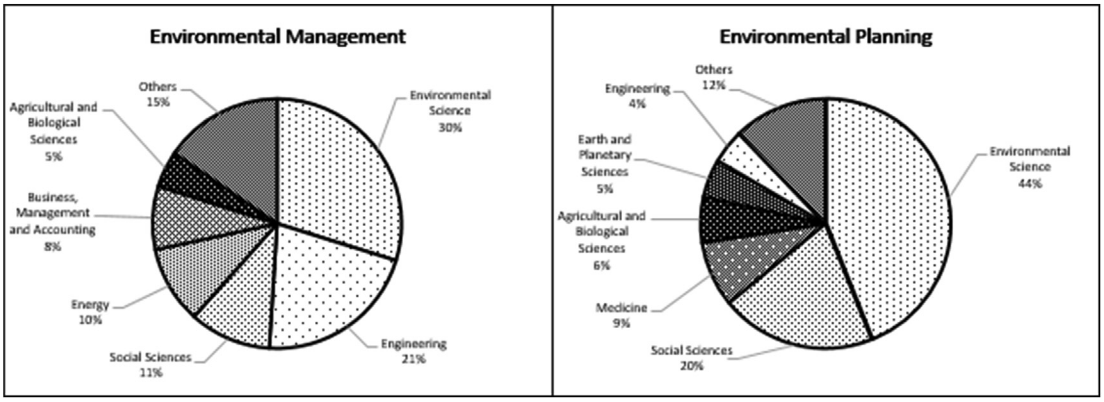

Fig. 10. Percentage of the different subject areas associated with the keywords; the six largest subject areas are shown, all other subject areas are combined in "others"; Number of papers for each keyword (every papers has several subject areas) Environmental Management: N = 2565, Environmental Planning: N = 574.

et al., 2017:p.27–28). Additionally, Mirski et al. (2017) stated that "environmental management is primarily directed at environmental resources and is implemented to protect the environment." (Mirski et al., 2017:p.28). In comparison, Prasad and Elmes (2005a,b) focused for their paper on the relationship between management and administration, on the one hand, and on ecological concerns, on the other hand, to explain "Environmental Management".

4.3.2.1. Environmental Planning. Daniels (2009) described that currently humanity is in the fifth era of "Environmental Planning" with a focus on achieving sustainability and perceive "Environmental Planning" itself more like a process rather than as a fixed system. According to Daniels (2009), "Environmental Planning" can be described as "the theory and practice of making good, interrelated decisions about the natural environment […], working landscapes […], public health […], and the built environment." (Daniels, 2009:p.178). In comparison, Richardson et al. (2016) described "Environmental Planning" as the interface between statutory planning systems and wider systems, such as flood risk and water quality management, with the dominant theme of "planning for sustainability and the global environment" (Richardson et al., 2016:p.4). Gilkes, Millmore, and Bell (1991) described "Environmental Planning" as managing environmental issues occurring with building projects such as flora, fauna and archaeological issues. Beatley (1995) took the approach of defining a sustainable city or community as goal for "Environmental Planning". In his point of view, a sustainable community is a community that limits its environmental impacts and reduces the consumption of natural resources.

4.3.3. Suggesting definitions

In comparison to previous phrases, both "Environmental Management" and "Environmental Planning" have many published papers during the observed period on average, a constant rise in publications within the searched area. However, "Environmental Planning" and "Environmental Management" both differ from these description as follows: Fig. 10 showed that the focus of the two phrases differs, as "Environmental Planning" is more often published in the Social Sciences, whereas "Environmental Management" is more often published in the subject area of "Engineering". The authors suggest to use the definition for "Environmental Management" provided by the (14001, 10.2015) and for "Environmental Planning" the definition provided by Richardson et al. (2016). These two definitions differ from each other, as "Environmental Planning" should answer the question: "What has to be done in order to achieve a sustainable environment?" whereas "Environmental Management" should answer the question: "How should this goal be achieved?" Therefore, "Environmental Planning" has a broader view that incorporated social sciences, whereas "Environmental Management" is more specific, focusing on engineering problems. The specific implementations of the management decisions could be part of the "Environmental Construction", if environmentally-friendly materials and construction methods are used.

4.4. Summary of results

In summary, the following definitions for the different terms can be recommended for a global understanding in the scientific community:

For the first group the following definitions were identified:

1. Environmental Building: "A building whose construction [both used materials and required processes for the construction] focuses on being environmentally-friendly."
2. Environmental Construction: "A construction focused primarily on the environmentally-friendly materials and construction methods, but not necessarily considering economic or social matters." (Švajlenka, Kozlovská, and Pošivíkoví, 2018)
3. Green Building: "The creation of structures that are environmentally-responsible [, socially-friendly] and resource-efficient throughout a building's lifecycle" (Hwang et al., 2017:p.2)
4. Green Construction: "Human-made constructions except buildings, which have an environmental focus not only on the required materials, but also throughout their lifecycle."

For the second group, the following definitions were derived:

1. Ecodesign: "Systematic approach, which takes environmental aspects into account with the goal to reduce adverse environmental aspects over the whole lifecycle of a product." (ISO 14006, 5.202
2. Environmental Design: "Advanced strategies that incorporate, as added value and growth factor, the reduction of CO2 emissions, the sustainable use of soil and resources, in addition to local development and social inclusion objectives." (D'Ambrosio and Leone, 2015:p. 138)
3. Sustainable Design: "A philosophical approach, which s besides the functional requirements, incorporates social, environmental

Table 2
Short overview of the derived definitions.

Subject	Eco-/Ecological	Environmental	Green	Sustainable
Building (e.g. house, office)	out of scope	Considers environmental aspects for building materials and processes	Considers environmental and social aspects throughout their life-cycle	Considers environmental, social and economic aspects throughout their life-cycle
Construction (e.g. road, embarckment)	should not be used in this context	Considers environmental aspects for building materials and processes	Considers environmental aspects throughout their life-cycle	Considers environmental, social and economic aspects throughout their life-cycle
Design	Considers environmental aspects over the whole life cycle of buildings or constructions	Reduces CO_2 emissions, increases the sustainable use of soil and resources and considers social aspects	out of scope	Incorporates social, environmental and economic criteria throughout the design process
Management	out of scope	Managing environmental aspects, compliance obligations and addressing risks and opportunities	out of scope	out of scope
Planning	out of scope	Dominant: Planning for sustainability and the global environment	out of scope	out of scope

and economic criteria and interdisciplinary methods throughout the design process."

Summing up, the following definitions are suggested for the terms in the group of management and planning:

1. Environmental Management: "[…] Part of the management (system) used to manage environmental aspects, fulfill compliance obligations, and address risks and opportunities […]" (14001, 10.2015:p.23)
2. Environmental Planning: "The interface between statutory planning systems and wider systems, such as flood risk and water quality management with the dominant theme being planning for sustainability and the global environment."

5. Discussion

Several different suggestions and definitions have been presented in the previous chapter for each of the eleven identified keywords. In the following, it will be discussed as to why the other suggested definitions were declared as not suitable by the authors. Furthermore, it will be discussed whether other keywords or definitions would have been more suitable for the cases where the current keyword or definitions do not fit the ones suggested here. However, some keywords were examined but no definitions for the sector related to sustainable buildings and construction could be assessed. Therefore, no definitions for these keywords are provided.

5.1. Group 1 - building/construction

The definition for "Green Building" provided by Y. Li et al. (2019) would be - according to the previous paragraphs - more suitable for the keyword "Environmental Building", as the authors focus primarily on construction materials, but do not consider the whole lifecycle of buildings, as they do not mention whether the demolition of the building and the further processing of the material has to be environmentally-friendly. Kats (2003), on the other hand, describes a sustainable building, as described in the introduction. Sustainable buildings differ from "Green Buildings" because the environmental aspects are considered in both, while additionally sustainable buildings consider the financial impact and social components equally to the environmental impacts when designing, constructing and demolishing a building. The definition of Kats (2003) therefore incorporates more factors than the definition for "Green Building" does and as such fulfills the suggested requirements to be called a "Sustainable Building".

According to the authors point of view, the description of "Green Building" provided by Ahmad et al. (2019) can be better assigned to "Environmental Design", as this keyword incorporates both the reduction of negative ecological impacts as well as increasing the social inclusion. A "Green Building", in comparison, does not necessarily incorporate the social aspects over the whole lifecycle of building. It is difficult to assess the definition provided by Paumgartten (2003a,b) as he did not mention the quality level of LEED a building has to fulfill in order to be green in his opinion. However, assuming "[â€¦] that meets the high standards [â€¦]" (Paumgartten, 2003a,b:p.26) refers to the highest standard of LEED, it is a suitable definition for "Green Building", as LEED considers the whole environmental lifecycle of a building, but does not consider financial and social criteria to be equal to the environmental factors (LEED, 2019). Eventhough LEED considers social and financial factors, it is important to keep in mind, that it does that not in equal shares to the environmental aspects. According to the definition provided by the authors, Hamid et al.

(2012) described more an “Environmental Construction” than a “Green Construction” as their focus is on the creation and maintenance of a built environment instead of considering the whole building lifecycle, which is essential for the term “green”. Kibert (1994) has equaled “Green Construction” with “Sustainable Construction”, even though sustainability incorporates elements not included in the term “green”. His criteria for a “Sustainable Construction” therefore fit the term “Environmental Construction” better as the focus is on building in an environmentally-friendly way; however, the definition provided does not consider the whole building lifecycle, which is why Kibert (1994) does not describe a “Green Building” in the authors point of view.

As the term “Ecological Construction” refers to a part of an Chinese strategy, with most authors of the examined papers being from China and referring to this strategy, the authors suggested not to use this term when writing about the sustainability and its construction and building aspects. The definitions and descriptions provided by Hisseine et al. (2019) and Suresh and Anand (2017) are therefore - according to the previous paragraphs - not considered to be suitable definitions of “Ecological Construction”. The descriptions would better suit the term “Environmental Building” as the authors describe environmentally-friendly materials and processes for the construction of buildings as being important. Spinks (2015) had the problem of not mentioning the degree of fulfillment of BREEAM necessary to describe a building which is – according to him - an “Environmental Building”. This made the assessment of his description impossible. Herbert (1998) also referred to BREEAM, although an assessment in this case was possible, as Herbert defined an “Environmental Building” as a building, which meets the highest available rating in BREEAM. As BREEAM focuses on the environmental aspects of the building, but does not consider its financial and social aspects equally to the environmental and not the whole lifecycle of a building either, the term “Environmental Building” is suitable in this case. The definition provided by S. Li, H. Xu, and Shen (2013) for the term “Environmental Construction” is likewise not suitable because according to their definition, economic, social and environmental aspects should be considered when planning urban development. It would be more suitable to use the term “Sustainable Planning” instead, as not only environmental considerations are important according to the definition by S. Li, H. Xu, and Shen (2013). Baranova, Maltsev, and Vasilyeva (2017) also do not describe “Environmental Construction”, as financial and human resources are important for them. Their description would also be better suited under the term “Sustainable Construction” as long as the consideration of human resource is equal to social aspects.

5.2. Group 2 - design/architecture

As already pointed out in the result section, the keyword “Architectural Design” is a very broad term and therefore should not be used when specifically describing buildings and constructions incorporating sustainability or environmental aspects. According to the ISO 14006 (5.202), “Ecodesign” should be used when designing a building whose environmental burden over the whole lifecycle should be reduced. Therefore, a building designed using the “Ecodesign” approach is always a “Green Building”. According to the definition, Charter and Tischner (2010) describe in their paper not “Ecodesign” but “Sustainable Design” when incorporating financial and social aspects into the decision-making process. Additionally, McAloone and Pigosso (2017) describe also not the keyword “Ecodesign” but “Environmental Building” because McAloone and Pigosso (2017) only consider the building materials necessary for the building and not the whole lifecycle of the building. However, considering the whole building life cycle is vital for both “Ecodesign” and “Green Building”. Even though Gangemi et al. (2000) used the term “Environmental Design”, it would be more suitable to use the term “Sustainable Design”, especially as they refer to sustainable buildings as an example. Sustainable buildings have higher requirements to fulfill, whereas “Environmental Buildings” only consider aspects reducing the environmental burden of a building. Their definition requires further research, so that their concept can be ranked with the others. Bangwal and Tiwari (2019) contradict the suggested definition as well, as the goal of “Environmental Design” is not to connect people with the natural environment, but to reduce the negative environmental impact of buildings through the use of alternative building materials and processes. Therefore, this definition cannot be allocated to a specific examined keyword. The same can be said for the definition provided by Jalilian (2013), as several different suggested definitions get mixed here as well and no precise suggestion can be made. Zagloul, and Dewidar (2017) use the term “Sustainable Design” for their description, even though they described “Environmental Design”. The focus of their description is the better environmental appearance, also for the future generations, which are other terms for the reduction of the environmental burden of buildings as well as a social inclusion in the building design and thus “Environmental Design”. The description of Bashir et al. (2016) for “Sustainable Design” does not fit sustainability criteria, as the financial and social components are not incorporated into their description. The description of the five parts by Bashir et al. (2016) fits “Environmental Building” better than “Sustainable Design”.

5.3. Group 3 - management/planning

Mirski et al. (2017) do not describe “Environmental Management” at its core, but rather sustainability management, as sustainability principles incorporate financial, ecological and social aspects, which need to be considered equally. This is broader than just “Environmental Management”, which incorporates both environmental and social issues, but not necessarily financial considerations. Prasad and Elmes (2005a,b) argue in their paper that “Environmental Management” is an intersection of management and the consideration of ecological concerns. However, the environmental part consists of more than just ecological aspects, wherefore Prasad and Elmes (2005a,b) should have used another keyword to describe their intersection. Gilkes, Millmore, and Bell (1991), however, use the keyword “Environmental Planning” too narrowly, as not only buildings are affected by “Environmental Planning”, but all human-made structures and their surroundings. Beatley (1995) had comparable restrictions, as in Beatley’s view, “Environmental Planning” has the goal of achieving a sustainable community, even though he defined sustainability from a pure environmental point of view, which is too narrow.

6. Conclusion

In academia the correct use of scientific terms is important for scientists to understand each other especially when being from different scientific backgrounds. The present paper set out to review 11 different keywords in the literature of sustainable building and construction, with the condensed results shown in Table 2. It could be shown that several different definitions for the examined keywords exist in the literature. Most keywords could be precisely defined after a systematic literature review and suggestions for the future use of these keywords have been provided. To underpin the definitions from the literature, a historic analysis of the number of publications, the journals publishing the keywords and the subject areas of the keywords were conducted and set into relation. The definitions and the assessed papers can be used as examples in future publications to have standardized scientific terms and definitions for keywords in the field of sustainable building and construction. However, as the definitions in Table 2 show only the term “sustainable” can satisfy the long-term requirements the construction industry has to fulfill regarding a livable planet for humankind and to avoid a dramatic climate change. As new keywords emerge constantly their classification into the proposed systematic should be made to avoid emerging confusion among scientists. This is especially important as several keywords exist to describe different kinds of buildings with reduced environmental impact. Additionally, as most definitions require the use of - at least - environmentally friendly materials and construction processes, future research should further assess the environmental impact of building materials and processes to filter environmentally friendly building materials and processes from those which are not. Finally, it has to be noted, that several more terms exist in the sector of sustainability in building and construction, covering multiple different aspects. Terms, which were not covered in the article due to length of the article are for example: zero-UHI impact building, nearly zero energy building, low-carbon building, net zero-carbon building. These terms need further research to differentiate them from one another.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References

Abas, D.N., et al., 2018. An Outlook on Strategic Framework Development Needs of Roles and Involvement of Joint Property Management in High Rise Green Buildings in Malaysia, vol. 63, pp. 427–432. https://doi.org/10.3303/CET1863072.

Abrantes, N., Alves, F.B., Abrantes, V., 2015. The City of Porto and the Public Housing: Learning with Design Practice, vol. 39, pp. 65–78, 2.

Ahmad, T., Aibinu, A.A., Stephan, A., 2019. Managing Green Building Development - A Review of Current State of Research and Future Directions, vol. 155, pp. 83–104. https://doi.org/10.1016/j.buildenv.2019.03.034.

Arnaudov, K., Genova, P., Dimitrov, L., 2005. For an unified and correct IFToMM terminology in the area of gearing. Mech. Mach. Theor. 40 (9), 993–1001. https://doi.org/10.1016/j.mechmachtheory.2005.01.004, 0094114X.

Bangwal, D., Tiwari, P., 2019. Environmental Design and Awareness Impact on Organization Image, vol. 26, pp. 29–45. https://doi.org/10.1108/ECAM-02-2017-0029, 1.

Baranova, Margarita, Maltsev, Andrey, Vasilyeva, Darya, 2017. Environmental construction safety on loess soils in the coastal zone of reservoirs. MATEC Web of Conferences 106 (9), 02015. https://doi.org/10.1051/matecconf/201710602015.

Baranyiovà, Eva, 2013. Correct terminology in science: the role of editors. Science Editor 36 (2). http://www.councilscienceeditors.org/wp-content/uploads/v36n2p63.pdf.

Barbosa, Gisele Silva, Patricia, Regina Drach, Daniel Corbella, Oscar, 2014. A conceptual review of the terms sustainable development and sustainability. Int. J. Soc. Sci. 3 (2). https://www_iises_net/download/Soubory/soubory-puvodni/pp-01-15_ijossV3N2.pdf.

Bashir, F.M., et al., 2016. Fundamental elements for sustainable design. Indian Journal of Science and Technology 9 (46). https://doi.org/10.17485/ijst/2016/v9i46/107128.

Baumann, H., Boons, F., Bragd, A., 2002. Mapping the green product development field: engineering, policy and business perspectives. J. Clean. Prod. 10 (5), 409–425. https://doi.org/10.1016/S0959-6526(02)00015-X, 9596526.

Beatley, Timothy, 1995. Planning and sustainability: the elements of a new (improved?) paradigm. J. Plann. Lit. 9, 383–395. https://doi.org/10.1177/088541229500900405, 4, 0885–4122.

Bocken, Nancy, et al., 2019. A review and evaluation of circular business model innovation tools. Sustainability 11 (8), 2210. https://doi.org/10.3390/su11082210.

Breeam, 2018. BREEAM UK New Construction: Technical Manual SD5078. BREEAM UK New Construction 2018 2.0. URL. www.breeam.com.

Brejnrod, K.N., et al., 2017. The absolute environmental performance of buildings. Build. Environ. 119, 87–98. https://doi.org/10.1016/j.buildenv.2017.04.003, 3601323.

Castellano, J., et al., 2015. Developing a simplified methodology to calculate Co2/m2 emissions per year in the use phase of newly-built, single-family houses. Energy Build. 109, 90–107. https://doi.org/10.1016/j.enbuild.2015.09.038. ISSN: 03787788.

Charter, Martin, Tischner, Ursula, 2010. Sustainable Solutions: Developing Products and Services for the Future. Greenleaf Pub, Sheffield, U.K, 978-1874719366. URL. http://search_ebscohost_com/login_aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=561569.

Cicconi, Paolo, Landi, Daniele, Germani, Michele, 2018. An Ecode- sign approach for the lightweight engineering of cast iron parts. Int. J. Adv. Manuf. Technol. 99 (9–12), 2365–2388. https://doi.org/10.1007/s00170-018-2649-7, 0268–3768.

D'Ambrosio, V., Leone, M.F., 2015. Climate Change Risks and Environmental Design for Resilient Urban Regeneration. Napoli Est Pilot Case, vol. 10. Firenze University Press, pp. 130–140. https://doi.org/10.13128/Techne-17509.

Daniels, Thomas L., 2009. A trail across time: American environmental planning from city beautiful to sustainability. J. Am. Plann. Assoc. 75 (2), 178–192. https://doi.org/10.1080/01944360902748206, 0194–4363.

Doan, D.T., et al., 2017. A critical comparison of green building rating sys tems. Build. Environ. 123, 243–260. https://doi.org/10.1016/j.buildenv.2017.07.007, 3601323.

Eberhardt, Charlotte Malabi, Leonora, Birgisdottir, Harpa, Birkved, Morten, 2019. Potential of circular economy in sustainable buildings. In: IOP Conference Series: Materials Science and Engineering, vol. 471, 092051. https://doi.org/10.1088/1757-899X/471/9/092051.

Elkington, John, 2002. Cannibals with Forks: the Triple Bottom Line of 21st Century Business. Reprint. Capstone, Oxford, 978-1841120843.

Farid, A.A., Zagloul, W.M., Dewidar, K.M., 2017. The process of holism: a critical analysis to bridge the gap between sustainable architecture design principles and elements defining Art of Sustainability. Intell. Build. Int. 9 (2), 67–87. https://doi.org/10.1080/17508975.2016.1170660.

Feria, Margarida, Amado, Miguel, 2019. Architectural design: sustainability in the decision-making process. Buildings 9 (5), 135. https://doi.org/10.3390/buildings9050135.

Forrester, Jay W., 1958. Industrial Dynamics: a major breakthrough for decision makers. Havard Business Review 38, 37–66.

Gangemi, V., Malanga, R., Ranzo, P., 2000. Environmental management of the design process. Managing multidisciplinary design. The role of environmental consultancy 19 (1–2), 277–284. https://doi.org/10.1016/S0960-1481(99)00041-5.

García-Sanz-Calcedo, J., López-Rodríguez, F., Cuadros, F., 2014. Quantitative analysis on energy efficiency of health centers according to their size. Energy Build. 73, 7–12. https://doi.org/10.1016/j.enbuild.2014.01.021, 3787788.

Gee, James Paul, 2015. Social Linguistics and Literacies: Ideology in Discourses, fifth ed. Routledge, London. 9781315722511.

Gilkes, P.W., Millmore, J.P., Bell, J.E., 1991. The roadford scheme: planning, reservoir construction and the environment. IWEM 91 Conference Paper 5 (6), 659–670. https://doi.org/10.1111/j.1747-6593.1991.tb00684.x.

Glavič, Peter, Lukman, Rebeka, 2007. Review of sustainability terms and their definitions. J. Clean. Prod. 15 (18), 18751885. https://doi.org/10.1016/j.jclepro.2006.12.006, 9596526.

Grierson, D., Moultrie, C., 2011. Architectural design principles and processes for sustainability: towards a typology of sustainable building design. Des. Princ. Pract. An Int. J. - Annu. Rev. 5 (4), 623–634. https://doi.org/10.18848/1833-1874/CGP/v05i04/38118.

Hallberg, D., Tarandi, V., 2011. On the use of open bim and 4D visualisation in a predictive life cycle management system for construction works. Electron. J. Inf. Technol. Construct. 16, 445–466.

Hamid, Z.A., et al., 2012. Towards a sustainable and green construction in Malaysia. Malaysian Construction Research Journal 11, 5564, 2.

Herbert, Pat, 1998. The environmental building. Struct. Surv. 16 (2), 87–90. https://doi.org/10.1108/02630809810219678, 0263–080X.

Hisseine, Ousmane A., et al., 2019. Nanocellulose for improved concrete performance: a macro-to-micro investigation for disclosing the effects of cellulose filaments on strength of cement systems. Construct. Build. Mater. 206, 84–96. https://doi.org/10.1016/j.conbuildmat.2019.02.042, 9500618.

Yunfeng, Hu, Daorina, Hu, Yang, 2019. Vegetation change and driving factors: contribution analysis in the loess plateau of China during 2000-2015. Sustainability 11 (5), 1320. https://doi.org/10.3390/su11051320.

Hwang, B.-G., Zhu, L., Ming, J.T.T., 2017. Factors Affecting Productivity in Green Building Construction Projects: the Case of Singapore, vol. 33. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000499, 3.

Hyland, K.E.N., Tse, P.O.L.L.Y., 2007. Is there an "academic vocabulary"? Tesol Q. 41 (2), 235–253. https://doi.org/10.1002/j.1545-7249.2007.tb00058.x. ISSN: 00398322.

Illankoon, I.M.C.S., Tam, V.W.Y., Le, K.N., 2017. Environmental, Economic, and Social Parameters in International Green Building Rating Tools, vol. 143. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000313, 2.

International Energy Agency, 2019. Global Energy and CO2 Status Report: the latest trends in energy and emissions in 2018. URL. https://www.iea.org/geco/.

ISO 14001, 2015. Umweltmanagementsysteme - Anforderungen und An- leitungen zur Anwendung. Berlin.

ISO 14006 10.2011. Umweltmanagementsysteme - Leitlinien zur Berücksichtigung umweltvertruäglicher Produktgestaltung. Berlin.

ISO 14006 5.202. Umweltmanagementsysteme - Leitlinien zur Berücksichtigung umweltverträglicher Produktgestaltung. Berlin.

ISO 4 1997-12. Information and Documentaiton - Rules for the Abbreviation of Title Words and Titles of Publications.

ISO14006, 2011. Environmental Management Systems — Guidelines for Incorporating Ecodesign (Berlin).
Jalilian, M., 2013. The specific look to environmental design and sustainability factors in vernacular residential architecture of Shoushtar, Iran. Middle East J. Sci. Res. (4), 195–198. https://doi.org/10.5829/idosi.mejsr.2013.17.12.11227.
Kats, Greg, 2003. The costs and financial benefits of green buildings: a report to California's sustainable building task force. URL. http://www.tateglobal.com/pdf/greenbuildingsfullreport.pdf.
Kayode, F., Ojo, B., Sheba, E.A., 2008. Design, Aesthetics and the Issue of Integrity in the Built Environment: the Nigerian Example, vol. 17, pp. 283–298. https://doi.org/10.1177/1420326X08094897, 4.
Kesidou, Sofia, Sovacool, Benjamin K., 2019. Supply chain integration for low-carbon buildings: a critical interdisciplinary review. Renew. Sustain. Energy Rev. 113 https://doi.org/10.1016/j.rser.2019.109274, 13640321.
Kibert, Charles J., 1994. Establishing Principles and a model for sustainable construction. CIB TG 16. Tampa, Florida. URL. https://www.irbnet.de/daten/iconda/CIB_DC24773.pdf.
Kilkis, B.I., 2006. Cost optimization of a hybrid HVAC system with composite radiant wall panels. Appl. Therm. Eng. 26 (1), 10–17. https://doi.org/10.1016/j.applthermaleng.2005.04.017.
Kwon, C., 2014. Form or performance in sustainable architecture. International Journal of Sustainable Building Technology and Urban Development 5 (1), 21–27. https://doi.org/10.1080/2093761X.2013.806061.
Lawson, Bryan, 2006. How Designers Think - the Design Process Demystified. University Press, Cambridge.
LEED, 2019. LEED v4 for building design and construction. URL. https://new.usgbc.org/leed.
Li, S., Xu, H., Shen, H., 2013. Research on the urban environmental construction index. Res. J. Appl. Sci. Eng. Technol. 5 (2), 475–480.
Li, Ji, et al., 2019. Research on a systematical design method for nearly zero-energy buildings. Sustainability 11 (24), 7032. https://doi.org/10.3390/su11247032.
Li, Y., et al., 2019. Review of critical success factors (CSFs) for green building projects. Build. Environ. 158, 182–191. https://doi.org/10.1016/j.buildenv.2019.05.020, 3601323.
Liu, Xusheng, Li, Xianwen, Sun, Tao, 2017. The evaluation of comprehensive benefits of forestry ecological construction projects of Dengkou County, Inner Mongolia, China. Acta Ecol. Sin. 37 (18) https://doi.org/10.5846/stxb201705050830, 1000–0933.
Liu, Min, et al., 2018. The impact of ecological construction programs on Grassland conservation in inner Mongolia, China. Land Degrad. Dev. 29 (2), 326–336. https://doi.org/10.1002/ldr.2692, 10853278.
Locke, John, Winkler, Kenneth P., 1996. An Essay Concerning Human Understanding: Abridged and Edited, with an Introduction and Notes. Hackett Pub, Indianapolis, Ind, 0872202178.
Mattoni, B., et al., 2018. Critical Review and Methodological Approach to Evaluate the Differences Among International Green Building Rating Tools, vol. 82, pp. 950–960. https://doi.org/10.1016/j.rser.2017.09.105.
McAloone, Tim C., Pigosso, Daniela C.A., 2017. From ecodesign to sustainable product/service-systems: a Journey through research contributions over recent decades. In: Rainer, Stark, Günther, Seliger, Jérémy, Bonvoisin (Eds.), Sustainable Manufacturing, vol. 33. Sustainable Production, Life Cycle Engineering and Management. Springer International Publishing, Cham, pp. 99–111. https://doi.org/10.1007/978-3-319-48514-0{\textunderscore}7, 978-3-319-48513-3.
McLennan, Jason F., Berkebile, Bob, 2004. The Philosophy of Sustainable Design: the Future of Architecture, first hardcover edition. 9780974903309.
Mensah, Justice, Enu-Kwesi, Francis, 2019. Implications of environmental sanitation management for sustainable livelihoods in the catchment area of Benya Lagoon in Ghana. J. Integr. Environ. Sci. 16 (1), 23–43. https://doi.org/10.1080/1943815X.2018.1554591, 1943–815X.
Mirski, Andrzej, Shaikan, Andrii, Abraham, Kome, 2017. International cooperation and management in global environment and sustainable development. Scientific Journal of Polonia University 24 (5), 25. https://doi.org/10.23856/2403, 1895–9911.
Moffatt, I., 1982. Environmental science at stirling. Int. J. Environ. Stud. 19 (3–4), 289–293. https://doi.org/10.1080/00207238208710003, 0020–7233.
Nagy, William, Townsend, Dianna, 2012. Words as tools: learning academic vocabulary as language acquisition. Read. Res. Q. 47 (1), 91–108. https://doi.org/10.1002/RRQ.011, 340553.
Discourses in action: introducing mediated discourse analysis. Routledge: New York. In: Norris, S., Jones, R. (Eds.), 2005. URL. https://www.academia.edu/3225995/Place_Pace_and_Meaning_Multimedia_Chronotopes.
Okoli, Chitu, Schabram, Kira, 2010a. A guide to conducting a systematic literature review of information systems research. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.1954824.
Okoli, Chitu, Schabram, Kira, 2010b. A guide to conducting a systematic literature review of information systems research. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.1954824.
Ortiz, Oscar, Castells, Francesc, Guido, Sonnemann, 2009. Sustainability in the construction industry: a review of recent developments based on LCA. Construct. Build. Mater. 23 (1), 28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012, 9500618.
Parliament, The European and the Council, 2009. Directive 2009/125/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (DIRECTIVE 2009/125/EC). URL. https://eur-lex.europa.eu/eli/dir/2009/125/oj.
Paumgartten, Paul von, 2003a. The business case for high performance green buildings: sustainability and its financial impact. J. Facil. Manag. 2 (1), 26–34. https://doi.org/10.1108/14725960410808096, 1472–5967.
Paumgartten, Paul von, 2003b. The business case for high performance green buildings: sustainability and its financial impact. J. Facil. Manag. 2 (1), 26–34. https://doi.org/10.1108/14725960410808096, 1472–5967.
Population Division, 2019. Entwicklung der Weltbevolkerungszahl von Christi geburt bis zum Jahr 2020 (in Milliarden). URL. https://de.statista.com/statistik/daten/studie/1694/umfrage/entwicklung-der-weltbevoelkerungszahl/.
Prasad, Pushkala, Elmes, Michael, 2005a. In the name of the practical: unearthing the hegemony of pragmatics in the discourse of environmental management*. J. Manag. Stud. 42 (4), 845867. https://doi.org/10.1111/j.1467-6486.2005.00521.x, 0022–2380.
Prasad, Pushkala, Elmes, Michael, 2005b. In the name of the practical: unearthing the hegemony of pragmatics in the discourse of environmental management*. J. Manag. Stud. 42 (4), 845867. https://doi.org/10.1111/j.1467-6486.2005.00521.x, 0022–2380.
Purbantoro, F., Siregar, M., 2019. Design of net zero energy building (NZEB) for existing building in Jakarta. IOP Conf. Ser. Earth Environ. Sci. 399 https://doi.org/10.1088/1755-1315/399/1/012076.
Reeves, Carol, 2005. The Language of Science. Intertext. Routledge, London and New York, 0415346363. URL. http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10163478.
Richardson, Douglas, et al. (Eds.), 2016. International Encyclopedia of Geography: People, the Earth, Environment and Technology. John Wiley & Sons, Ltd, Oxford, UK, 9780470659632.
Ruske, Klaus-Dieter, et al., 2010. Transportation & Logistics 2030: Volume 3. Emerging Markets - New hubs, new spokes, new industry leaders? URL. https://www.pwc.com/gx/en/transportation-logistics/tl2030/emerging-markets/pdf/tl2030_vol3_final.pdf.
Ryan, Carole, 2011. Traditional Construction for a Sustainable Future. Routledge. https://doi.org/10.4324/9780203895504, 9780203895504.
Sandewall, M., Nilsson, N.-E., 2001. The area production model: a tool and concept for sustainable land-use and forest-resource management. J. Environ. Manag. 62 (4), 415–427. https://doi.org/10.1006/jema.2001.0450.
Shi, X., 2010. Performance-based and performance-driven architectural design and optimization. Front. Architect. Civ. Eng. China 4 (4), 512518. https://doi.org/10.1007/s11709-010-0090-6.
Spinks, M., 2015. Understanding and actioning BRE environmental assessment method: a socio-technical approach. Local Environ. 20, 131–148. https://doi.org/10.1080/13549839.2013.838212, 2.
Suresh, Abhirami, Anand, K.B., 2017. Strength and durability of rammed earth for walling. J. Architect. Eng. 23 (4), 06017004 https://doi.org/10.1061/(ASCE)_AE.19435568.0000281, 1076–0431.
Švajlenka, Jozef, Kozlovská, Mária, Pošiváková, Terézia, 2018. Analysis of selected building constructions used in industrial construction in terms of sustainability benefits. Sustainability 10 (12), 4394. https://doi.org/10.3390/su10124394.
Tan, Chen, Xiao, Yu, Yang, Cheng Long, 2013. Green construction application in project of Xi'an. Appl. Mech. Mater. 368–370, 1168–1173. 10.4028/www.scientific.net/AMM.368-370.1168.
Tenopir, Carol, King, Donald Ward, 2004. Communication Patterns of Engineers. Wiley-Interscience IEEE Press and IEEE Xplore, Hoboken, New Jersey. https://doi.org/10.1002/0471683132. Piscataway, New Jersey, and Piscataway, New Jersey, 9780471484929.
The World Bank, 2019. GPD (current US-Dollar) - World. URL. https://data.worldbank_org/indicator/NY.GDP.MKTP.CD?end_=_2017&locations=1W&start=1960&year_low_desc=false.
Townsend, Dianna, Brock, Cynthia, Morrison, Jennifer D., 2018. Engaging in vocabulary learning in science: the promise of multimodal instruction. Int. J. Sci. Educ. 40 (3), 328347. https://doi.org/10.1080/09500693.2017.1420267, 0950–0693.
United Nations Environmental Programme, 2009. Common carbon metric: for measuring energy use & reporting greenhouse gas emissions from building operations. URL. https://wedocs.unep.org/bitstream/handle/20.500.11822/7922/-Common%5C%20Carbon%5C%20Metric%5C%20for%5C%20Measuring%5C%20Energy%5C%20Use%5C%20and%5C%20Reporting%5C%20Greenhouse%5C%20Gas%5C%20Emissions%5C%20from%5C%20Building%5C%20Qperations-20094112.pdf?sequence=3&isAllowed=y.
Vahs, Dietmar, Schäfer-Kunz, Jan, 2012. *Einführung in die Betriebswirtschaftslehre.* 6. Aufl. Schäffer-Poeschel Verlag: s.l., 978-3-79102932-0. URL. http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10773117
Williams, James David, 2013. It's just a theory": trainee science teachers' misunderstandings of key scientific terminology. Evolution: Education and Outreach 6 (1), 1936–6426. https://doi.org/10.1186/1936-6434-6-12.
Xia, Chunhong, Li, Yan, 2018. Evaluation of ecological construction in kunming using the DPSIR model. International Journal of Technology 9 (7), 1338. https://doi.org/10.14716/ijtech.v9i7.2489, 2086–9614.
Xu, Guoce, et al., 2018. Soil total nitrogen sources on dammed farmland under the condition of ecological construction in a small watershed on the Loess Plateau, China. Ecol. Eng. 121, 19–25. https://doi.org/10.1016/j.ecoleng.2017.09.005, 9258574.
Yang, Jie, Song, Lingchuan, Xing, Zhongdan, 2019. Credit default of local public sectors in Chinese government-pay PPP projects: evidence from ecological construction. Adv. Civ. Eng. 2019 (8), 1–19. https://doi.org/10.1155/2019/

2138525, 1687–8086.
Zabihi, Hossein, Habib, Farah, Mirsaeedie, Leila, 2012. Sustainability in building and construction: revising definitions and concepts. Int. J. Emerg. Sci. 2 (4), 570–578.
Zanni, M.-A., Soetanto, R., Ruikar, K., 2014. Defining the sustainable building design process: methods for BIM execution planning in the UK. Int. J. Energy Sect. Manag. 8 (4), 562587. https://doi.org/10.1108/IJESM-04-2014-0005.
Zuo, Jian, et al., 2017. Green building evaluation from a life-cycle perspective in Australia: a critical review. Renew. Sustain. Energy Rev. 70, 358–368. https://doi.org/10.1016/j.rser.2016.11.251, 13640321.
Zuo, J., Zhao, Z.-Y., 2014. Green building research-current status and future agenda: a review. Renew. Sustain. Energy Rev. 30, 271–281. https://doi.org/10.1016/j.rser.2013.10.021, 13640321.

FULL PAPER: ESTIMATING THE USE OF MATERIALS AND THEIR GHG EMISSIONS IN THE GERMAN BUILDING SECTOR

Cleaner Environmental Systems 7 (2022) 100095

Contents lists available at ScienceDirect

Cleaner Environmental Systems

journal homepage: www.journals.elsevier.com/cleaner-environmental-systems

Estimating the use of materials and their GHG emissions in the German building sector

Felix Rheude *, Hubert Röder

Chair of Sustainable Business Economics, TUM Campus Straubing for Biotechnology and Sustainability, Weihenstephan-Triesdorf University of Applied Sciences, Essigberg 3, 94315, Straubing, Germany

ARTICLE INFO

Keywords:
Top-down material flow analysis
Building sector
Sustainability
Greenhouse gas emissions

ABSTRACT

The construction and building sector is one of the largest emitters of greenhouse gases. In this study, we calculated the material used in shell construction in the German building sector from 2012 to 2020 using material flow analysis. Subsequently, the annual greenhouse gas emissions in the German building sector were simulated using the environmental product declarations from the Ökobaudat database and the modeled materials. We can show that biogenic materials account for an ever-larger share of value creation and are growing disproportionately. We can also show that by increasing biogenic materials, construction is becoming lighter and more efficient, and greenhouse gas emissions of shell construction are reduced during this period. In summary, the building sector in Germany still has very high greenhouse gas emissions of around 26 million metric tons of CO_2 eq. Still, it is in a better overall position than at the beginning of the study period, thanks to the efficient use of available resources.

1. Introduction

From a global perspective, climate change is currently the greatest threat to humanity's prosperity and quality of life (Kalnay et al., 1996; Foley et al., 2005; Change, 2014). Climate change is human-induced and primarily due to increased greenhouse gas emissions since the beginning of industrialization. To maintain prosperity in the currently developed and enable underdeveloped countries to create prosperity in the long term, it is, therefore, necessary to prevent further climate change by significantly reducing greenhouse gas emissions and applying suitable measures to sequester already emitted carbon dioxide (Hong et al., 2012). The Paris Agreement stated that the rising atmospheric greenhouse gas emissions should only cause global warming of 1.5 °C (United Nations, 2015). Therefore, it is necessary to minimize greenhouse gas emissions and remove carbon dioxide from the atmosphere in the long term to achieve this goal (United Nations, 2015; D'Ambrosio and Leone, 2015; Alkaya et al., 2015).

One of the largest global emitters of carbon dioxide is the building sector, which is responsible for 32–40% of global carbon dioxide emissions (Doan et al., 2017; Esa et al., 2017). However, it must be considered that these figures comprise several components. On the one hand, there are materials, but on the other hand, there is also the consumption of energy through heating, ventilation, and air conditioning (HVAC) and others and including the whole building lifecycle as such (Blom et al., 2010; Kim et al., 2019). Therefore, drawing direct conclusions about these figures' greenhouse gas emissions of materials or construction processes is impossible.

A large share of the GHG emissions of the construction sector results from the energy embodied in construction materials, the energy that has to be expended to extract, transport, manufacture, and assemble the materials for building construction (Galán-Marín et al., 2015; Azari and Abbasabadi, 2018). Mineral building materials account for a large part of this embodied energy. In contrast, biogenic materials can even sequester net carbon if produced sustainably and thus reduce atmospheric carbon dioxide (ZabalzaBribián et al., 2011).

Because the building sector also significantly impacts daily life and greenhouse gas emissions globally, there has been some past research on building structures and how to improve them (Honic et al., 2019; Geldermans, 2016; Hossain and Ng, 2018; Pomponi and D'Amico, 2018; D'Amico and Pomponi, 2018). For example, Churkina et al. (2020) describe in their article that a strongly increased use of wood and the construction of so-called "timber cities" can lead to a global carbon sink and be significantly safer and more successful than storing it underground, for example. They were able to show that a substantial increase

* Corresponding author.
E-mail addresses: felix.rheude@hswt.de (F. Rheude), hubert.roeder@hswt.de (H. Röder).

https://doi.org/10.1016/j.cesys.2022.100095
Received 16 May 2022; Received in revised form 19 August 2022; Accepted 25 August 2022
Available online 29 August 2022
2666-7894/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

in the use of wood can lead to significant carbon savings, both as a direct substitute for other building materials and by reducing their use in the construction of foundations.

However, Pompino et al. (Pomponi et al., 2020) noted that with the current data situation, it could not be established beyond doubt that the current wood supply is sufficient to construct all buildings worldwide from wood in the future. In their article, they correctly note that the construction of buildings must also be based on local conditions. Thus, the use of bamboo or the preparation of grass may make more sense in some cases. Therefore, the discussion section of this study also compares the figures obtained from regions with comparable geographical and climatic conditions.

Hertwich et al. (2019) also describe how the building sector could improve its greenhouse gas emissions globally. For example, they describe how lightweight construction, the increased use of wood, and the recycling of metals, in particular, on as large a scale as possible result in low greenhouse gas emissions. It is important to emphasize that increased emissions in the construction phase can lead to lower lifecycle emissions, provided that materials are used to save energy in the construction phase, and efficient HVACs are installed (Chastas et al., 2016).

In order to quantify the environmental impact of individual buildings and minimize it in the long term, several - currently still voluntary - certificates have already been introduced globally. The most widespread globally are LEED, BREEAM, and - for the German market - the DGNB (Doan et al., 2017; Shan and Hwang, 2018; Yu et al., 2015; Chandratilake and Dias, 2015). These examine the sustainability of buildings with a holistic approach, in terms of emissions as well as social and economic factors. In addition to energy and materials, other relevant factors include location, indoor quality, land use, and outdoor quality, as well as water and the degree of innovation of the building concerning new, sustainable technologies or materials (Illankoon et al., 2017a, 2017b; Zhang et al., 2017; Liu et al., 2019). However, especially in the case of the DGNB certificate, which is particularly relevant for Germany, there are hurdles for the auditors in assessing environmental sustainability. These can have a negative impact on the evaluation of the buildings (Wuth and Scope, 2021). Although the approach of the certificates is mostly evaluated very positively in the literature, a common weakness remains that they are all currently still awarded on a voluntary basis (Illankoon et al., 2017a, 2017b).

Besides the certificates, efforts in Germany have been underway for several decades to make buildings more sustainable (Gesetz zur Einsparung von Energie, 1976; Verordnung über einen energiesparenden Wärmeschutz, 1977; Verordnung über energiesparende Anforderungen an, 1978). In the past, the focus was mainly on the energy consumption during the lifecycle of buildings (Verordnung über energiesparenden Wärmeschutz und, 2001). Examples of government directives to improve the energy balance are the Building Energy Act or the subsidies provided by the German Credit Institute for Reconstruction (Kreditanstalt für Wiederaufbau, KfW) with the KfW 55 loan for passive houses (Kreditanstalt f ü r Wiederaufbau, 2022; Gesetz zur Einsparung von Energie, 2020). If the energy balance during the utilization phase is improving more and more in recent years due to regulations and incentive systems, the emissions of the building materials are coming into focus. Currently, the building envelope (depending on construction type and energy consumption) accounts for only a low single-digit percentage of a building's total emissions during its life cycle (König, 2017; Gardner et al., 2020). The lower the emissions during the use phase, the greater the emissions of the building envelope in relation to the total emissions (Ramesh et al., 2010). Therefore, in parallel to improving energy efficiency during the use phase, for example, through more efficient HVACs and better insulation of buildings, it is also important to improve the materiality with regard to its emissions.

Policymakers have also recognized this. Thus, in addition to the aforementioned incentive systems to improve energy efficiency (Gesetz zur Einsparung von Energie, 2020), there are now also incentive systems to reduce the carbon dioxide emissions of materiality. For example, the German state of North Rhine-Westphalia has set up a subsidy per ton of biogenic carbon used (NRW, 2022; SKHolzbau, 2020). Comparable programs have been established by the states of Berlin and Bavaria (Bauen mit Holz, 2019; Bayerisches Staatsministerium für Wohnen Bau und Verkehr, 2022), and others are being planned, such as in the federal state of Baden-Württemberg (Holzbau Offensive, 2020). This will lead to an increase in the timber construction quota in Germany. In this regard, it should be noted that the environment ministers of the federal states have issued a joint declaration that building with biogenic raw materials, especially wood, is explicitly climate-friendly and should therefore be particularly promoted (Federal Ministry of Finance, 2021; Forstwirtschaft in Deutschland, 2022). Overall, this shows that materiality is now also receiving increased attention and its environmental impact is to be reduced.

In many developed countries, the construction sector is one of the main economic drivers, a significant employer, and thus often the focus for promoting the circular economy (Gorecki, 2019).

Also, the German construction industry is one of the economic sectors with the most employees subject to social security contributions and - despite the current pandemic - has not experienced a drop in production capacity or sales. (Federal Employment Agency, 2022). This is particularly interesting because the period covered is a boom phase with historically low-interest rates and only shaken by a crisis in the last year modeled (2020). The crisis years in the construction industry - caused by the real estate and financial crisis in the USA in 2008 - had already been overcome at the start of the modeling.

At the same time, the building sector is also one of the largest emitters of climate-damaging greenhouse gas emissions (Nejat et al., 2015). Therefore, for the long-term climate neutrality of the German economy, it is necessary for the building sector to change. Housing is a basic need that cannot be substituted. Since current population forecasts assume that the German population will shrink only slightly or even grow in the coming years (Federal Statistical Office, 2022a), and the living space per inhabitant in Germany has been growing continuously for decades (Federal Statistical Office, 2021a), it can be assumed that the construction sector will retain a high economic and social relevance in the coming years. Against this backdrop, the global forecast by Eberhardt et al. (2019) states that it is likely that the construction industry will need to erect more buildings in the next 40 years than in the last 4, 000 years combined.

In order to transform the building sector in a climate-friendly way and at the same time maintain its economic importance, it is necessary to replace the materials currently used with more suitable ones. Mineral building materials, in particular, currently make up a predominant part of the construction industry, both in terms of the quantity used and the climate footprint (Göswein et al., 2018, 2019).

However, for the sustainability debate in Germany, knowledge and information about the materials used in the German building sector are essential to assess how climate-friendly the building sector actually is or how climate-friendly it can become, and which are the political and social levers to achieve this. In order to construct sustainable buildings, both the materials used and the processes associated with the building must be sustainable (Rheude et al., 2021). It can be concluded that materiality in the building sector cannot be neglected; but for sustainable buildings, a holistic approach that includes - besides electricity and water consumption in the operational phase - also materiality is essential (Churkina et al., 2020).

Furthermore, it must be taken into account here that a large part of the value creation of construction activity in Germany occurs in the building sector (Gornig et al., 2021). This is also the lever for more sustainability: In civil engineering, e.g., road construction, tunnel construction, hydraulic engineering, mineral materials like cement and steel cannot be replaced with biogenic materials because of the high, permanent load-bearing capacity and the frequent and intensive change of humidity cannot yet be fulfilled by biogenic raw materials (Pacheco-Torgal and Labrincha, 2014). Since hardly any biogenic building materials can be used in civil engineering as substitutes for most mineral and fossil building materials for the above reasons, civil engineering is not considered in this study.

Therefore, the research question for this publication can be summarized as follows: How significant has been the material-based climate effect of buildings developed in Germany in recent years?

2. Methods

2.1. Material flow analysis

In this study, the focus is on the shell construction of buildings in Germany. Here we describe shell construction to include the walls, ceilings, and roofs of the buildings, as well as the insulation. The complete interior finishing of the buildings (floor coverings, wallpaper, electrics, water and sewer pipes and others), doors and windows, and all paints, varnishes, and plasters, are not considered. When the study refers to shell construction in the following, it means the description preceding it. The reason that doors and windows are not taken into account is that the statistics only include the number of doors and windows produced, not their size (e.g., square meters) and composition (double vs. triple glazing, aluminum vs. steel), and therefore their environmental impact cannot be quantified. Although the interior fittings of buildings accounts for a significant share in terms of financial turnover (Federal Office for Building and Regional Planning, 2022), it is often comparatively short-lived (Kohler and Yang, 2007). While the shell of a building has a high volume and a very long lifetime and is only partially replaced even in core renovations, the finishing is very much subject to the taste and financial means of the respective owner. For example, floor coverings and wallpaper are often replaced before reaching the end of their technical service life (Kohler and Yang, 2007). For the climate neutrality of the German building sector, the interior construction is thus not irrelevant, but due to the high masses and the long-lived nature of the shell, the latter is more relevant overall and will be the focus of this study.

The exact system boundaries used and material flow taken into account are shown in Fig. 1 as well as the corresponding tables in the appendix.

For the calculation of the construction quantities, a top-down approach was used, based on the approach of Schiller et al. (2015), which was supplemented with further data, as explained below:

Production statistics were combined with foreign trade statistics data to model the in- and outflow of construction materials into the German building sector (Federal Statistical Office, 2022b, 2022c). Combining these two statistics allows conclusions to be drawn about the domestic use of building materials in Germany because the three areas of domestic production, imports, and exports of the various goods are now taken into account. According to Kohler and Yang (2007), top-down approaches (as used in this study) tend to overestimate the actual values, while bottom-up approaches tend to underestimate the built substance.

Since not all building materials were indicated in the production statistics with their masses, but partly in cubic meters or other volumes, appropriate material intensity coefficients were used to convert volumes to mass.

As already mentioned above, all substances are given with their masses in the trade statistics. The consumption of each construction material is calculated as domestic production plus imports minus exports. However, the simplification is made that the building materials are used on the construction site in the year of their manufacture. Since there is little storage capacity for building materials, the impact on the results is negligible and equals out over longer periods.

A detailed compilation of the various products can be found in the appendix. It should be noted that only materials relevant to the end user were considered in this study (for example precast concrete elements, wood products, and bricks, instead of sand or cement). Overall, 70 so-called types of goods were identified in the production statistics relevant to Germany's building sector. However, there are a few points to consider here:

1. The production statistics only cover enterprises with more than 20 employees (Federal Statistical Office, 2022d). Small and micro enterprises are therefore not recorded. This is not relevant for many goods in the building sector, as they are produced on a large industrial scale. However, more exotic, renewable insulating materials with a small market share could not be represented sufficiently.
2. Upon request, companies can prevent their production quantities from being listed in the quarterly production statistics. This can be the case, for example, for national security goods, but also if a market is highly consolidated, meaning that there are only very few producers. However, a sharp dividing line could not be discerned in the data. There were types of goods for which the number of producing companies was five, but no quantity produced was declared. In other cases, detailed production quantities were available for three producing companies.
3. The statistics are revised at irregular intervals (Federal Statistical Office, 2022d, 2022e). The reason for this is that there is a technical change, and the needs of consumers are constantly changing. Therefore, new types of goods have to be created, others are no longer needed, and some existing ones have to be revised. The last revisions were in 2019 (hereafter GP, 2019), 2009 (hereafter GP, 2009), and 2002. Especially the change from GP 2002 to GP 2009 resulted in a significant structural reorganization. The main reason

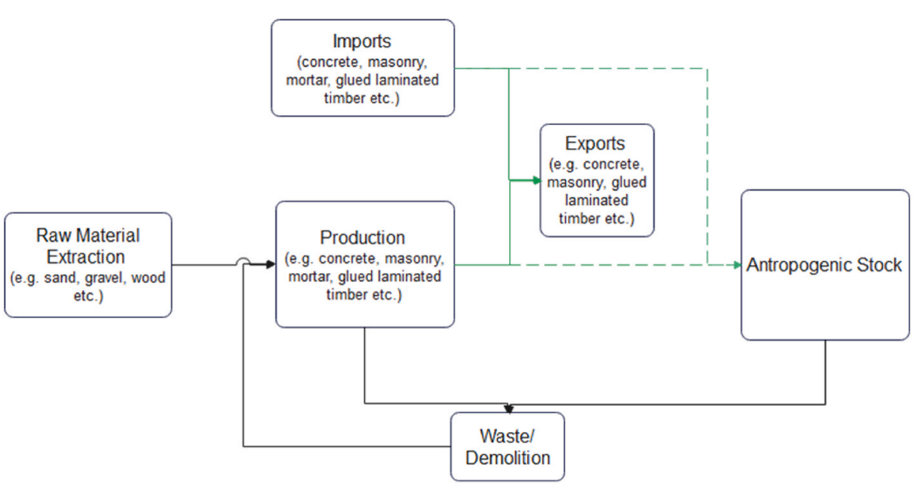

Fig. 1. In this study, all green lines were modeled for the Material Flow Analysis, the dashed lines were additionally modeled for the GHG emissions. Extraction of raw materials was not taken into account to avoid double counting in the statistics. Furthermore, demolition was not modeled. Since the buildings are primarily new constructions, the amount of generated waste is negligible. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

for the revision was an adjustment to the statistical survey of the EU: Types of goods from 2008 can therefore only be compared with types of goods from 2009 and subsequent years.

4. The production statistics have sometimes different units of measure for individual types of goods. Some of these are metric tons, some square meters, some cubic meters, and others.

These production goods were compared with 37 groups of goods in foreign trade statistics. These are adjusted annually to the revised EU foreign trade statistics. The quantitative recording of foreign trade over several years is, therefore, more complex than that of the production goods and is explained briefly below:

1. All goods that cross the German border are recorded for foreign trade statistics. There is no restriction according to the number of employees at the production site or the number of producing companies. If we now compare these two statistics directly with each other without adding other sources, this leads to an overweighting of the trade statistics compared to the production statistics, since some production sites are not recorded for statistical reasons, but the same restriction does not apply to trade.
2. The commodity groups of foreign trade statistics and the commodity types of production statistics are rarely congruent in their definitions. Therefore, certain goods in production statistics may refer to several commodity groups in trade statistics and vice versa. Following this, different assumptions must be made for allocating the masses, and further information must be added. Overlaps must also be taken into account.

We cannot, therefore, speak of an exact calculation of the building materials used in the German construction sector but of a quantitative estimation and modeling of the quantities of goods used based on government statistics supplemented by information from associations, standards, and other statistical sources (e.g., Baier et al. (2021), Basten (2018), Bergmann (Bergmann et al., 2015), the German Federal Association of the Brick and Tile Industry (Bundesverband deutscher Ziegelindustrie) (Bundesverband der DeutschenZiegelindustrie, 2015), Reinhardt et al. (2019)). For this reason, only the products intended for sale were modeled and not the total raw material input (e.g., from sand, gravel, or petroleum). The modeled masses will therefore be smaller in this study than in comparative studies (especially for import and export).

Furthermore, building materials in Germany are generally not manufactured at the construction site, but are either delivered as precast elements and installed at the construction site or delivered directly. It is therefore sufficient to compare only the products sold from the production statistics with the trade statistics and, if necessary, to supplement these with further information (e.g., on the ratio of concrete use in building construction and civil engineering). The commodity groups have been heavily revised in recent years, so only data from 2012 onwards were considered for this publication. For the numerical values before that, it is impossible to find the corresponding allocation of commodity groups to the types of goods, as the Federal Statistical Office only publishes the allocations for the last ten years.

Therefore, the present modeling deals with the period 2012 to 2020 and enables a statement about the building materials used in Germany's building sector. As the following modeling is mainly based on production and foreign trade statistics, the renovation and new construction sectors are included in the building construction sector. No distinction is made as to whether materials are used for which sector. In purely monetary terms, the renovation sector is significantly larger than the new construction sector (Gornig et al., 2021). However, making a statement about materiality is impossible, as no figures are collected on material consumption. In particular, it should be noted that the renovation sector very often involves small but expensive measures that do not consume a lot of materials (e.g., a new kitchen or bathroom). It is therefore not possible to say what percentage of the modeled material masses are used in the renovation sector compared to the new construction sector.

A distinction between residential and non-residential construction is also not made.

Many building materials, especially concretes, are used in building construction and civil engineering. To estimate the quantities currently used in building construction, ISO standards and mainly association publications were consulted (e.g., the German Federal Gypsum Association (Bundesverband der Gipsindustrie) (Bundesverband der Gipsindustrie, 2013), der dichtebau.de (de, 2020), Frederichs (2020), Basten (2020), and others in the supplements). These allowed a detailed market assessment and thus a conclusion on the composition of the types of goods for a quantitative conversion of the values. The market estimate makes it possible to say how much of the various materials were used in the building construction sector in which year.

This concerns specifically some of the substances that are produced in large mass: Concretes, which primarily differ in their strength class, sand-lime bricks, and bricks. Furthermore, the market analysis was also needed for wood to estimate how much of it would end up being used in the construction sector. The entire table of all the types of goods studied and the distribution among the different groups of goods over the years can be found in the appendix. The types of goods were selected according to their relevance to the construction sector. In the table, the name of the product group can often provide an initial classification (e.g., precast concrete components or sand-lime ceilings). For other groups (e.g., wood and fresh concretes), further market analysis is required, as mentioned above. Due to the high level of aggregation, no direct statement can be made about the masses used in the building sector and in civil engineering. In the case of fresh concrete, the market analysis made it possible to find out that in 2014 around 83% of fresh concrete was used in building construction, while the remainder was used in civil engineering (Bundesverbrand der DeutschenTransportbetonindustrie, 2015). Thus, the inclusion of other sources allowed to specify the government statistics for the present study.

The appendix also includes a document containing all literature references sorted by types of goods that were used to model the masses in building construction.

As already mentioned above, the groups from the production statistics do not always correspond directly with the groups from the trade statistics. It can happen that a group from the trade statistics includes several groups in the production statistics. This becomes relevant for this study especially when a group in the trade statistics includes several groups in the production statistics, not all of which are relevant for this study. For example, the group with the identifier "6904 10 00″ includes bricks for masonry and pavements and roads.

For this group, the following simplifying formula was used to calculate the masses:

$$T_1 = \frac{m_1}{m_1 + m_2 \dots m_n} * T_{Group\ x} \tag{1}$$

Here T stands for the difference between imports and exports. This is multiplied by the quotient of the mass from the production statistics (divisor), which is primarily of interest, and all other groups with which the group from the trade statistics and the production statistics overlap (dividend). In the above example, the bricks for masonry would be the divisor, while the sum of all bricks would be the dividend. This simplified calculation calculates the relevant mass T_1 at the end. This calculation was carried out for each year. This means that the mass from the trade statistics, which is relevant for the material flow, is now calculated and can be added to the production statistics to arrive at the mass that was actually used in the respective year.

2.2. Estimating the greenhouse gas emissions

In order to estimate the climate impact of production, the determined masses are linked with information from the Ökobaudat database (Federal Ministry of Housing Urban Development and Construction, 2022). Ökobaudat is a database of the Federal Ministry of Housing, Urban Development and Construction that is intended to facilitate uniform standards in the life cycle assessment of buildings. The aim of the database is to present the life cycle assessments of buildings (Federal Ministry of Housing Urban Development and Construction, 2022). The database contains environmental product declarations (EPDs) for various products and processes that are relevant to construction (Del Rosario et al., 2021). The database is structured in such a way that the user can see at a glance which product the EPD refers to, whether it is the specific product of a manufacturer or generic EPDs that are representative of an entire product group. All EPDs are made in accordance with EN 15804 (German Institut for Standardization, 2022) as well as independently verified and regularly updated, so the user can access expired EPDs, for example, to model specific years. The EPDs do not show one absolute value but are divided into different modules, as shown in Fig. 2.

Since this study focuses on green-house gas emissions related to the production of construction materials, the data from modules A1 to A3 were used, resulting in a scope from cradle to gate. For the modeling in this study, EPDs were used that were not explicitly issued by one company but covered as large a product group as possible. The background is that EPDs specific to one company's product are often not representative of the whole market of these products. Therefore, EPDs from associations and institutions such as the Thünen-Institut or the Association of the German Brick and Tile Industry were used (Th ü nen Institute for International Forestry and Forest Economics, 2020; Federal Association of the German Brick Tile Industry, 2015), which tend to represent market averages. However, many previously calculated product groups cannot be assigned to a single EPD. For example, concretes of different strength classes have a joint group within the production statistics but several EPDs. Since this can cause uncertainties because different EPDs can come to different results, a Monte Carlo simulation was carried out.

For this purpose, several EPDs were assigned to a product group; thus, the minimum and maximum values for the emission values per product group were calculated. These were used in the following as extreme values of a distribution. Normal distribution was chosen as the distribution for the Monte Carlo simulation. The Python software Brightway2 from Mutel (2017) was used to calculate the Monte Carlo simulation. In this way, a distribution can be calculated, and thus a statement made about the greenhouse gas emissions of the building materials used in the German construction sector from 2012 to 2020. These steps were only carried out for product groups to which several EPDs could be assigned. Most product groups (e.g. bricks, glulam or various roof tiles) could be assigned a single EPD.

3. Results

3.1. Materials use in the building sector

Fig. 3 shows how, on the one hand, the ratio of mineral and fossil to metallic and biogenic raw materials in the raw materials sector has changed in recent years. On the other hand, however, the change in the absolute masses has also changed. It can be seen here that there were only minor changes in material use in the German construction sector in the years 2012–2015, with 2015 being the year with the lowest use in the entire modeled period. From 2015 to 2017, a substantial increase in material use can be seen in the following, which continues to weaken into 2020. In total figures, the fluctuations and eventual increase are primarily due to the use of mineral and fossil building materials. Overall, there is apparent growth in the sector over the modeled period. This growth is also evidenced by other statistics, such as the construction volume in euros (Federal Office for Building and Regional Planning, 2022). It is striking that most building materials are still of mineral origin, but the most considerable percentage growth in the period under consideration in recent years has been in biogenic building materials. This growth is evident from 2014 onwards but has mainly occurred from 2018 to 2020. Overall, almost 33.2% more biogenic building materials were used in 2020 than in 2012.

It is striking that the use of metals in the building construction sector has decreased in net terms, with the lowest point being 1.5 million metric tons of steel used in 2018. Throughout 2012 to 2020, metals used fell from 1.9 million metric tons to 1.8 million metric tons.

Fig. 4 shows the Sankey diagram resulting from the modeling. The bars are the cumulative values of the modeled period from 2012 to 2020. The different years' figures were aggregated here to give an overall view of the modeled period.

It can be seen that Germany is not significantly dependent on imports in the construction sector but is even a net exporter. In other words, it exports more than it imports. This applies to all modeled material groups of the construction sector. Although exports are more significant than imports, 92.7% of the mass-produced and imported in the modeled period flowed into the country's own anthropogenic stock. Only just under 8.3% of the modeled masses were exported in return. The ratios of the various modeled groups to each other never change. Both for imports, domestically produced goods, domestically used goods and exports, mineral and fossil materials are the largest, followed by biogenic and metallic materials.

In Fig. 5, the enclosed space in cubic meters was overlaid on the left

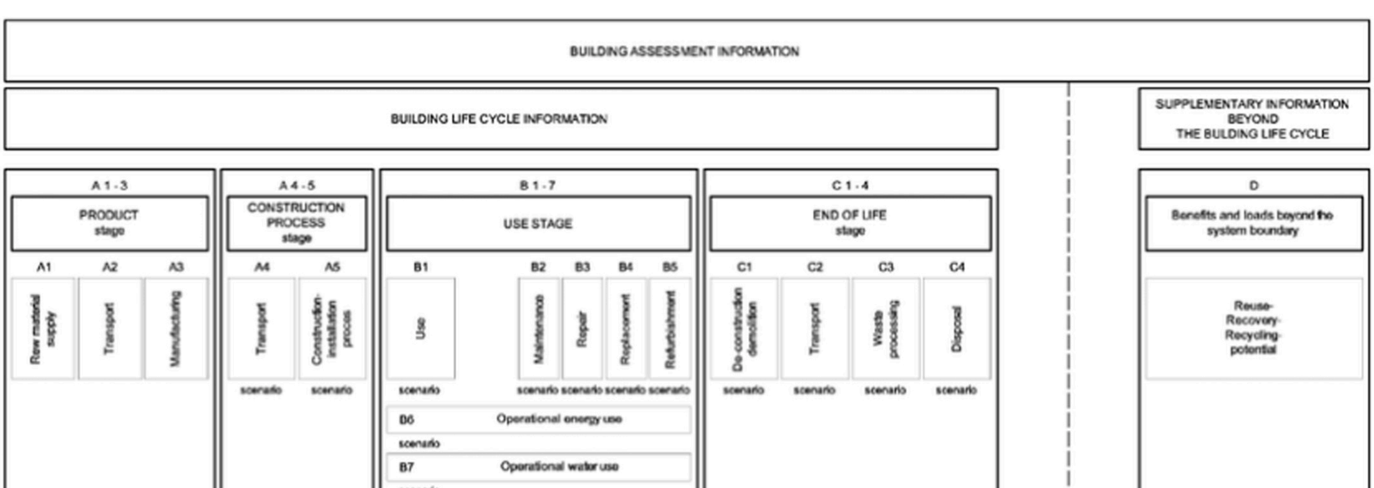

Fig. 2. Life cycle stages and modules according to EN 15804, from (Trinius and Goerke, 2019).

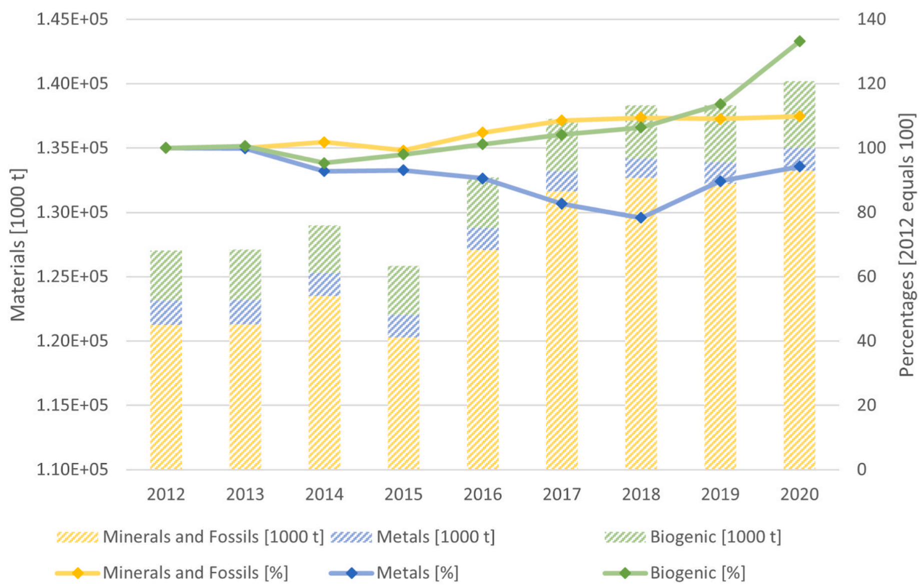

Fig. 3. Annual input into the German building sector from 2012 to 2020 sorted by mineral and Fossils, metallic and biogenic building materials [in 1,000 t] on the left y-axis and the changes in percentages on the right y-axis. For clarity, the left y-axis does not start at the value 0.

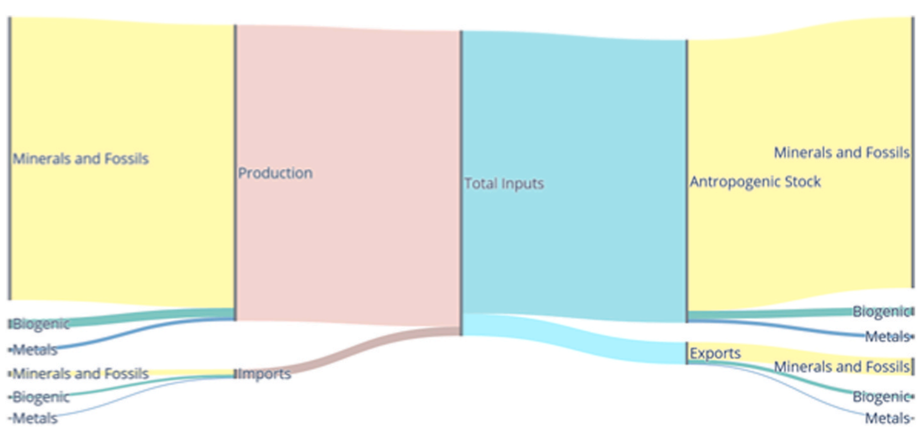

Fig. 4. Sankey diagram with the cumulative figures by production, import, and export for the complete modeled period from 2012 to 2020.

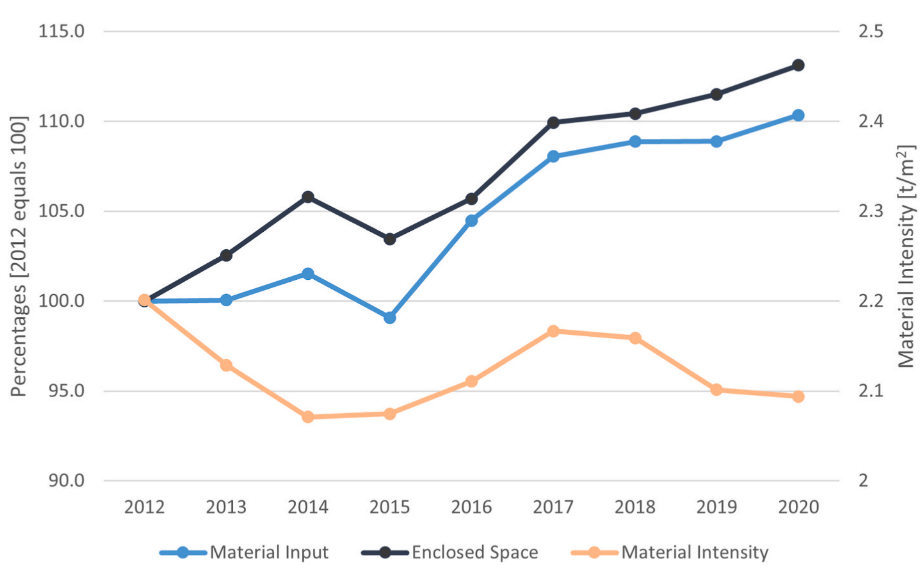

Fig. 5. Indices for the base year 2012 of the total material input for shell construction in German building construction [t] and the buildings completed in this period [in cubic meters of enclosed space floor area] as well as the average material intensity (data for volume and area from (Federal Statistical Office, 2022f)).

y-axis with the material input indexed for the modeled period. The year 2012 represents 100% in each case. It can be seen that the two graphs of material input and enclosed space run almost parallel to each other. This is an indication that the modeled data are very close to reality. Only in 2013 there is an increase in the enclosed space, which is not reflected in the material used. The low level of material used in 2015, which is already noticeable in Fig. 3 for material use, is also reflected in the built-up space in 2015. Therefore, less was built in 2015 compared to the other years, which is why less material was needed overall. The graph increases overall, so that in 2020 the total material input is 10% higher than in 2012.

At the same time, this graph also shows the ratio of metric tons to square meters of built space for the modeled period on the right-hand y-axis. Here we can see that the material intensity in metric tons per square meter fluctuates by a maximum of 5.9% in the modeled period, with the year with the lowest material input per year being 2014 with 2,071 t/m^2, while the highest material input is in 2012 with 2,201 t/m^2. Overall, it can be seen that the graph of material intensity runs in the opposite direction to the previous two graphs, as would be expected because the enclosed space has grown faster than the material input over the modeled period.

3.2. Greenhouse gas emissions

Fig. 6 shows the GHG emissions of the building products over the simulated years. Due to the significant uncertainty due to the use of EPDs in the composition of some types of goods, there is a high variance in the results. Therefore, the different years are not significantly different from each other. Again, 2015 has a lower average of 24,593 million metric tons of CO_2 eq. In contrast, the year with the highest average emissions is 2018, with 27,259 million metric tons of CO_2 eq. Overall, average emissions for the modeled period have increased slightly, although not significantly.

For the years 2018–2020, a slight average decrease in GHG emissions can even be seen, although material consumption has increased by roughly 3% overall in the same period (see Figs. 3 and 5).

Fig. 7 shows the greenhouse gas emissions of non-biogenic building materials. These include mineral, fossil and metallic building materials. The trend from 2012 to 2017 is very similar to the same years in Fig. 6. Again, 2015 is the year with the lowest emissions. From 2015 onwards, there is a continuous increase in the average up to and including 2020. In 2020, the emissions, according to the Monte Carlo simulation, were on average 32,124 million metric tons of CO_2 eq, which is the highest value in the simulated period. Overall, however, the values fluctuate around 30 million metric tons of CO_2 eq and do not differ significantly from each other for the modeled years.

Fig. 8 shows the greenhouse gas emissions (global warming potential) for the period from 2012 to 2020 for the building materials identified as biogenic. In terms of quantity, these are primarily wood or wood-based materials. Compared to the previous figures, it can be seen that Fig. 8 is the only one whose emissions are clearly in the negative range. It can also be seen that, although often not significantly different from each other, the mean values that resulted from the simulation became more negative as each year progressed from 2014 onward. As of 2018, there is a significant increase in the use of wood in the construction sector. This can be seen from the fact that carbon dioxide emissions drop significantly and differ significantly from previous years for 2019 and 2020. The lower use of building materials in 2015 as seen in the other figures is not evident for biogenic building materials.

Emissions in building construction in Germany have not changed significantly in recent years, although a slight decline can be observed from 2018 to 2020. Fig. 3 shows that the amount of materials used has increased in recent years and an increase in greenhouse gas emissions of the same order of magnitude could have been expected. This has not occurred mainly due to the strong growth of wood and other biogenic materials in the building sector, recognizable in Fig. 5. Wood has a robust negative emission in modules A1- A3 because carbon dioxide is sequestered during the growth of the trees. The increase in wood products in the construction sector has ensured that - although mineral building materials have also increased - emissions in 2020 were not significantly higher than in 2012. A further increase in the wood construction quota could therefore, even lead to a net savings of carbon dioxide in the shell construction.

4. Discussion

By its very nature, a model only represents part of reality and can never be all-encompassing. It is, therefore, a simplified version of reality. This must always be considered when creating, interpreting, and evaluating models. In the model presented here, the use of building materials in German building construction was modeled for 2012 to 2020.

In this discussion, the results obtained are first compared and

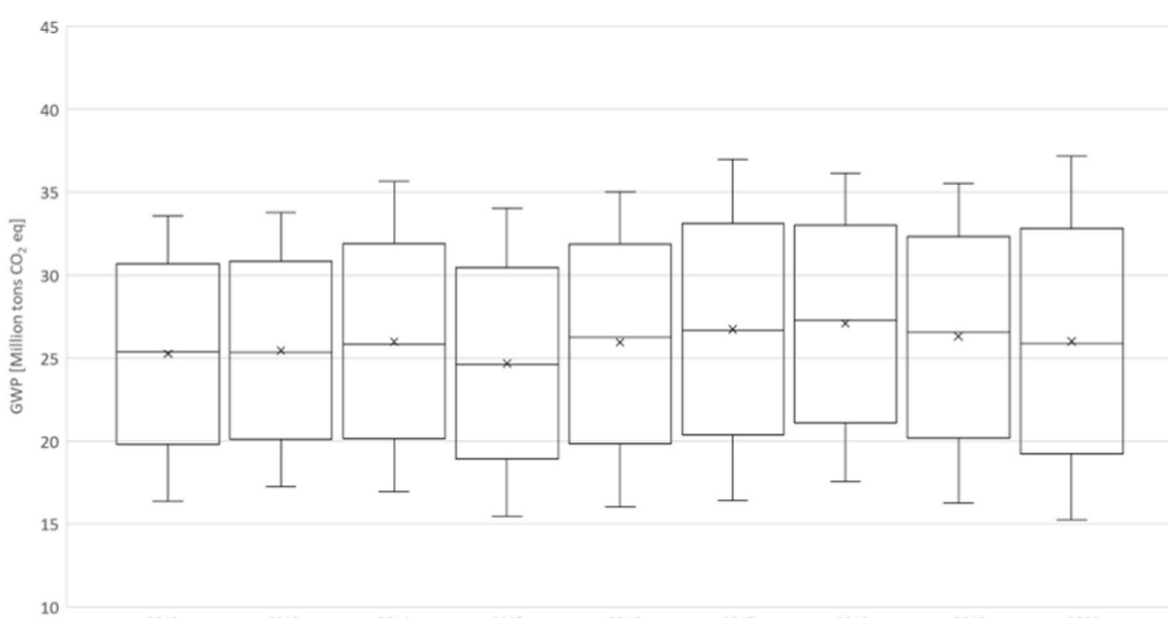

Fig. 6. Greenhouse Gas Emissions from 2012 to 2020 in million metric tons per year.

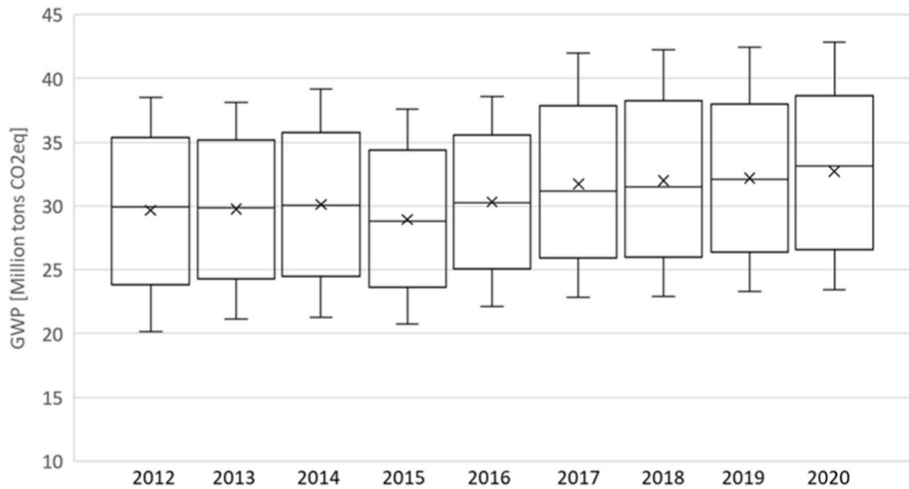

Fig. 7. Greenhouse Gas Emissions from 2012 to 2020 for the group of non-biogenic building materials in million metric tons per year (minerals, fossils, and metals).

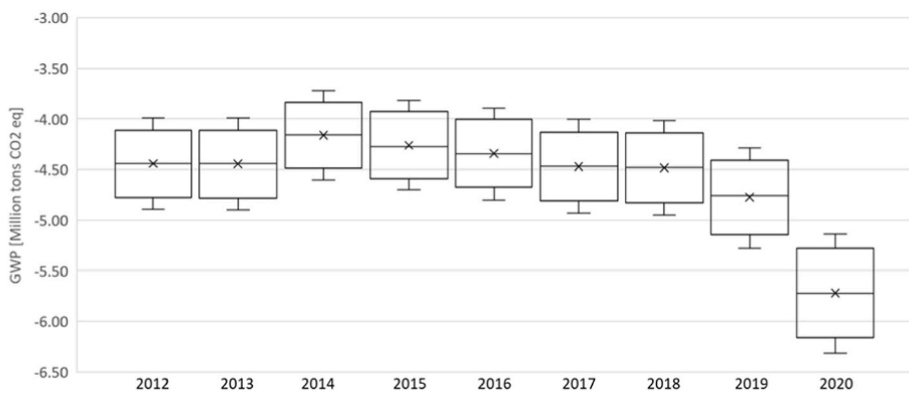

Fig. 8. Greenhouse Gas Emissions from 2012 to 2020 for the group of biogenic building materials in million metric tons per year.

discussed per se before being placed in relation to other publications dealing with the German construction sector. In a last step, we compare our findings with results obtained for other European countries.

4.1. Discussion of method

The research question was how the greenhouse gas emissions of the German building sector have changed in recent years. To answer this question, the construction volume in metric tons for the shell of the buildings was first modeled. For shell construction, all walls, ceilings, roofs and insulation were taken into account; the electrical system and pipes for water and sewage as well as windows and doors were not calculated. This results in a low mass, especially with regard to metals, as well as lower emission values, because metals cause higher emissions in relation to their mass than other building materials. This limitation must be taken into account.

This resulted in the corresponding masses for the different years sorted according to biogenic, metallic, mineral, and fossil building materials. This sorting was chosen because biogenic and metallic building materials can be easily distinguished from each other, but some composite building materials are both mineral and fossil in origin.

The modeled building materials were then linked to the EPDs from the Ökobaudat database, thus simulating the greenhouse gas emissions for the German building construction sector in the period 2012 to 2020.

This showed that the modeled masses increased by 10% in the modeled period (Fig. 3). Due to the scattering of the various EPDs and the associated Monte Carlo simulation, no significant increase in emissions can be determined. The average emissions increased by under 2% for the modeled period (Fig. 6). This means that a large part of the increase in weight was quasi “climate neutral".

This can be explained above all by the fact that significantly more wood has flowed into the construction sector as of 2018 (see Fig. 8), thus mainly offsetting the emissions caused by mineral, fossil, and metallic building materials (see Fig. 7). Among other things, this results in 2018 being the year with the highest average GHG emissions in the simulated data, but 2020 being the year with the highest material use.

The high timber use figures evident in 2019, and especially in 2020 in Fig. 8 compare to the previous years, are supported by the increased number of completed timber houses from the public statistics for construction completions (Federal Statistical Office, 2021b). Also the influence of politics to set up support programs for timber construction in recent years can be noted here. The fact that significantly more timber construction was carried out in 2019 and 2020 than in previous years seems to be due to the subsidy programs (SKHolzbau, 2020; Bauen mit Holz, 2019; Holzbau Offensive, 2020).

However, the methodology must be discussed at this point: First, the EPDs used are discussed, followed by the Monte Carlo simulation that led to the uncertainties in Figs. 6–8.

All EPDs used were prepared according to EN 15804 and independently verified. The EPDs used can thus be attested to have high credibility. However, it was only possible to select EPDs that had already been prepared and verified.

This means that only the currently recognized accounting standards are used. For example, wood consists of biogenic carbon, which is considered a negative emission, while the carbonation of concrete (Xi et al., 2016), for example, is not currently taken into account, which is why concrete has higher greenhouse gas emissions in the currently used accounting standards than it would if its carbonation is considered (Xi et al., 2016). Carbonation is not taken into account for two main reasons: 1. Carbonation is not an active process induced by humanity but takes place in concrete exposed to cool temperatures and humidity. Therefore, in many cases, it is not possible to say at the factory gate how much and how strongly a particular concrete part will be carbonated precisely because it can vary considerably even within a building (Mak et al., 2019). 2. Reinforced concrete is not improved by carbonization but can age faster - and in some cases, this is not visible from the outside - than without it due to the rusting of the steel. For reinforced concrete, carbonization can, therefore, even be detrimental (Li et al., 2022; Busch et al., 2022).

In addition, manufacturers who know that their current production methods are worse in terms of emissions than the market averages already in place currently have no incentive to put their products' EPDs into the eco-audit. Therefore, the greenhouse gas emissions for the modeled substances are only as good as the data available but cannot guarantee to cover the entire market. This may result in the present study underestimating rather than overestimating the emissions. Products that are at a very early stage of innovation and are therefore only used in very small quantities, such as climate-neutral concrete, cannot be fully mapped with the present method either (Beatty et al., 2022; Heveran et al., 2020; Chen et al., 2021).

This also has a direct impact on the Monte Carlo simulation, as products that may have extreme values in GHG emissions - especially significantly higher than the market standard products - may not be included, as manufacturers currently have no incentive to publish them but instead refer to the market-representative EPDs of the associations. Thus, the modeled and simulated uncertainties are probably smaller than in reality.

Even though there is no direct correlation between the weight and the emissions of the various building materials and there have been many further developments in recent years (e.g. recycled concrete or recycled bricks (Belaïd, 2022; Al-Faesly et al., 2023; Zhao et al., 2022; Khan et al., 2023)) to reduce the emissions of various building materials, it is nevertheless a good sign that the material efficiency expressed as material input per building volume has not increased significantly.

It must be taken into account that the model in this publication includes both renovations and new construction. This cannot be separated from each other, as the refurbishment sector's material input is unknown. Accumulated data on the monetary turnover of refurbishments in Germany are known (Federal Institute for Research on Building and Urban Affairs and Spatial Development at the Federal Office for Building and Regional Planning, 2019). However, the calculated capital values are so strongly aggregated that it is impossible to conclude individual construction measures or building materials. Therefore, further differentiation between new construction and renovation is not possible with the model presented here.

4.2. Comparisons with other German studies

In the following section, the results obtained are placed in relation to other statistically recorded figures to assess the plausibility of the figures modeled here. Schiller et al. (2015) used a bottom-up methodology to calculate the materials used in residential and non-residential building construction in 2010. The figures are in very good agreement with those modeled here. Table 1 compares the data with results from other studies that estimated material used in the German building sector.

Schiller et al. (2015) estimate stocks at 119 million metric tons, namely 6.3% lower than the estimate in this study. Compared to Schiller et al. (2015), the modeled imports and exports are significantly lower in the present study. This can be explained because Schiller et al. modeled both raw materials and finished products. Here, only finished products for the end consumer are modeled and not the raw extraction. Therefore, many raw materials that can account for large quantities are not included. Furthermore, production losses are not taken into account either in the present study. For these reasons, the modeled masses in the present study are lower than in Schiller et al. (2015).

Table 1
Comparison of the values modeled here with the results of other studies (*Pauliuk and Herren calculated the cement produced annually, as this accounts for about 1/5 of the mass of concrete, approximate values can be extrapolated here).

	Year of reference	Approach	Scope of study	Construction volume [1000 t]
Own calculations	2012	Top-Down	Shell construction	127,245
Schiller et al. (Schiller et al., 2015)	2010	Bottom-Up	The whole building and non-building sector, excluding civil engineering	119,200
Schiller et al. (Schiller et al., 2017)	2010	Top-Down	The whole building and non-building sector, excluding civil engineering	~242,000
Own calculations	2020	Top-Down	Shell construction	140,189
Pauliuk and Heeren (Pauliuk and Heeren, 2021)	2020	Bottom-Up	Cement, wood, and steel of residential and non-residential buildings	~36,000

Using concrete as an example, it is easy to explain why end-use products were used in this study: Since concrete is usually mixed in the concrete plant and then delivered to the construction site either as a prefabricated element or as ready-mixed concrete, there would be the risk for double counting if both sand and prefabricated concrete elements were taken into account. To avoid this double counting, therefore, only ready-mixed concretes and precast concrete elements are considered in this study.

Furthermore, it must be taken into account that Schiller et al. (2015) modeled the entire building sector, including civil engineering and other components (e.g., windows and doors), which is not the case here. As a result, the modeled metals in the present study are also significantly lower than in comparable studies, since, for example, the entire building services, aluminum windows and door frames were not taken into account. The fact that the surrounding infrastructure was often taken into account in other studies also lowers the metal content in the present study. For example, attachments such as carports or other light metal buildings such as garden pavilions were not considered in the present study. The same applies to connections to the public sewer system or the power grid. This is justified because primarily, the materials that form the envelope of a building and can be (partially) replaced should be modeled. This is not the case with building services. The same applies, for example, to window glass, which today and in the future consists mainly of quartz sand. Therefore, this extension was not modeled. Furthermore, only the building construction sector was modeled in the present study, i.e., metals and woods used in garden houses, for example, were also not considered. In the production statistics, this is a single production category.

Another study, also conducted by Schiller et al. (2017), estimated a material use of 242 million metric tons. Both studies by Schiller et al. refer to the same year but have different approaches: While the first study (Schiller et al., 2015) takes a bottom-up approach, the second study (Schiller et al., 2017) takes a top-down approach. The top-down approach thus nearly doubles the material input in the model. Although a top-down approach was also chosen in the present study, the modeled values are closer to the bottom-up approach of Schiller et al. This is partly because in the study by Schiller et al., all materials with one year of service life or longer (so-called durable goods) were modeled. It must also be taken into account that Schiller et al. model a different year than in this study, which also makes the values difficult to compare.

The same assumption can be made for the publication of Pauliuk and Heeren (2021) for data for 2020: Here, only the main emitters of greenhouse gases in the German building sector were modeled, which is cement. Neither mortar nor bricks were taken into account, and in the case of steel, the automotive sector, which was also modeled, must be subtracted. However, the values modeled by Pauliuk and Heeren are significantly lower than in the present study. Here, the modeled values account for 115 million metric tons of materials for the same material groups (concrete, steel and wood).

No explicit calculations for greenhouse gas emissions of the building sector have been carried out for the period under review that would allow for a direct comparison with the results of this study. However, rough comparisons can be drawn from the environmental and economic accounts (in German: Umweltökonomische Gesamtrechnung) (Federal Statistical Office, 2022g). While this does not have a precise breakdown by building shell in building construction (the category "F construction industry" refers only to construction processes, not building materials), a rough estimate can be made of whether the data simulated in this study are within a plausible range. For example, Germany's greenhouse gas emissions in 2019 were approximately 751 million metric tons (in the production areas). The categories from the environmental economic accounts that are relevant for this study have the codes: CPA 02, CPA 16, CPA 20, CPA 23.2–9, CPA 24.1–3, CPA 24.4, and CPA 25. They add up to around 113 million metric tons for 2019 and include the entire construction sector, i.e., building construction as well as civil engineering. In this study, a total of about 26 million metric tons of CO_2 eq of greenhouse gas emissions were simulated for the year 2019. If it is taken into account that the 113 million metric tons also include the complete expansion, especially civil engineering, and here not only the materiality but also the movement of earth and sand, around 26 million metric tons for the pure shell construction seem realistic.

The environmental economic accounts are very similar to the National Inventory Report (Strogies et al., 2022). Both end up with virtually no difference in the published figures, as both also publish according to the Kyoto Protocol (Strogies et al., 2022). Only the different assessments of land use, land use change, and forestry mean that the emissions are not the same but are sometimes higher in one report and sometimes higher in the other. The National Inventory Report clearly shows that the most significant energy consumption in the building sector is currently in the use phase of the buildings. This is why it is currently receiving the most attention in Germany. By using more and better insulation materials and more efficient HVACs, the energy consumption in the use phase of the buildings can be reduced. Therefore, it may be that higher GHG emissions in the construction phase lead to overall lower GHG emissions in the entire life cycle of the building (Chastas et al., 2016).

4.3. Comparison with european studies

In the following section, the results obtained are compared with studies conducted in Germany's neighboring European countries. For this purpose, each case calculated and compared the greenhouse gas emissions in CO_2/m^2 floor area.

Zimmermann et al. (2021) published a report in 2021 with the LCA of a total of 60 buildings from Denmark. The embodied energy of these buildings can also be taken from this report. This is highly dependent on the materials used and thus varies between 180 kg CO_2 eq/m^2 and 540 kg CO_2 eq/m^2, with most buildings in the range between 300 and 450 kg CO_2 eq/m^2. Approximately 10% of the emissions can be attributed to building components that were not considered in this study (e.g., windows, PV modules, and HVAC's).

For the present study, an average value of 404 kg CO_2 eq/m^2 can be calculated over all years, with the most considerable value in 2012 being 438 kg CO_2 eq/m^2 and the smallest value in 2020 being 377 kg CO_2 eq/m^2. Thus, the present study is in the range of Zimmermann et al.'s already calculated.

Hoxha et al. (2017) studied several single- and multi-family houses in France. Here, greenhouse gas emissions from embodied energy are higher than in Denmark and than those calculated for Germany in this study. There may be two reasons for this: First, only single- and multi-family dwellings were considered, while office buildings and other non-residential buildings tend to have lower emissions per square meter because the wall-to-room ratio is more favorable. This also explains why emissions per square meter are higher for single-family homes than for multi-family homes. In addition, the modeled buildings appear to contain significantly less wood than those in Denmark and Germany, increasing the average GHG emissions per square meter. Overall, the average GHG emissions per square meter are around 480 kg CO_2 eq/m^2 (Hoxha et al., 2017), which is around 80 kg CO_2 eq/m^2 higher than in the present study. Approximately half of this increased value can be attributed to building components that were not considered in this study (e.g., windows, HVAC's, sewer pipes).

John (2012) wrote that the buildings studied have greenhouse gas emissions of about 400–500 kg CO_2 eq/m^2 in terms of embodied emissions. Here, depending on the building, approximately 10%–20% of the embodied emissions can be attributed to building components that were not taken into account in the present study. This puts her study from Switzerland in the same order of magnitude as the others but slightly higher than the other studies, but this may be since in Denmark, buildings are built very lightly and with many biological building materials. From all these comparisons, it can be concluded that the results obtained are outstanding since all the studies examined are of the same order of magnitude, and only minor differences attributable to local design and the small number of samples can be detected.

In summary, the following can be concluded: The modeled and simulated data were compared with data from Germany and other European countries. Both materiality and greenhouse gas emissions were considered. It was found that the data collected and extracted are within the realistic range compared to the studies used.

5. Conclusion

The demand for raw materials in the shell of German building construction remains very high and increased during the period under study. The study also shows that mineral building materials - especially concretes - still account by far for the largest share of all materials used in shell construction in German building construction. However, wood as a building material has recorded the highest growth rates in recent years compared with the base year 2012. Among other things, political efforts to increase the use of biogenic raw materials in construction can be used as an explanation for the increase in the years since 2017. Since these laws and regulations have been beneficial for the use of biogenic materials in construction and more are in the planning stages by other states, it can be assumed that the trend to use more biogenic building materials for the construction of buildings will continue in the coming years.

The increase in biogenic raw materials, although representing a small percentage of the total materiality, has contributed to keep emissions at a stable level, in spite of an increasing use of construction materials.

The modeling of greenhouse gas emissions for the building envelope has shown that this sector accounts for about 3.5% of the total emissions of the German economy, but still has a high potential for optimization to reduce greenhouse gas emissions. In particular, the use of biogenic raw materials or the increased use of innovative building materials could still greatly reduce emissions while lowering overall life cycle emissions through greater energy efficiency (Busch et al., 2022; Heveran et al., 2020).

Despite an intensified sustainability debate in recent years, environmental improvements in the area of shell construction in Germany have not yet led to a significant change.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2022.100095.

References

Al-Faesly, Z., Noël, M., 2023. The feasibility of reuse in the concrete industry. In: Walbridge, S., Nik-Bakht, M., Ng, K.T.W., et al. (Eds.), Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021: CSCE21 Construction Track, , first ed.1. Springer Nature Singapore; Imprint Springer, Singapore, pp. 375–394. 251.

Alkaya, E., Bogurcu, M., Ulutas, F., et al., 2015. Adaptation to Climate Change in Industry: Improving Resource Efficiency through Sustainable Production Applications, 87, pp. 14–25. https://doi.org/10.2175/106143014X14062131178952.

Azari, R., Abbasabadi, N., 2018. Embodied energy of buildings: a review of data, methods, challenges, and research trends. Energy Build. 168, 225–235. https://doi.org/10.1016/j.enbuild.2018.03.003.

Baier, M., Bookhagen, B., Eicke, C., et al., 2021. Deutschland - Rohstoffsituation 2020. Hannover.

Basten, M., 2018. bbs-Zahlenspiegel 2018: Struktur- und Konjunkturdaten der Baustoff-, Steine- und Erden-Industrie. Berlin.

Basten, M., 2020. bbs-Zahlenspiegel 2020: Daten und Fakten zur Baustoff-Steine-Erden-Industrie. Berlin.

Bauen mit Holz, 2019. Holzbau-Zentrum: Berlin fördert den urbanen Holzbau. https://www.bauenmitholz.de/holzbau-zentrum-berlin-foerdert-den-urbanen-holzbau-26032019. (Accessed 25 July 2022).

Bayerisches Staatsministerium für Wohnen, Bau und Verkehr, 2022. Holzbauzuschuss: bayern zahlt Klimaprämie für Holzhäuser. https://www.stmb.bayern.de/med/aktuell/archiv/2022/220601bayfholz/#:~:text=Die%20Zuwendungsh%C3%B6he%20betr%C3%A4gt%20500%20Euro,sp%C3%A4testens%20Ende%202022%20gestellt%20werden. (Accessed 25 July 2022).

Beatty, D.N., Williams, S.L., Srubar, W.V., 2022. Biomineralized materials for sustainable and durable construction. Annu. Rev. Mater. Res. 52, 411–439. https://doi.org/10.1146/annurev-matsci-081720-105303.

Belaïd, F., 2022. How does concrete and cement industry transformation contribute to mitigating climate change challenges? Resources. Conservat. Recyc. Adv. 15, 200084 https://doi.org/10.1016/j.rcradv.2022.200084.

Bergmann, T., Bleher, D., Jenseit, W., 2015. Ressourceneffizienzpotenziale im Tiefbau: Materialverwendung und technische Lösungen.

Blom, I., Itard, L., Meijer, A., 2010. LCA-Based Environmental Assessment of the Use and Maintenance of Heating and Ventilation Systems in Dutch Dwellings, 45, pp. 2362–2372. https://doi.org/10.1016/j.buildenv.2010.04.012.

Bundesverband der Deutschen Ziegelindustrie, e.V., 2015. Halbjahresbericht 2015.

Bundesverband der Gipsindustrie, 2013. GIPS - Datenbuch.

Bundesverbrand der Deutschen Transportbetonindustrie, e.V., 2015. Jahresbericht 2014/2015.

Busch, P., Kendall, A., Murphy, C.W., et al., 2022. Literature review on policies to mitigate GHG emissions for cement and concrete. Resour. Conserv. Recycl. 182, 106278 https://doi.org/10.1016/j.resconrec.2022.106278.

Chandratilake, S.R., Dias, W., 2015. Ratio based indicators and continuous score functions for better assessment of building sustainability. Energy 83, 137–143. https://doi.org/10.1016/j.energy.2015.02.007.

Change, IPoC., 2014. Climate Change 2013 - the Physical Science Basis. Cambridge University Press, Cambridge.

Chastas, P., Theodosiou, T., Bikas, D., 2016. Embodied energy in residential buildings-towards the nearly zero energy building: a literature review. Build. Environ. 105, 267–282. https://doi.org/10.1016/j.buildenv.2016.05.040.

Chen, X., Matar, M.G., Beatty, D.N., et al., 2021. Retardation of portland cement hydration with photosynthetic algal biomass. ACS Sustain. Chem. Eng. 9, 13726–13734. https://doi.org/10.1021/acssuschemeng.1c04033.

Churkina, G., Organschi, A., Reyer, C.P.O., et al., 2020. Buildings as a global carbon sink. Nat. Sustain. 3, 269–276. https://doi.org/10.1038/s41893-019-0462-4.

D'Ambrosio, V., Leone, M.F., 2015. Climate change risks and environmental design for resilient urban regeneration. In: Napoli Est Pilot Case, 10. Firenze University Press, pp. 130–140. https://doi.org/10.13128/Techne-17509.

D'Amico, B., Pomponi, F., 2018. Accuracy and reliability: a computational tool to minimise steel mass and carbon. emiss. early-stage struct. design 168, 236–250. https://doi.org/10.1016/j.enbuild.2018.03.031.

de, derdichtebau, 2020. Stabile Entwicklung bei Polymerbitumenbahnen: marktzahlen 2019. https://www.derdichtebau.de/stabile-entwicklung-bei-polymerbitumenbahnen.27084.htm. (Accessed 16 March 2022).

Del Rosario, P., Palumbo, E., Traverso, M., 2021. Environmental product declarations as data source for the environmental assessment of buildings in the context of level(s) and DGNB: how feasible is their adoption? Sustainability 13, 6143. https://doi.org/10.3390/su13116143.

Doan, D.T., GhaffarianHoseini, A., Naismith, N., et al., 2017. A critical comparison of green building rating systems. Build. Environ. 123, 243–260. https://doi.org/10.1016/j.buildenv.2017.07.007.

Eberhardt, L.C.M., Birgisdottir, H., Birkved, M., 2019. Potential of circular economy in sustainable buildings. IOP Conf. Ser. Mater. Sci. Eng. 471, 92051 https://doi.org/10.1088/1757-899X/471/9/092051.

Esa, M.R., Halog, A., Rigamonti, L., 2017. Developing strategies for managing construction and demolition wastes in Malaysia based on the concept of circular economy. J. Mater. Cycles Waste Manag. 19, 1144–1154. https://doi.org/10.1007/s10163-016-0516-x.

Federal Association of the German Brick, Tile Industry, e.V., 2015. Mauerziegel. In: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=f98eea66-671c-4014-bfbb-2db1ffba8331&version=00.05.000&stock=OBD_2021_II&lang=de. (Accessed 25 April 2022).

Federal Employment Agency, 2022. Employees by economic sector (WZ 2008): beschäftigte nach Wirtschaftszweigen (WZ 2008). https://statistik.arbeitsagentur.de/SiteGlobals/Forms/Suche/Einzelheftsuche_Formular.html?nn=20898&topic_f=beschaeftigung-sozbe-wz-heft. (Accessed 31 March 2022).

Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) at the Federal Office for Building and Regional Planning, 2019. Structural Data on Production and Employment in the Construction Industry - Calculations for 2018. Bonn.

Federal Ministry of Finance, 2021. Klimafreundliches Bauen mit Holz. https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Europa/DARP/Leuchtturm-Projekte/klimafreundliches-bauen-mit-holz.html. (Accessed 25 July 2022).

Federal Ministry of Housing, Urban Development and Construction, 2022. Ökobaudat. https://www.oekobaudat.de/. (Accessed 25 April 2022).

Federal Office for Building and Regional Planning, 2022. Structure of the construction volume by construction sector in Germany in 2020. https://www.bbsr.bund.de/BBSR/DE/veroeffentlichungen/bbsr-online/2021/bbsr-online-32-2021-dl.pdf;jsessionid=6460D137E1162161E4C7CD972ECAC8E0.live11314?_blob=publicationFile&v=3. (Accessed 31 March 2022).

Federal Statistical Office, 2021a. Living space per inhabitant in dwellings in Germany from 1991 to 2020. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Wohnen/Publikationen/Downloads-Wohnen/fortschreibung-wohnungsbestand-pdf-5312301.pdf?_blob=publicationFile. (Accessed 31 March 2022).

Federal Statistical Office, 2021b. Construction and housing: construction completions of residential and non-residential buildings (new construction) by predominantly used building material. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Bauen/Publikationen/Downloads-Bautaetigkeit/baufertigstellungen-baustoff-xlsx-5311202.xlsx?_blob=publicationFile. (Accessed 31 March 2022).

Federal Statistical Office, 2022a. Projected population: Germany, reference date, Variants of the population projection. https://www-genesis.destatis.de/genesis/online?sequenz=tabelleErgebnis&selectionname=12421-0001#abreadcrumb. (Accessed 31 March 2022).

Federal Statistical Office, 2022b. Production value, quantity, weight and enterprises of the Quarterly production survey: Germany, years, List of goods (9-digit): 42131-0003. https://www-genesis.destatis.de/genesis//online?operation=table&code=42131-0003&bypass=true&levelindex=0&levelid=1648791359504#abreadcrumb. (Accessed 1 April 2022).

Federal Statistical Office, 2022c. Manufacturing industry: persons employed and turnover of enterprises in the construction industry. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Bauen/Publikationen/Downloads-Baugewerbe-Struktur/personen-umsatz-baugewerbe-2040510217004.pdf?_blob=publicationFile. (Accessed 11 March 2022).

Federal Statistical Office, 2022d. Production value, quantity, weight and enterprises of the Quarterly production survey: Germany, years, List of goods (9-digit): 42131-0003. https://www-genesis.destatis.de/genesis//online?operation=table&code=42131-0003&bypass=true&levelindex=0&levelid=1648791359504#abreadcrumb. (Accessed 1 April 2022).

Federal Statistical Office, 2022e. Exports and Imports (Foreign Trade): Germany, Years, List of Goods (8-digit), 51000-0013.

Federal Statistical Office, 2022f. Completions in building construction: Germany, Years, Construction activities, Building type/owner, code: 31121-0001. https://www-genesis.destatis.de/genesis//online?operation=table&code=31121-0001&bypass=true&levelindex=0&levelid=1660202725886#abreadcrumb. (Accessed 11 August 2022).

Federal Statistical Office, 2022g. Umweltökonomische gesamtrechnungen. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/_inhalt.html. (Accessed 25 April 2022).

Foley, J.A., Defries, R., Asner, G.P., et al., 2005. Global consequences of land use. Science 309, 570–574. https://doi.org/10.1126/science.1111772.

Forstwirtschaft in Deutschland, 2022. Minister Peter Hauk MdL: „Der verstärkte Einsatz von Holz beim Bauen kann einen wesentlichen Beitrag für mehr Klimaschutz leisten. https://www.forstwirtschaft-in-deutschland.de/aktuelles/news-detailansicht/news/minister-peter-hauk-mdl-der-verstaerkte-einsatz-von-holz-beim-bauen-kann-einen-wesentlichen-beitrag/. (Accessed 25 July 2022).

Frederichs, M., 2020. Jahresbericht 2020. Berlin.

Galán-Marín, C., Rivera-Gómez, C., García-Martínez, A., 2015. Embodied energy of conventional load-bearing walls versus natural stabilized earth blocks. https://doi.org/10.1016/j.enbuild.2015.03.054, 97:146-154.

Gardner, H.M., Hasik, V., Banawi, A., et al., 2020. Whole building life cycle assessment of a living building. J. Architect. Eng. 26, 4020039 https://doi.org/10.1061/(ASCE)AE.1943-5568.0000436.

Geldermans, R.J., 2016. Design for change and circularity – accommodating circular material & product flows in construction. Energy Proc. 96, 301–311. https://doi.org/10.1016/j.egypro.2016.09.153.

German Institut for Standardization, 2022. Nachhaltigkeit von Bauwerken - Umweltproduktdeklarationen - Grundregeln für die Produktkategorie Bauprodukte: Deutsche Fassung 13.020-80, 91.010.99, 91.040.01(EN 15804:2012+A2:2019 + AC:2021).

1976) Gesetz zur Einsparung von Energie in Gebäuden: Energieeinsparungsgesetz - EnEG.

2020) Gesetz zur Einsparung von Energie und zur Nutzung erneuerbarer Energien zur Wärme- und Kälteerzeugung in Gebäuden: Gebäudeenergiegesetz - GEG, vol 2020.

Gorecki, J., 2019. Circular economy maturity in construction companies. IOP Conf. Ser. Mater. Sci. Eng. 471, 112090 https://doi.org/10.1088/1757-899X/471/11/112090.

Gornig, M., Michelsen, C., Révész, H., 2021. Strukturdaten zur Produktion und Beschäftigung im Baugewerbe. https://www.bbsr.bund.de/BBSR/DE/veroeffentlichungen/bbsr-online/2021/bbsr-online-32-2021-dl.pdf;jsessionid=6460D137E1162161E4C7CD972ECAC8E0.live11314?_blob=publicationFile&v=3. (Accessed 31 March 2022).

Göswein, V., Krones, J., Celentano, G., et al., 2018. Embodied GHGs in a Fast Growing City: Looking at the Evolution of a Dwelling Stock Using Structural Element Breakdown and Policy Scenarios, 22, pp. 1339–1351. https://doi.org/10.1111/jiec.12700.

Göswein, V., Rodrigues, C., Silvestre, J.D., et al., 2019. Using anticipatory life cycle assessment to enable future sustainable construction. https://doi.org/10.1111/jiec.12916.

Hertwich, E.G., Ali, S., Ciacci, L., et al., 2019. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. Environ. Res. Lett. 14, 43004 https://doi.org/10.1088/1748-9326/ab0fe3.

Heveran, C.M., Williams, S.L., Qiu, J., et al., 2020. Biomineralization and successive regeneration of engineered living building materials. Matter 2, 481–494. https://doi.org/10.1016/j.matt.2019.11.016.

Holzbau Offensive, 2020. Aufruf für kommunale Ideen zur Entwicklung innovativer Holzbau- und Hybridprojekte wie Quartiere, eigene Liegenschaften oder zur Kommunikation. https://www.holzbauoffensivebw.de/de/p/massnahmen-landesregierung/fordermittel-1089.html#:~:text=Im%20Rahmen%20der%20Holzbau%2DOffensive%20des%20Landes%20Baden%2DW%C3%BCrttemberg%20werden,Euro%20zur%20Verf%C3%BCgung. (Accessed 25 July 2022).

Hong, S.H., Strlič, M., Ridley, I., et al., 2012. Climate change mitigation strategies for mechanically controlled repositories. Thecase of The Na. Arch. Kew 49, 163–170. https://doi.org/10.1016/j.atmosenv.2011.12.003.

Honic, M., Kovacic, I., Rechberger, H., 2019. Improving the recycling potential of buildings through Material Passports (MP): an Austrian case study. J. Clean. Prod. 217, 787–797. https://doi.org/10.1016/j.jclepro.2019.01.212.

Hossain, M.U., Ng, S.T., 2018. Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: an analytical review. J. Clean. Prod. 205, 763–780. https://doi.org/10.1016/j.jclepro.2018.09.120.

Hoxha, E., Habert, G., Lasvaux, S., et al., 2017. Influence of construction material uncertainties on residential building LCA reliability. J. Clean. Prod. 144, 33–47. https://doi.org/10.1016/j.jclepro.2016.12.068.

Illankoon, I., Tam, V., Le, K.N., 2017a. Environmental, Economic, and Social Parameters in International Green Building Rating Tools, 143. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000313.

Illankoon, I., Tam, V., Le, K.N., et al., 2017b. Key Credit Criteria Among International Green Building Rating Tools, 164, pp. 209–220. https://doi.org/10.1016/j.jclepro.2017.06.206.

John, V., 2012. Derivation of Reliable Simplification Strategies for the Comparative LCA of Individual and "typical" Newly Built Swiss Apartment Buildings. ETH Zurich.

Kalnay, E., Kanamitsu, M., Kistler, R., et al., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77, 437–471. https://doi.org/10.1175/1520-0477(1996)077. <0437:TNYRP>2.0.CO;2.

Khan, M.T., Saha, A.S., Amanat, K.M., 2023. A few mechanical and flexural properties of brick, recycled and natural aggregate concrete. In: Walbridge, S., Nik-Bakht, M., Ng, K.T.W., et al. (Eds.), Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021: CSCE21 Materials Track, , first ed.248. Springer Nature Singapore; Imprint Springer, Singapore, pp. 221–233.

Kim, H., Hong, T., Kim, J., 2019. Automatic Ventilation Control Algorithm Considering the Indoor Environmental Quality Factors and Occupant Ventilation Behavior Using a Logistic Regression Model, 153, pp. 46–59. https://doi.org/10.1016/j.buildenv.2019.02.032.

Kohler, N., Yang, W., 2007. Long-term management of building stocks. Build. Res. Inf. 35, 351–362. https://doi.org/10.1080/09613210701308962.

König, H., 2017. Projekt: Lebenszuklusanalyse von Wohngebäuden: Lebenszyklusanalyse mit Berechnung der Ökobilanz und Lebenszykluskosten.

Kreditanstalt für Wiederaufbau, 2022. The efficiency house level for a new building. https://www.kfw.de/inlandsfoerderung/Privatpersonen/Neubau/Das-Effizienzhaus/. (Accessed 25 July 2022).

Li, Y., Zhang, J., He, Y., et al., 2022. A review on durability of basalt fiber reinforced concrete. Compos. Sci. Technol. 225, 109519 https://doi.org/10.1016/j.compscitech.2022.109519.

Liu, Y., Wu, X., Ten, J., et al., 2019. Research on green project certification in China based on LEED and GBES. IOP Conf. Ser. Earth Environ. Sci. 233, 52036 https://doi.org/10.1088/1755-1315/233/5/052036.

Mak, M.W.T., Desnerck, P., Lees, J.M., 2019. Corrosion-induced cracking and bond strength in reinforced concrete. Construct. Build. Mater. 208, 228–241. https://doi.org/10.1016/j.conbuildmat.2019.02.151.

Mutel, C., 2017. Brightway: an open source framework for life cycle assessment. JOSS 2, 236. https://doi.org/10.21105/joss.00236.

Nejat, P., Jomehzadeh, F., Taheri, M.M., et al., 2015. A global review of energy consumption, CO 2 emissions and policy in the residential sector (with an overview of the top ten CO 2 emitting countries). Renew. Sustain. Energy Rev. 43, 843–862. https://doi.org/10.1016/j.rser.2014.11.066.

NRW. Bank Fördermittel des Landes Nordrhein-Westfalen: die NRW.BANK unterstützt Kommunen und Investoren dabei, bezahlbaren und modernen Wohnraum zu schaffen. https://www.bauen-mit-holz.nrw/foerdermittel/. (Accessed 25 July 2022).

Pacheco-Torgal, F., Labrincha, J.A., 2014. Biotechnologies and bioinspired materials for the construction industry: an overview. Int. J. Sustain. Eng. 7, 235–244. https://doi.org/10.1080/19397038.2013.844741.

Pauliuk, S., Heeren, N., 2021. Material efficiency and its contribution to climate change mitigation in Germany: a deep decarbonization scenario analysis until 2060. J. Ind. Ecol. 25, 479–493. https://doi.org/10.1111/jiec.13091.

Pomponi, F., D'Amico, B., 2018. Carbon mitigation in the built environment: an input-output analysis of building materials and components in the UK. Procedia CIRP 69, 189–193. https://doi.org/10.1016/j.procir.2017.10.007.

Pomponi, F., Hart, J., Arehart, J.H., et al., 2020. Buildings as a global carbon sink? A reality check on feasibility limits. One Earth 3, 157–161. https://doi.org/10.1016/j.oneear.2020.07.018.

Ramesh, T., Prakash, R., Shukla, K.K., 2010. Life cycle energy analysis of buildings: an overview. Energy Build. 42, 1592–1600. https://doi.org/10.1016/j.enbuild.2010.05.007.

Reinhardt, J., Veith, C., Lempik, J., et al., 2019. Ganzheitliche Bewertung von verschiedenen Dämmstoffalternativen.

Rheude, F., Kondrasch, J., Röder, H., et al., 2021. Review of the terminology in the sustainable building sector. J. Clean. Prod. 286, 125445 https://doi.org/10.1016/j.jclepro.2020.125445.

Schiller, G., Ortlepp, R., Krauß, N., 2015. Mapping of the Anthropogenic Stockpile in Germany for the Optimization of Secondary Raw Materials Management (Kartierung des Anthropogenen Lagers in Deutschland zur Optimierung der Sekundärrohstoffwirtschaft). Environmental Research Plan of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Umweltforschungsplan des Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit), Dessau-Roßlau.

Schiller, G., Müller, F., Ortlepp, R., 2017. Mapping the anthropogenic stock in Germany: metabolic evidence for a circular economy. Resour. Conserv. Recycl. 123, 93–107. https://doi.org/10.1016/j.resconrec.2016.08.007.

Shan, M., Hwang, B.-G., 2018. Green building rating systems. Glob. rev. pract. res. eff. 39, 172–180. https://doi.org/10.1016/j.scs.2018.02.034.

SKHolzbau, 2020. NRW-Politik fördert Holzbau mit bis zu 7.500 Euro pro Bauvorhaben. https://www.skholzbau.de/nrw-foerdert-bauen-mit-holz/#:~:text=NRW%2DPolitik%20f%C3%B6rdert%20Holzbau%20mit,in%20nicht%20unbetr%C3%A4chtlichem%20Ma%C3%9F%20gef%C3%B6rdert. (Accessed 25 July 2022).

Strogies, M., Gniffke, P., Günther, D., et al., 2022. Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol: National Inventory Report for the German Greenhouse Gas Inventory 1990 - 2020, UNFCCC Submission.

Thünen Institute for International Forestry and Forest Economics, 2020. Balkenschichtholz (durchschnitt DE). In: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=c253ae30-eb7d-4f9c-8e8c-1df00344d5b2&version=00.00.022&stock=OBD_2021_II&lang=de. (Accessed 25 April 2022).

Trinius, W., Goerke, J., 2019. Declaration of the end-of-life for building products. IOP Conf. Ser. Earth Environ. Sci. 323, 12050 https://doi.org/10.1088/1755-1315/323/1/012050.

United Nations, 2015. The paris agreement. In: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. (Accessed 31 March 2022).

1977) Verordnung über einen energiesparenden Wärmeschutz bei Gebäuden: Wärmeschutzverordnung - WärmeschutzV.

1978) Verordnung über energiesparende Anforderungen an heizungstechnische Anlagen und Brauchwasseranlagen: Heizungsanlagen-Verordnung - HeizAnlV.

2001) Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden, vol 2001.

Wuth, J., Scope, C., 2021. Nachhaltiges Bauen in der Praxis: bewertung des Zertifizierungsprozesses der ökologischen Qualität nach DGNB System/Sustainable building in practice: evaluation of the certification process of environmental quality according to the DGNB system. Bauingenieur 96, 296–308. https://doi.org/10.37544/0005-6650-2021-09-40.

Xi, F., Davis, S.J., Ciais, P., et al., 2016. Substantial global carbon uptake by cement carbonation. Nat. Geosci. 9, 880–883. https://doi.org/10.1038/ngeo2840.

Yu, W., Li, B., Yang, X., et al., 2015. A development of a rating method and weighting system for green store buildings in China. Renew. Energy 73, 123–129. https://doi.org/10.1016/j.renene.2014.06.013.

Zabalza Bribián, I., Valero Capilla, A., Aranda Usón, A., 2011. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build. Environ. 46, 1133–1140. https://doi.org/10.1016/j.buildenv.2010.12.002.

Zhang, Y., Wang, J., Hu, F., et al., 2017. Comparison of Evaluation Standards for Green Building in China, 68, pp. 262–271. https://doi.org/10.1016/j.rser.2016.09.139. Britain, United States.

Zhao, Z., Xiao, J., Duan, Z., et al., 2022. Performance and durability of self-compacting mortar with recycled sand from crushed brick. J. Build. Eng. 57, 104867 https://doi.org/10.1016/j.jobe.2022.104867.

Zimmermann, R.K., Andersen Camilla, Ernst, Kanafani, K., et al., 2021. Whole Life Carbon Assessment of 60 Buildings: Possibilities to Develop Benchmark Values for LCA of Buildings.

FULL PAPER: RESIDENTIAL DEMOLITION AND RECYCLING – AN ECO-BALANCING CASE STUDY

Cleaner Waste Systems 3 (2022) 100056

Contents lists available at ScienceDirect

Cleaner Waste Systems

journal homepage: www.journals.elsevier.com/cleaner-waste-systems

Residential demolition and waste management - An ecobalancing case study

Felix Rheude*, Aljoscha Bucher, Hubert Röder

Chair of Sustainable Business Economics, TUM Campus Straubing for Biotechnology and Sustainability, Weihenstephan-Triesdorf University of Applied Sciences, Am Essigberg 3, D-94315 Straubing, Germany

ARTICLE INFO

Keywords:
Demolition
Consequential LCA
Regulations
Waste management

ABSTRACT

Due to their structure and age, many buildings will be demolished in Germany in the coming years. The present case study investigates the demolition of a typical detached residential house in Southern Germany built in the 1950s. Legal regulations were taken into consideration, and a life cycle assessment was conducted to simulate the environmental burdens of the demolition and monitor compliance with legal requirements. It was shown that 80.3 % of the total construction volume went to landfills, 14.4 % to thermal recycling, and 0.6 % to material recycling, while 4.7 % was reused. In addition, the global warming potential was evaluated for a mean of 96.59 kg CO_2 eq per square metre of gross external area. These results show that there is still room for ecological optimization of the demolition and recycling of residual materials from buildings in Germany.

1. Introduction

Waste is a crucial environmental problem (Wouterszoon Jansen et al., 2020) and represents a significant economic loss. This issue has been discussed by the United Nations General Assembly, which defined one of the goals as the proper management of all waste in an environmentally sound manner (United Nations General Assembly, 2015). Waste volumes should be reduced as far as possible through reduction, reuse, and recycling (Bashir et al., 2016). This so-called 3R-principle is not only of supranational importance but is also highly relevant to large economies and can improve the reduction of construction and demolition waste (CDW) (Huang et al., 2018; Jain et al., 2020). Across Europe, approximately 2.5 billion tons of waste were produced in 2016. Of this, 36 % is accounted for by the construction industry (European Parliament, 2018). Between 350 and 412 million tonnes of waste are statistically recorded in Germany annually (Destatis, 2020b). The German government has committed itself to this topic and launched the national strategy for reducing waste with the “Law to promote the circular economy and ensure environmentally friendly waste management” (Federal Ministry of Justice and Consumer Protection, 2012). According to EU waste management statistics, Germany and Austria have the highest recycling rates within their waste management sectors (European Parliament, 2018). Although Germany has a very high recycling rate by international standards, it still has improvement potential (Knappe and Lansche, 2010). This is further put into perspective when considering which areas use the most recycled building materials: For example, the most considerable quantity is used in road construction, followed by recycling in earthworks. Building construction currently only plays a subordinate role here and is not listed as a separate area in the statistics (Federal Statistical Office, 2021).

As the construction sector is the largest consumer of resources and the largest single source of waste in Europe (Zhang et al., 2022), the European Union is also striving to transform the previous linear business models in the construction sector into circular economy business models through various initiatives. In this regard, the EU has recognised that with higher recycling and reuse rates, the likelihood of circularity of the reused material increases (Nadazdi et al., 2022). However, statements for the whole of Europe in this respect are partly confusing, as Gálvez-Martos et al. (2018) point out. Especially the heterogeneity regarding the treatment of waste and the development of the market for recycling products play a significant role.

Buildings have a diverse ecological impact on their surroundings (Lichtenberg, 2004). Therefore, one way to reduce this mostly negative influence is to use existing materials as efficiently as possible and reduce the general use of resources (Lee et al., 2015). Therefore, structured and sorted reuse of as many building materials as possible is necessary.

Michael Braungart and William McDonough developed the “cradle to cradle” principle, which describes the use of recyclable raw materials as the solution to the problem of waste since residual materials left over from production or that remain after the end-of-life phase of a product can be fed back into the economic cycle on a one-to-one basis (McDonough and Braungart, 2002). In recent years, the need to conserve natural resources on the one hand and secure the supply of raw

* Corresponding author.
E-mail addresses: felix.rheude@tum.de (F. Rheude), aljoschabucher@gmx.de (A. Bucher), hubert.roeder@hswt.de (H. Röder).

https://doi.org/10.1016/j.clwas.2022.100056
Received 14 March 2022; Received in revised form 31 October 2022; Accepted 16 November 2022
2772-9125/© 2022 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

materials on the other has led to discussions about creating a circular economy in the construction industry that is more resource-friendly than ever before (Eberhardt et al., 2019). According to Schiller et al. (2015), enormous value exists in Germany in the form of buildings and infrastructure. This can be interpreted as a capital reserve for the future (Koutamanis et al., 2018). However, it has to be appropriately managed if it is to be used. The strengthening of recirculation in construction processes is an issue explicitly taken up by the German Resource Efficiency Programme (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2016). It aims to maximise the recycling of secondary raw materials from mineral construction and demolition waste (CDW) to conserve primary raw materials and reduce the future need for landfill space. The separation of construction waste at source is essential for the safe removal and disposal of waste fractions containing hazardous substances (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2016; Gálvez-Martos et al., 2018; Huang et al., 2018).

For a building that has already been constructed, the dismantling, gutting and demolishing essentially determines the nature of the circular economy in the construction industry (Bashir et al., 2016). However, this can only work if the appropriate infrastructure for recycling is in place and legislation provides incentives for companies and individuals to use it. For buildings erected today with the knowledge of deconstruction and the environmental impacts, the materiality and design have an even higher importance for the effectiveness of deconstruction (Geldermans, 2016). Only if care is taken to ensure a high degree of selectivity and separate material streams, the return of these materials to the building-material cycle will be efficiently and effectively possible (Huang et al., 2018). However, it is still common practice to demolish buildings in Germany with relatively little regard for separating materials (Federal Ministry of Education and Research, 2018). The construction industry in Germany uses 555–663 million tonnes of raw materials annually (Destatis, 2020a). With approximately 250 million tonnes per year, CDW accounts for the largest share of total waste generated (Destatis, 2020b). Construction site waste and road demolition waste make up around half, the other half being soil waste. Waste management needs to be further developed ecologically until it ultimately becomes available as raw material for a future circular economy (Gálvez-Martos et al., 2018).

The present study develops an analysis of the handling of construction and demolition waste, underpinned by a life cycle assessment (LCA), which takes into account the legal requirements, available deconstruction, separation, expected waste volumes and the long-term political aims. As the inappropriate demolition processes represent an economic loss and negatively impact the climate and the environment, this case study also contains a life cycle assessment to indicate environmental enhancement potentials. The LCA has the potential to reveal specifically which steps in the demolition process have the highest environmental impact. This enables further enhancement of the environmental burden. LCAs have long been used in the building sector (Anand and Amor, 2017; 2018; Thibodeau et al., 2019). Therefore, many international rating systems for sustainable buildings have already incorporated life cycle assessment in their evaluation catalogues (BREEAM, 2018; CASBEE, 2015; 2018; Hiete et al., 2011; Illankoon et al., 2017). Due to data availability and the regulations of some rating systems, the focus is often on the building's construction and use phase (e.g. Biswas (2014), Hafner and Schäfer (2017)). Concerning deconstruction, many publications assess construction elements that are designed for reuse (Cruz Rios et al., 2019; Vares et al., 2020; Xia et al., 2020). Reusing construction elements aims to minimise future construction waste, as elements that are not needed anymore can be used on other construction sites, thus reducing the environmental burden and waste (Xia et al., 2020) while also benefiting the economy. However, most future demolitions in Germany will be of buildings constructed 50 or more years ago, as around 72 % of all residential buildings in Germany were built before 1978 (Metzger et al., 2019). These buildings will not have been designed with the deconstruction or reuse of construction elements beyond their life in mind (Metzger et al., 2019), which will generate a large volume of construction waste. Therefore, it is necessary to develop information and regulations on handling and reducing construction waste fifty years from now and in the nearer future.

This leads to the following research questions:

1. How are construction and demolition wastes sorted during the demolition of a typical detached residential house in Southern Germany?
2. What are the potential environmental impacts of demolition using an LCA?
3. To what extent does the practice of demolishing a typical building reflect current legislation?

2. Methods

2.1. Assessing the demolition

The demolition of a detached residential house (built-in 1954) was accompanied by scientific observation and evaluated as a single-case study. The building was choosen as case study, as it is very typical for a detached residential house built in Germany in the 1950s (Loga et al., 2015). Around 40 % of residential buildings in Germany were built between 1949 and 1978 (Loga et al., 2015). Many will have reached the end of their projected lifetime in the coming years, reflected in an increasing number of demolitions. However, as the present study investigates the demolition of a typical detached residential house from the mid-50s, it typifies many demolitions in the coming years due to the structural similarities of the current residential building stock in Germany (Metzger et al., 2019). The observation in the case study was based on the systematic approach by Weischer and Gehrau (2017) and verified by control questions in an observation protocol. The research is based on open, passive-participatory, knowing, non-standardised outside statements conducted in the field directly, manually, without mediation, and without stimulus. The investigator did not influence the demolition and the choice of the demolition company. The following data was collected and prepared in advance of the demolition: The plot and building were compared with the construction plan and characterised in terms of their dimensions, construction and interior fittings based on the "Deconstruction and Disposal Concept [Rückbau und Entsorgungskonzept]" case study (BFR Recycling, 2015).

The structural elements of the building and the garden and path were sorted and stored into material groups based on the construction plan and a house inspection. The lengths, widths, and thicknesses were measured using a laser range finder and a folding rule. Holes were drilled in all walls and floors to determine the thicknesses of the various material layers. The window and door areas were measured and subtracted from the wall area. In the case of repetitive building elements, such as paving stones, doors, roof tiles, the length, width and thickness of single items were measured and then multiplied to calculate the total volume. The components' length, width, and thickness are rounded to whole centimetres. The data was used to determine how much construction and demolition waste should ideally be separated in the demolition at hand. The demolition procedure was recorded on ten observation days and documented in an observation protocol. This procedure was carried out without external influence, which means that the demolition would have been carried out in this way even if this study had not been conducted.

Further, field notes were made of working times, dismantling groups, and the sorting of building elements into material groups and volumes, following the example of Koch (1997). The names of the recycling and disposal companies used by the demolition contractor were recorded by questioning the truck drivers. The interpretation covers the following parameters: Dismantling groups, allocation of building materials to recycling groups, and the resulting work stages and sorting rates for the respective material group. The volume of the material groups defined in the building description is constant in the calculations. The sorting and recycling rates of the demolition waste are recorded based on this volume.

The volumes of the elements in the parts lists were checked twice during the observation. Once before, the professionals demolished the building in different steps and once after, the different building material fractions were demolished and sorted. The lengths, widths, and thicknesses of individual elements were measured again on the various piles in the garden using a folding rule. The volumes calculated before demolition were then slightly corrected. The piles were loaded for disposal into containers and compacted in a second test. The calculated volumes were compared with the container dimensions and found valid. The data quality can therefore be classified as very good.

2.2. Methodology of the life cycle assessment

The Life cycle assessment (LCA) study was carried out according to DIN 14040 and 14044. According to the DIN standard, every LCA study must contain a goal and scope definition, a life cycle inventory, an impact assessment and the evaluation (DIN EN ISO 14044:2021–02, 2021; EN ISO 14040:2021–02, 2021).

The study aims to objectively and systematically present the environmental impact of demolishing a typical single-family house from the 1950 s in Germany. This is done against Germany's background with a comparatively old building stock with partly unknown material structure. For this reason, the results can only be compared with other demolitions to a limited extent. However, they orient the probable environmental impacts and effects of future demolitions. The study is primarily aimed at interested scientists, less at practitioners or homeowners.

The scope is the demolition of a single-family house in southern Germany. The material groups resulting from the demolition are of primary interest. Since a consequential LCA was used as an approach, allocations are unnecessary in this study and are not performed.

The volumes recorded were used to conduct a life cycle assessment of the demolition and the environmental influence of the generated wastes. Even though many life cycle assessments for buildings are calculated based on the attributional approach, a consequential approach and databases were used here. The reasons for this are as follows:

1. According to Curran et al. (2005), attributional and consequential LCAs aim to answer different types of questions. Whereas an attributional approach asks, "How are things flowing within the chosen temporal window?" (Curran et al., 2005, p. 856), a consequential approach answers the question "How will flows change in response to decisions?" (Curran et al., 2005, p. 856). As the goal is to assess whether the current legislation of the European Union and Germany is used in a practical context and whether decisions have to be made to reduce construction waste, the latter seems appropriate.
2. Furthermore, Weidema et al. (2018) point out that consequential life cycles measure the "impact" component of the sphere of influence. They also describe product life cycles as consequential, which is applicable here.
3. Finally, Weidema et al. (2018) state that all social responsibility paradigms ultimately imply a consequential perspective. The construction sector has always had a significant social and economic impact. When considering building law measures, it is, therefore, necessary to take the social components into account when finding solutions.
4. Even though most available environmental product declarations use an attributional approach, Weidema et al. (2020) have stated that clients may strongly prefer a consequential approach and should therefore be increasingly used. The results of this study can also serve as orientation for building owners as customers of waste management companies. It, therefore, makes sense to present the results from the perspective of the future customer.
5. Finally, the ILCD Handbook (European Commission, 2010) states that if a life cycle assessment is used for decision support, a life cycle impact (LCI) model should reflect the consequences of the decision.

For these reasons, a consequential approach was chosen. The EPD LCIA method (2018) was used to calculate the results; this is intended for use in environmental product declarations, which are well established in the building sector. The method was developed by the Swedish Environmental Management Council (SEMC) (EPD International AB, 2021). The method involves calculating a total of eight midpoint impact categories. Further information about the impact categories can be found on the website of EPD International AB (2021). It must be taken into account that this methodology is not fully compatible with EN 15804, since for the indicators AP (Acidification potential) and EP (Eutrophication potential) are defined differently. However, according to the manufacturer of this LCIA methodology, corresponding revisions are planned. Since this study is not primarily intended to produce an EPD, this methodology can still be used.

The system boundaries can be seen in detail in Fig. 1, and include the materiality of the building, the machinery used, including fuel

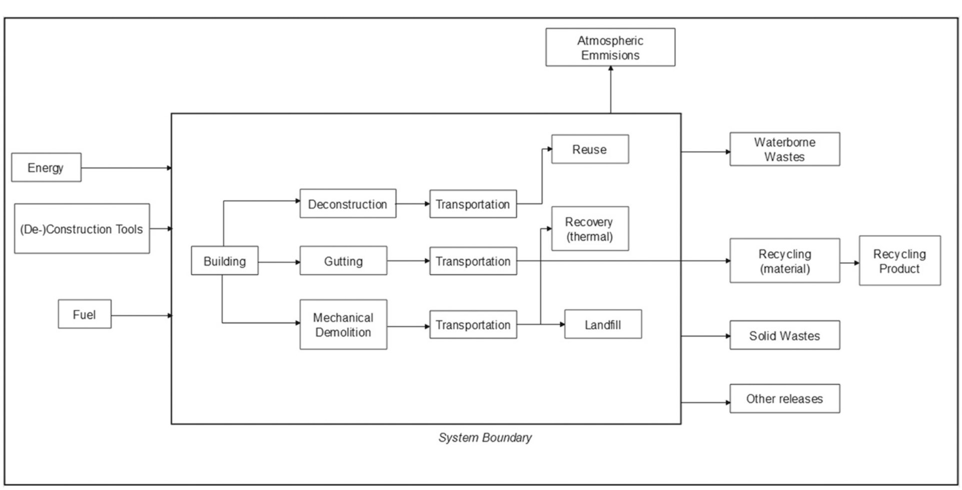

Fig. 1. System boundaries of the LCA study. The functional unit of the study is square meter gross external floor area. Material recycling was not simulated because the necessary data for this was not available.

consumption, and the subsequent recovery processes if known at the time of writing the study. According to standard DIN 15978 (E DIN EN 15978–1:2021–09, 2021; DIN EN 15978:2012–10, 2012), this LCA study thus corresponds to a description of disposal phase C with its subdivisions into deconstruction/demolition (C1), transport (C2), and disposal (C4). For module C3 (waste treatment for reuse, recycling and energy recovery), thermal recycling is included in the study, whereas material recycling is not. It was not possible to record the corresponding processes with the resulting energy consumption. At the time the study was conducted, the recycling companies were not yet able to say exactly which processes the materials would go into. The companies stated that they would be guided by short-term demand. Therefore, the recycling processes cannot be calculated for module C3. The module C3 can therefore not fully comply with DIN 15978. However, as shown in Table 3, this only concerns just under 4.7% by volume of the waste collected.

The data quality of the study can be classified as very good: All data were self-collected and confirmed by two temporally and methodologically independent measurement procedures. Subsequently, the professionals were finally interviewed again on site to verify the data. The data used thus meet the highest possible standard for life cycle assessment. The Ecoinvent 3.6 consequential - unit processes database from December 2019 was used, as it is one of the largest databases available and already well-established in life cycle assessments (Ecoinvent, 2019). In the first step of the calculations, the background system was built using SimaPro version 9.0.1.7 (PRé, 2020). The results were exported to a CSV file and processed using Python code based on Brightway2, including a Monte Carlo simulation (Mutel, 2017). This approach allows a deeper insight into the calculation and, as such, provides more information. The Monte Carlo simulation was chosen, as the volumes were measured precisely; however, converting from volumes to the masses used in Ecoinvent is prone to errors. As shown by Hauschild et al. (2017), the Monte Carlo simulation is a viable method used in life cycle assessments to estimate the uncertainty of simulations. For the Monte Carlo simulation, 1000 iterations were used and the following changes to the inventory data were made: Each volume was converted into masses by way of the average density of the product. Afterwards, each volume was given a uniform distribution of + /- 10 % of the calculated mass to manage the uncertainty of this transformation. Regarding transportation, both the kilometres driven and the vehicles used are known.

After setting the system boundaries, the right choice of a functional unit is very important (EN ISO 14040:2006, 2009; DIN EN ISO 14044:2021–02, 2021). Different choices are possible in this case study according to the international norm. However, the functional unit of 1 m^2 external area was chosen to enable comparisons with future demolitions (Hafner and Rüter, 2018). The functional unit was chosen to maximize comparison to other studies. Since the number of functional units in the construction field is very versatile, this functional unit was chosen.

The various volumes of waste products were measured and then converted into their weight for the LCA using the average densities of the substance groups. The life cycle inventory can be taken from Table 1 (for module C1 and C4) and Table 2 (for module C2). Details are described in the chapter "Building description".

It can be seen that the entire demolition of the building and transportation of the demolished materials were simulated in the life cycle assessment. Subsequent reuse of the recycled materials was not simulated. The construction and use phase of the building was not modeled, as it is only the consequences of demolition that are of interest in this case study.

3. Results

3.1. Building description

The building under investigation was 9 m wide and 8.6 m long and was not a listed monument. Accordingly, the gross external area is 77.4 m^2, the ridge height is 5.8 m, and the gross volume, including the 10.5 m^2 annexes, is 606.5 m^3. An image of the building before and during demolition can be seen in Fig. 2.

Table 1
Total construction volume of the case study building according to the European waste list, including the density to convert the values;.

Substance group	Waste code	Volume [m^3]	Volume [%]	Density [kg/m^3]
Marble	17 01 07	0.13	0.04	2700
Wallpaper	17 09 04	0.187	0.06	170
Cork	17 09 04	0.192	0.06	480
Glass	17 02 02	0.225	0.07	Reuse
Plaster	17 08 02	0.485	0.16	1300
Bitumen mixture	17 03 02	0.828	0.28	1800
Dispersion paint	17 0904	0.83	0.28	1.5
Tiles / Ceramic	17 01 03	0.884	0.29	2000
Granite	17 01 07	1.925	0.65	1300
Composite	17 09 04	3.949	1.33	reuse
Plastic	17 02 03	4.999	1.69	60
Metal	17 04 01	10.059	3.40	7850
Wood	17 02 01	19.697	6.66	450
Brick	17 01 02	32.503	10.99	1600
Insulation material	17 06 04	39.364	13.31	20
Concrete	17 01 01	179.289	60.66	2200
Total		295.546	100	

It is a solid-construction, multi-story building with a basement. The foundations and load-bearing walls are concreted, the interior consists of brick masonry, and the roof truss is of wooden construction. The total construction volume is given in Table 1, divided into the ten material groups to be separated according to the research question, plus other miscellaneous construction and demolition waste. A total volume of 295,546 m^3 of construction and demolition waste was recorded. These ten material groups make up 97.6% of the total construction volume. Table 1 also includes other material groups from construction and demolition waste recorded at the site, listed under the waste code 17 01 07 and 17 09 04. Cavities in bricks, walls and floors for heating and sewage pipes and electrics were not included. Electrical components, screws and nails were not considered, as they would have been too difficult to detect in a demolished state. Moreover, as the building was built over 60 years ago, it can be assumed that the number of electrical components would be far smaller than in modern facilities and thus irrelevant in terms of their environmental impact.

3.2. Demolition

Each construction element was assigned to a work stage, a pile and a recovery or disposal stage. The building was fully decluttered by the builder. The client hired a janitorial service for two working days for the deconstruction. The demolition process as described in this section was conducted according to established guidelines and without interference from the observer.

A total of 13.877 m^3 of building materials were removed for reuse - equivalent to 4.7 % of the total construction volume - and transported away in four car trips. Mainly metal was reused, as well as individual wooden elements. This was already intended by the owner of the house beforehand, since these elements were on the one hand still in good condition, and on the other hand could be easily removed and reinstalled elsewhere.

The building was gutted over three working days by one skilled worker and one unskilled worker. The building elements were separated into material groups and sorted into different piles in the garden. A total of 23.335 m^3 of building elements were cored - corresponding to 7.9 % of the total construction volume - and transported away in five lorry trips. Afterwards, the building was mechanically demolished from the rear to the front with a demolition and sorting grab connected to a hydraulic crawler excavator over three working days by two skilled

Table 2
Recovery/disposal of material groups after demolition, 1 large passenger car with a maximum transportation capacity of 3.5 t, 2 lorry with a maximum transportation capacity of 26 t, 3 large lorry with a maximum transportation capacity of 40 t.

Substance group	Volume [m^3]	Utilisation	Distance [km]	Number of trips / Means of transport
Construction debris, Concrete, Dispersion paint	187.332	Landfill	22.4	9 trucks[3]
Wood, Plastic, Insulation material, Composite material, Cork, Mixed waste	42.433	Recycling/ Recovery (thermal)	< 54.9	6 trucks[2]
Concrete, Bitumen, Dispersion paint	27.649	Landfill	20.3	2 trucks[2]
Insulation Material	22.477	Landfill	> 54.9	2 trucks[2]
Wood, Metal, Glass, Composite material	11.136	Reuse	17	4 passenger car[1]
Wood, Concrete, Metal	2.741	Reuse	0	Not transported
Metal	0.99	Recycling (material)	> 54.9	1 truck[2]
Granite	0.788	Recycling (material)	22.4	1 truck[3]

Fig. 2. Images of the house before the demolition (left) and while demolishing (right).

workers and one unskilled worker following DIN 18007 (18007, 2000). A total of 258.334 m^3 of elements were mechanically demolished - representing 87.4 % of the total construction volume - and removed in 16 truck trips. The hydraulic excavator consumed around 850 litres of diesel from mechanical demolition to remove the outer basement wall. Table 3 presents a sorting rate calculation for each material group in the research question. The sorting rate indicates as a percentage how cleanly each material group was sorted during demolition. Cork, composites, granite, marble, emulsion paint and wallpaper are listed as well as volumes of accrued mixed waste and building rubble. BV [m^3] stands for the measured construction volume before demolition. The deconstruction of reuse (D [m^3]), gutting (G [m^3]) and the mechanical demolition (M [m^3]) values refer to the unmixed separated building elements in the respective material group. No sorting was carried out for this material group if no value was entered during the work stage.

The highest homogeneity rate for the ten material groups was recorded for wood, with a sorting rate of 91.2 %. A total of 2.522 m^3 of wood was removed for reuse, which corresponds to 12.8 % of the total wood used. 4.869 m^3 of wood was removed from the building by gutting (24.7 %), and 10.573 m^3 was recorded as unmixed by mechanical

Table 3
Sorting rates for building demolition BV: total construction volume, D: deconstruction for reuse, G: gutting, M: mechanical demolition, SQ: sorting rate, 1: concrete (60 m^3) with coating in emulsion paint, 2: concrete without Paint.

Substance group	BV [m^3]	D [m^3]	D [%]	G [m^3]	G [%]	M [m^3]	M [%]	SQ [%]
Wood	19.697	2.522	12.8	4.869	24.7	10.573	53.7	91.2
Metal	10.059	7.9	78.5	0.31	3.1	0.68	8.6	88.4
Bitumen mixture	0.828			0.577	69.7			69.7
Plastic	7.999			3.167	63.4			63.4
Insulation material	39.364			11.19	28.4	10.05	25.5	53.9
Concrete	179.289	2.702	1.5			60.251[1] 27.0722[2]	48.4	49.9
Glass	0.225	0.073	32.4					32.4
Plaster		0.485						0
Brick	32.503							0
Tiles / Ceramic	0.884							0
Cork	0.192			0192	100			100
Composite	3.949	0.68	17.2	1.995	50.5			67.7
Granite	1.925					0.788	40.9	40.9
Marble	0.13							0
Dispersion paint	0.83							0
Wallpaper	0.187							0
Mixed waste				1.035		21.839		
Construction waste					127.082			
Total	295.546	13.877	4.7	23.335	7.9	258.334	87.4	

demolition (53.7 %). The remaining 8.8 % of the wood was part of the mixed waste. Metals achieved the second-highest sorting rate, at 88.4 %. The remainder, recorded as construction waste, consists of cast iron pipes, heating pipes, window grates, railing supports, and metal reinforced concrete. The sorting rate of bituminous mixtures ranks third at 69.7 %. This corresponds to the proportion of separated floor pavement made of mastic asphalt. The bituminous coating on the exterior basement wall (0.141 m^3) was not separated from the wall, and the bonded roofing felt was recorded as mixed waste.

1. The sorting rate for the total building demolition is:
2. 92.3 %, if only the mixed waste is regarded as unsorted material
3. 49.3 % if mixed waste and construction waste are regarded as unsorted material
4. 40.1 % if, in addition, the basement wall with a bituminous coating is considered as unsorted material
5. 19.7 % if, in addition, the concrete with a coat of emulsion paint is regarded as unsorted material

The research question can be answered to the effect that 19.7 % of the building materials used in the demolition of the building investigated was homogeneously recorded into material groups.

3.3. Life cycle inventory

From the demolition of the building and the removal of the sorted waste, a Life Cycle Inventory can be formed. The sorted waste volumes can be taken from Table 3, the transport routes after demolition including the vehicles used can be taken from Table 2. For the Life Cycle Inventory, Table 1 was not used as a basis, as this shows the ideally sorted waste according to the European waste code. In reality, however, the wastes were not sorted so cleanly, so mixtures have to be taken into account. On this basis Table 3 serves as life cycle inventory.

Furthermore, it must be taken into account that the demolition was mainly carried out by hand, but that the use of an excavator consumed 850 l of diesel. These are also to be taken into account.

Additionally, Table 2 shows the distance of the demolition site from the recycling or disposal sites for the respective material groups. It also shows how they were recycled and how large the quantities and the corresponding transportation requirements were. It can be seen that 80.3 % of the total construction volume went to landfills, 14.4 % to thermal recycling, and 0.6 % to material recycling, while 4.7 % was reused. The result is a material recycling rate of 5.3 % in terms of total volumes.

3.4. Life cycle impact assessment

The results of the Life Cycle Assessment correspond to the Impact Assessment according to DIN 14044 and DIN 14040 as well as DIN 15978 (DIN EN ISO 14044:2021–02, 2021; E DIN EN 15978–1:2021–09, 2021; EN ISO 14040:2021–02, 2021). The results are calculated according to the functional unit in square meters external gross area. The results can be taken from Table 4.

The results, which are listed in Table 4, show on the one hand the mean value that emerged as a result of the Monte Carlo simulation for each impact category, and on the other hand the different quartiles to give an impression of the distribution.

The following describes the results for each impact category.

Acidification potential, which describes the increase in the acidity of water and soils (Goedkoop et al., 2013), has a mean value of 0.091 kg SO_2 eq per square metre gross external area of the building. The acidification potential is calculated based on such gases like ammonia, nitrogen oxides and sulphur oxides, which mainly occur through the use of (biological) products (e.g. burning wood, applying fertilisers or burning fuel in combustion engines) (Hauschild et al., 1998). The weight and volume of biological products resulting from the demolition are comparatively low (mainly cork and old wood from the roof framework), as most of the building was made from concrete and bricks. However, transportation of the demolition products results in a significant amount of diesel being burnt in the vehicle engines, resulting in the overall value.

Eutrophication potential describes the increase in nitrogen and phosphorus concentrations in an ecosystem. It is measured in kg PO_4 eq. Some areas of the world, such as Germany, lack sufficient natural nitrogen and phosphorus availability. The resulting massive import of these substances leads to many ecological problems in rivers and lakes, such as the growth of algae, which harms the water quality to the detriment of animal and plant populations. In this case study, the value of this impact category varies between 0.020 and 0.024 kg PO_4 eq, with a mean value of 0.024. Another impact category is global warming potential, which shows that around 96.596 kg of CO_2 eq / m^2 GEA is released. However, most of this is due to material transport to recycling or landfilling. The variations in the results are mainly attributable to variations in the waste volumes.

The photochemical oxidant formation potential, which is formed due to non-methane volatile organic compounds (NMVOC) and NO_x (Goedkoop et al., 2013), varies between 0.557 and 0.595 kg NMVOC. In this case study, NMVOCs are mainly attributable to either transportation or the bitumen from the basement wall, which is placed in a landfill and not further processed. The abiotic depletion potential of the elements is measured in kg Sb eq (see Table 4). Due to the transportation involved in thermal recovery and landfills, the abiotic depletion potential of fossil fuels is comparatively high. It varies between roughly 1838 and 1937 MJ, with a mean of 1886 MJ. The water scarcity footprint assesses the impacts of water consumption based on available water remaining in cubic metres H_2O eq (Boulay et al., 2018). Table 4 shows the results vary by approximately 10 % between the highest and lowest value, with a mean of around 28.7 m^3 H_20 eq.

Finally, the method also includes the ozone depletion potential. It should be noted that this impact factor is not included on the website of EPD International AB (EPD International AB, 2021) but results from the SimaPro method EPD2018. The ozone depletion potential in this case

Table 4
Results of the LCA calculations; results shown are per square metre gross external area of the demolished building, IC = impact category, AP = acidification potential, EP = eutrophication potential, GWP100 = global warming potential, POFC = photochemical oxidant formation potential, ADPE = abiotic depletion potential (mineral resource elements), ADPF = abiotic depletion potential (non renewable fossil energy resources), WSF = water scarcity footprint, ODP = ozone depletion potential.

IC	AP	EP	GWP 100	POFP	ADPE	ADPF	WSF	ODPO
Unit	[kg SO_2 eq]	[kg PO_4 eq]	[kg CO_2 eq]	[kg NMVOC]	[kg Sb eq]	[MJ]	[m^3 H_2O]	[kg CFC-11 eq]
Mean	0.091	0.024	96.596	0.574	0.001	1886.69	28.732	3.226e-05
Min	0.068	0.020	92.839	0.557	0.001	1838.09	26.702	3.184e-05
25 %	0.068	0.023	95.743	0.570	0.001	1873.21	28.230	3.214e-05
50 %	0.084	0.024	96.605	0.574	0.001	1887.05	28.763	3.225e-05
75 %	0.098	0.024	97.491	0.579	0.001	1898.68	29.264	3.237e-05
Max	0.115	0.027	100.122	0.595	0.001	1937.23	30.944	3.268e-05

Table 5
Impact Assessment according to the different modules according to DIN 15978 per squaremeter external Gross Area; AP = acidification potential, EP = eutrophication potential, GWP100 = global warming potential, POFP = photochemical oxidant formation potential, ADPE = abiotic depletion potential elements, ADPF = abiotic depletion potential fossil fuels, WSF = water scarcity footprint, ODP = ozone depletion potential.

Impact category	Unit	Module C1	Module C2	Module C3	Module C4
AP	kg SO2 eq	0.03803776	0.35012354	-0.28635455	-0.00991846
GP	kg PO4— eq	0.00679213	0.08361876	-0.22114483	0.15471302
GWP100	kg CO2 eq	4.30951001	104.575903	-20.2698358	8.0023911
POFP	kg NMVOC	0.03036988	0.45228669	-0.12394434	0.21603956
ADPE	kg Sb eq	2.1629E-05	0.00067158	-1.233E-05	0.00043446
ADPF	MJ	457.099336	1604.41508	-405.334425	231.312791
WSF	m3 eq	0.13850889	5.51489929	-12.0466152	35.0662863
ODP	kg CFC-11 eq	5.8801E-06	1.9432E-05	2.7584E-10	6.9475E-06

study is at 3.226e-05 kg CFC-11 eq. Comparisons with other studies are difficult, as this is a specific case study of a building erected in 1954, based on the EPD2018 method. However, due to the low recycling rates and the ratio of construction material to gross external area, this value is relatively high (for example, Pantini and Rigamonti (2020) and Ruggeri et al. (2019)).

Table 5 shows the influence of demolition on the different modules according to DIN 15978. It is striking that Module 3, waste treatment for recovery, recycling and energy recovery, have exclusively negative values. This is due to two reasons: 1. the module is not complete, as the steps for material recycling could not be simulated, as these were not yet known at the time of the study and 2. as it is a consequential LCA, there are net savings from burning the wood in the German energy mix, as coal would alternatively be burned for energy recovery. Overall, module 2 has the most significant impact on environmental impacts. This is due to the fact that waste has to be transported over longer distances in trucks with internal combustion engines. This creates by far the greatest environmental impact. Module C1, on the other hand, contains only the fuel consumption of the excavator at the construction site. A switch to electric construction site vehicles could significantly improve the climate footprint of demolition overall.

4. Discussion

4.1. Building demolition

The record of the construction elements shows that the material groups amount to 97.6 % of the construction volume. The European Waste Catalogue has proven to be a good orientation for recording total waste quantities. Despite this comprehensive requirement, only 19.7% of these material groups are separated by type, and the recycling rate is 5.3 %. Practically relevant and data-based statements have shown that despite compliance with the specifications for sorting the ten waste fractions according to the Commercial Waste Ordinance, there is a strong deviation from the recycling rate by the Federal Statistical Office and the specifications of the waste hierarchy in the EU Waste Framework Directive and the Closed Substance Cycle Waste Management Act. Recycling in the third place of the waste hierarchy proved difficult in the demolition in question. Even though 70 % of the weight of CDW should be recycled in Germany according to the 3 R principle (Federal Ministry of Justice and Consumer Protection, 2017, 14), this requirement stands in great contrast to the 5.3 % measured in this study. It should be emphasised here that the 5.3 % refers to the total construction volume and not to the percentage by weight. Nevertheless, the discrepancy is high. 71.7 % of the identified building volume consists of concrete and brick (Table 1) and have not been recycled but landfilled. In particular, the heaviest components were not recycled, so the 70 mass- % cannot be achieved in any case. Calculations by Asam et al. (2017) show that, in Germany, depending on the building type, 55–90 % of a building's substance - and in turn the waste material released during demolition - currently consists of concrete and bricks. This century's largest construction waste fraction will be concrete demolition waste (Xia et al., 2020). The diffuse distribution in the building and the heterogeneity, both within the material groups themselves and within often existing material bonding, represent a special problem for generating different material flows. In the present study, although 48.4 % of the concrete was separated from the construction waste during mechanical demolition, the separated concrete had a coating of bitumen and dispersion paint and was thus not completely unmixed (see Table 3). Bricks in the construction waste were found to have an exclusive sorting rate of 0 %. According to a study by Asam et al. (2017), the recycled content of bricks and concrete used in building construction in Germany is less than 1 %. Economic efficiency in separating the ten waste fractions covered in the research question is also rooted in the Commercial Waste Ordinance. The obligation to separate collected materials does not apply if it is technically impossible or economically unreasonable (Federal Ministry of Justice and Consumer Protection, 2017, 8). It is not specified what percentage deviation from the customary costs in the industry is deemed as strongly deviating and thus disproportionate. Therefore, economic unreasonableness cannot be determined with legal certainty, and non-separation can easily be justified to the legislator. In the present study, the other recovery, which ranks second to last in the waste hierarchy, amounts to 14.4 % of the total construction volume through thermal recovery. Failure to separate materials (see **Error! Reference source not found.**) groups during demolition results in them remaining in construction waste. This supports the assumption that subsequent sorting is too costly or impossible for waste fractions not sorted during demolition. However, there is a great deal of research in this area, so it can be assumed that the share of RC building materials in all building materials will increase in the coming years. After demolition, the lack of grade purity and sufficient demand for recycled materials inhibit waste fractions' processing (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2016). In the present study, mixed waste is regarded as unsorted, but it acquires a value concerning the waste hierarchy through its thermal recovery. Thermal recycling of mixed waste saves landfill space, and the separate formation of mixed waste and construction waste results in an added value. This contrasts with conventional demolition, where construction waste consists entirely of a heterogeneous mixture of all building materials used in the demolished building. 80.3 % of the building volume is landfilled and thus categorised as the disposal on the last level of the waste hierarchy for waste management measures. The materials deposited include construction waste with 2.1 % slightly adhering non-mineral foreign components in plaster, metal, glass, emulsion paint and wallpaper. Bitumen mixtures and insulating material are also landfilled. It is currently impossible to completely dispense with landfilling in Germany, as no large-scale recycling processes exist for artificial mineral fibres, gypsum boards, or fibre cement boards. There is a ban on the reuse of glass wool extracted in the present study, classified as carcinogenic (Seit, 2015). This shows that sorting materials in a demolition do not necessarily save resources or landfill space. The high proportion of landfill materials in the building volume contrasts sharply with the waste balance set by the Federal Statistical Office, according to which 88–90 % of construction and demolition waste was recycled each year between 2006 and 2017 (Destatis, 2020b). This discrepancy is due to the calculation model used in the official statistics, which follows an input-oriented model for the first disposal stage, so the calculated rates refer to the plant input. According to the formula for the recycling rate given by the Federal Statistical Office, the recycling rate for the present demolition is 82.2 %, since only 17.8 % went directly to landfill (bituminous mixtures, fibre cement panels, and glass wool). The remaining materials were also landfilled, as shown in Table 2, but were first run through a waste sorting facility. As a result, they no longer count as landfill waste under the law, but as recycled (Federal Ministry of Justice and Consumer Protection, 2012). This results in a large overstatement of the recycling rate (Destatis, 2020b). The results enable the assertion that not all components can be removed or reused in a non-destructive manner and that a truly circular value creation, in which construction and demolition are understood as a closed-loop, is not at the level that the official statistics imply.

4.2. Evaluation of the life cycle assessment

As mentioned above, it is complex to classify LCA results in the literature, as they represent individual case studies, which vary significantly, even within a single country, in terms of materials, processes, and transportation. It must also be taken into account that the present study was designed and conducted as a consequential LCA. However, most sustainability studies in the construction sector are designed as attributional LCA. Many studies also use environmental product declarations (EPDs), often designed as attributional LCA. Therefore, comparisons with other studies are often impossible, as outlined in DIN 14040 (EN ISO 14040:2021–02, 2021). Especially the comparison between consequential and attributional LCAs is actually impossible, but shall be done here for purely illustrative purposes anyway.

A look at the DGNB system for deconstruction (DGNB, 2020) shows that there are points given for demolitions if an LCA is carried out, but this only concerns modules C1 and C2 (i.e. only deconstruction and transport, but not waste recycling and disposal) and does not include a benchmark. An LCA is also carried out in the criteria catalogue for new buildings (DGNB, 2018), and benchmark values are also provided. Still, these do not include deconstruction and transport within their system boundaries. If a comparison is still desired, the benchmark values show a GWP of 9.4 kg CO2 eq/ (m2 *a). Conversion of the values shown here into DGNB-compliant ones results in 1.463 kg CO_2 eq/ (m^2 * a), with a building age at the time of demolition of 66 years. This shows that the demolition has a comparatively high share of the total reference value and should not be underestimated. The same can be concluded for the other environmental categories.

When the results are processed according to DIN 15978 (cf. Table 5), it becomes even more apparent that the greatest influence across all environmental categories (except WSF) is exported waste. The actual demolition on site has only a comparatively small environmental impact, while in module C4, sorting plants still influence the final result. These were interposed for some waste streams before the waste was landfilled.

Even though these results were expected, the magnitude was surprising. The Monte Carlo simulation shows that significant variations are possible, especially with the GWP100. However, these emissions are likely to be reduced significantly in the future when electric or biofuel-powered vehicles are in use (Baral et al., 2021). For the LCA analysis, it was necessary to locate the different materials from Table 3 in the Ecoinvent database. Due to the age of the building, the composition of some materials had to be assumed. This results in uncertainty, which could influence the overall results. An attempt was made to minimise this uncertainty by presenting the distribution through quartiles of possible results in the Monte Carlo simulation. The same applies to the subsequent processes. However, there is still a lack of certainty concerning the results. Indeed, both problems often occur with LCAs, and overall they do not constitute quality restrictions (Ecoinvent, 2019). Furthermore, the results do not allow any assertions to be made regarding general demolitions of German detached residential homes, as this is a specific case study. It is always difficult to draw general conclusions from LCA studies as they tend to refer to particular products or processes based on different scopes and study objects (DIN EN ISO 14044:2021–02, 2021).

Nevertheless, a comparison with Hafner and Schäfer (2017) (e.g. buildings of concrete or brick and mineral wool) shows that the GWP values for these demolitions are significantly lower than those measured here. In Hafner and Schäfer (2017) study, all investigated buildings were constructed after 2000 and reflected the current state of the art. This greatly influences the outcome and reduces the possibility of direct, whole comparisons. It should be noted that the overall impact of demolition on a building's life cycle is far smaller than the influence of both the construction and use phase of the building (Gardner et al., 2020). As Albertí et al. (2019) have previously shown, life cycle assessments only retain their validity for a short period, which is an obstacle in assessing the present for the demolition of a building in the distant future. This problem, which not only occurs in the building sector but also, for example, in the scaling of future industrial processes, is currently a subject to discussion in the LCA community with the keyword: "Prospective LCA" (e.g. Pizzol et al. (2021), Bergerson et al. (2020) and Arvidsson et al. (2018)).

5. Conclusion

Many aggregate statistics on resource use exist in Germany, but few specifically address the demolition of postwar buildings, although this will increase in importance and frequency in the coming years. Therefore, this study provides valuable insight into the demolition details of single-family homes in Germany, both process and environmental impact.

Contrary to the demonstrated importance of the construction sector, a circular economy based on high-quality recycling of demolition waste has not yet been achieved on an industrial scale. The present case study relates to the demolition and associated processes of a detached residential house in Southern Germany, built in the 1950s. Practically relevant and data-based statements showed that despite complying with the specifications for sorting the ten waste fractions according to the Commercial Waste Ordinance, the recycling rate achieved is far lower than the recycling rate required by the Federal Statistical Office and the specifications of the waste hierarchy in the EU Waste Framework Directive and the Closed Substance Cycle Waste Management Act (Federal Ministry of Justice and Consumer Protection, 2017). Furthermore, the LCA demonstrated the environmental impacts associated with the demolition of the building. It was shown that the destruction of an old building has a tremendous environmental impact that harms both the climate and the environment.

Also, in this study it must be considered that a large part of the recorded GWP emissions resulted from the transport of the demolition material. If the transport is converted to battery electric vehicles with renewable electricity, the emissions are significantly reduced. The same applies to the abiotic depletion potential (non-renewable fossil energy resources) (ADPF) and the water scarcity footprint. Other major impacts are due to the large mass of both the concrete and the insulation materials. Overall, metal has a small influence on the result due to the recycling and reuse share. Marble, wallpaper, cork, and plaster also have no significant influence on the final result due to their low mass in relation to other materials.

Even though regulations exist to reduce landfill materials and their environmental impact, the current legislation lacks practical realization. It requires further improvements by more accurate monitoring and statistics, as shown by this study. The current statistical documentation of the first stage after demolition instead of final waste disposal hinders public awareness of building waste management's improvement towards a circular and environmentally friendly economy. Overall the high volumes of construction and demolition waste remain a considerable challenge and should be answered more consequentially.

Among the demolition companies, it was found that many employees do not have a clear idea of sustainability, sustainability strategies and current developments. This emerged in the interviews but was not the study's primary objective. Lambrechts et al. (2019) already suggest that knowledge of individual sustainability competence is unevenly distributed in the construction sector. However, focus Lambrechts et al. on building construction. A structured study on personal sustainability competence for companies in the demolition and recycling sector could reveal previously hidden, missing knowledge of the actors. Based on this, improvements in communication could contribute to a higher sustainability and recycling rate in the construction sector. A focus on non-academic personnel is of particular interest because this target group has hardly been studied so far, as Lambrechts et al.also points out.

Data Availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.clwas.2022.100056.

References

Albertí, J., Raigosa, J., Raugei, M., Assiego, R., Ribas-Tur, J., Garrido-Soriano, N., Zhang, L., Song, G., Hernández, P., Fullana-i-Palmer, P., 2019. Life cycle Assessment of a solar thermal system in Spain. eco-Des. Altern. Deriv. Clim. Change Scenar. Span. Chin. Natl. Lev. 47. https://doi.org/10.1016/j.scs.2019.101467

Anand, C.K., Amor, B., 2017. Recent developments, future challenges and new research directions in LCA of buildings: a critical review. Renew. Sustain. Energy Rev. 67, 408–416. https://doi.org/10.1016/j.rser.2016.09.058

Arvidsson, R., Tillman, A.-M., Sandén, B.A., Janssen, M., Nordelöf, A., Kushnir, D., Molander, S., 2018. Environmental assessment of emerging technologies: recommendations for prospective LCA. J. Ind. Ecol. 22, 1286–1294. https://doi.org/10.1111/jiec.12690

Asam, C., Haferkorn, W., Deilmann, C., Reichenbach, J., Krauß, N., Gruhler, K. (Eds.), 2017. Materialströme im Hochbau: Potenziale für eine Kreislaufwirtschaft, 2016th ed. Bundesinstitut für Bau- Stadt- und Raumforschung im Bundesamt für Bauwesen und Raumordnung, Bonn, 86 pp.

Baral, N.R., Asher, Z.D., Trinko, D., Sproul, E., Quiroz-Arita, C., Quinn, J.C., Bradley, T.H., 2021. Biomass feedstock transport using fuel cell and battery electric trucks improves lifecycle metrics of biofuel sustainability and economy. J. Clean. Prod. 279, 123593. https://doi.org/10.1016/j.jclepro.2020.123593

Bashir, F.M., Ahmad, M.H., Sale, A.U., Abdullahi, A., Aminu, A.S., 2016. Fundamental elements for sustainable design. Indian J. Sci. Technol. 9. https://doi.org/10.17485/ijst/2016/v9i46/107128

Bergerson, J.A., Brandt, A., Cresko, J., Carbajales-Dale, M., MacLean, H.L., Matthews, H.S., McCoy, S., McManus, M., Miller, S.A., Morrow, W.R., Posen, I.D., Seager, T., Skone, T., Sleep, S., 2020. Life cycle assessment of emerging technologies: evaluation techniques at different stages of market and technical maturity. J. Ind. Ecol. 24, 11–25. https://doi.org/10.1111/jiec.12954

B.F.R. Recycling, 2015. Appendix 8 - Case study of dismantling and disposal concept (Anhang 8 - Fallbeispiel Rückbau- und Entsorgungskonzept). Bundesministerium des Innern, für und Heimat; Bundesministerium der Verteidigung. 〈https://www.bfr-recycling.de/anhang_8.html〉 (accessed 13 January 2021).

Biswas, W.K., 2014. Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. Int. J. Sustain. Built Environ. 3, 179–186. https://doi.org/10.1016/j.ijsbe.2014.11.004

Boulay, A.-M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A.V., Ridoutt, B., Oki, T., Worbe, S., Pfister, S., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE. Int J. Life Cycle Assess. 23, 368–378. https://doi.org/10.1007/s11367-017-1333-8

BREEAM, 2018. BREEAM UK New Construction: Technical Manual SD5078: BREEAM UK New Construction 2018 2.0. BRE. www.breeam.com (accessed 3 August 2019).

CASBEE, 2015. An overview of CASBEE. http://www.ibec.or.jp/CASBEE/english/overviewE.htm (accessed 3 August 2019).

Cruz Rios, F., Grau, D., Chong, W.K., 2019. Reusing exterior wall framing systems: a cradle-to-cradle comparative life cycle assessment. Waste Manag. (N. Y., N. Y.) 94, 120–135. https://doi.org/10.1016/j.wasman.2019.05.040

Curran, M.A., Mann, M., Norris, G., 2005. The international workshop on electricity data for life cycle inventories. J. Clean. Prod. 13, 853–862. https://doi.org/10.1016/j.jclepro.2002.03.001

Destatis, 2020a. Environmental economic accounts (Umweltökonomische Gesamtrechnungen). Federal Statistical Office. 〈https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/_inhalt.html〉 (accessed 13 January 2021).

Destatis, 2020b. Waste balance (waste generation/fate, waste intensity, waste generation by economic sector) 2018 (Abfallbilanz (Abfallaufkommen/ -verbleib, Abfallintensität, Abfallaufkommen nach Wirtschaftszweigen) 2018). Wiesbaden.

DGNB, 2020. DGNB System - Criteria Catalog Building Deconstruction: Material Flow Balance Sheet (DGNB System - Kriterienkatalog Gebäude Rückbau): Materialstrombilanz (ENV1-R).

DGNBC.V., 2018. Das DGNB System: Kriterienkatalog Gebäude Neubau. 〈https://www.dgnb-system.de/de/gebaeude/neubau/kriterien/〉 (accessed 28 January 2021).

Eberhardt, L.C.M., Birgisdottir, H., Birkved, M., 2019. Potential of Circular Economy in Sustainable Buildings. IOP Conf. Ser.: Mater. Sci. Eng. 471, 92051. https://doi.org/10.1088/1757–899X/471/9/092051.

Ecoinvent, 2019. Ecoinvent database. 〈https://www.ecoinvent.org/〉 (Accessed 5 February 2021).

EPD International AB, 2021. Method EPD 2018. 〈https://www.environdec.com/about-us〉 (accessed 03:02:2021).

European Commission, 2010. International reference life cycle data system (ILCD) handbook - general guide for life cycle assessment - detailed guidance. Publ. Off., Luxemb. 398.

European Parliament, 2018. Waste Management in the EU: Facts and Figures. European Parliament. https://www.europarl.europa.eu/news/de/headlines/society/20180328STO00751/abfallwirtschaft-in-der-eu-zahlen-und-fakten (accessed 7 February 2022).

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2016. German Resource Efficiency Programm 2: Programme for the sustainable use and conservation of natural resources. Berlin.

Federal Ministry of Education and Research, 2018. Resource-efficient circular economy (Ressourceneffizente Kreislaufwirtschaft). BMBF. 〈https://www.fona.de/medien/pdf/Ressourceneffiziente_Kreislaufwirtschaft.pdf?m＝1548322553&〉 (accessed 15 January 2021).

Federal Ministry of Justice and Consumer Protection, 2012. Act to Promote the Circular Economy and Ensure Environmentally Sound Waste Management (Gesetz zur Förderung der Kreislaufwirtschaft und Sicherungder umweltverträglichen Bewirtschaftung von Abfällen): Kreislaufwirtschaftsgesetz - KrWG.

Federal Ministry of Justice and Consumer Protection, 2017. Ordinance on the Management of Commercial Municipal Waste and Certain Construction and Demolition Waste (Verordnung über die Bewirtschaftung von gewerblichen Siedlungsabfällen und von bestimmten Bau- und Abbruchabfällen): (Gewerbeabfallverordnung - GewAbfV).

Federal Statistical Office, 2021. Recovery of recycled building materials by area in Germany in 2018 (Verwertung von Recycling Baustoffen nach Bereich in Deutschland im Jahr 2018). Statistisches Bundesamt. 〈https://de.statista.com/statistik/daten/studie/743227/umfrage/verwertung-von-recycling-baustoffen-nach-bereich-in-deutschland/〉 (accessed 7 February 2022).

Gálvez-Martos, J.-L., Styles, D., Schoenberger, H., Zeschmar-Lahl, B., 2018. Construction and demolition waste best management practice in Europe. Resour., Conserv. Recycl. 136, 166–178. https://doi.org/10.1016/j.resconrec.2018.04.016

Gardner, H.M., Hasik, V., Banawi, A., Olinzock, M., Bilec, M.M., 2020. Whole building life cycle assessment of a living building. J. Archit. Eng. 26, 4020039. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000436

Geldermans, R.J., 2016. Design for change and circularity – accommodating circular material & product flows in construction. Energy Procedia 96, 301–311. https://doi.org/10.1016/j.egypro.2016.09.153

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. de, Struijs, J., van Zelm, R., 2013. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Ministerie van Volkshuisvesting. 〈https://www.rivm.nl/en/life-cycle-assessment-lca/downloads〉 (accessed 6 February 2021).

Hafner, A., Rüter, S., 2018. Method Assess. Natl. Implic. Environ. Impacts Timber Build. - Ex. Study Resid. Build. Ger. 50, 139–154. https://doi.org/10.22382/wfs-2018-047

Hafner, A., Schäfer, S., 2017. Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level. J. Clean. Prod. 167, 630–642. https://doi.org/10.1016/j.jclepro.2017.08.203

Hauschild, M., Wenzel, H., Alting, L., 1998. Scientific Background, first ed. Chapman & Hall, London, pp. 565.

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I. (Eds.), 2017. Life cycle assessment: Theory and practice. Springer, Cham, 1216 pp.

Hiete, M., Kühlen, A., Schultmann, F., 2011. Analysing the interdependencies between the criteria of sustainable building rating systems. Constr. Manag. Econ. 29, 323–328. https://doi.org/10.1080/01446193.2011.558105

Huang, B., Wang, X., Kua, H., Geng, Y., Bleischwitz, R., Ren, J., 2018. Construction and demolition waste management in China through the 3R principle. Resour., Conserv. Recycl. 129, 36–44. https://doi.org/10.1016/j.resconrec.2017.09.029
Illankoon, I., Tam, V., Le, K.N., 2017. Environmental, Economic, and Social Parameters in International Green Building Rating Tools 143. https://doi.org/10.1061/(ASCE)EI.1943–5541.0000313.
Jain, S., Singhal, S., Pandey, S., 2020. Environmental life cycle assessment of construction and demolition waste recycling: a case of urban India. Resour., Conserv. Recycl. 155, 104642. https://doi.org/10.1016/j.resconrec.2019.104642
Knappe, F., Lansche, J., 2010. Optimizing the utilization of mineral construction waste in Baden-Württemberg (Optimierung der Verwertung mineralisicher Bauabfälle in Baden-Württemberg). Ministry of the Environment Baden-Württemberg. 〈https://www.lubw.baden-wuerttemberg.de/documents/10184/148174/bauabfaelle_bericht_end_ifeu.pdf/c3832a4e-54dc-4840–9cbe-cdfb09ac4568〉 (accessed 7 February 2022).
Koch, E. (Ed.), 1997. Land recycling through controlled deconstruction: resource-saving demolition of buildings and industrial plants: Flächenrecycling durch kontrollierten Rückbau: Ressourcenschonender Abbruch von Gebäuden und Industrieanlagen. Springer, Berlin, pp. 259.
Koutamanis, A., van Reijn, B., van Bueren, E., 2018. Urban mining and buildings: a review of possibilities and limitations. Resour., Conserv. Recycl. 138, 32–39. https://doi.org/10.1016/j.resconrec.2018.06.024
Lambrechts, W., Gelderman, C.J., Semeijn, J., Verhoeven, E., 2019. The role of individual sustainability competences in eco-design building projects. J. Clean. Prod. 208, 1631–1641. https://doi.org/10.1016/j.jclepro.2018.10.084
Lee, S., Tae, S., Roh, S., Kim, T., 2015. Green template for life cycle assessment of buildings based on building information modeling: focus on embodied environmental impact. Sustainability 7, 16498–16512. https://doi.org/10.3390/su71215830
Lichtenberg, J., 2004. slimbouwen©, a rethinking of building, a strategy for product development. Plea2004 - The 21th Conference on Passive and Low Energy Architecture, 2004, Einhoven, the Netherlands.
Loga, T., Stein, B., Diefenbach, N., Born, R., 2015. German residential building typology (Deutsche Wohngebäudetypologie): Example measures for improving the energy efficiency of typical residential buildings (Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden), 2nd ed. IWU, Darmstadt.
Matthias Buyle, 2018. Towards a structured consequential modelling approach for the construction sector: the Belgian case. A fairy tale on methodological choices in LCA. Unpublished.
McDonough, W., Braungart, M., 2002. Cradle to Cradle: Remaking the Way We Make Things, first ed. North Point Press, New York, NY, pp. 193.
Metzger, S., Katy, J., Walikewitz, N., 2019. Housing and renovation (Wohnen und Sanieren): Empirical residential building data since 2002 (Empirische Wohngebäudedaten seit 2002). Dessau-Roßlau.
Mutel, C., 2017. Brightway: an open source framework for life cycle assessment. JOSS 2, 236. https://doi.org/10.21105/joss.00236
Nadazdi, A., Naunovic, Z., Ivanisevic, N., 2022. Circular economy in construction and demolition waste management in the western balkans: a sustainability assessment framework. Sustainability 14, 871. https://doi.org/10.3390/su14020871
Pantini, S., Rigamonti, L., 2020. Is selective demolition always a sustainable choice? Waste Manag. 103, 169–176. https://doi.org/10.1016/j.wasman.2019.12.033
Pizzol, M., Sacchi, R., Köhler, S., Anderson Erjavec, A., 2021. Non-linearity in the life cycle assessment of scalable and emerging technologies. Front. Sustain 1, 611593. https://doi.org/10.3389/frsus.2020.611593
PRé, 2020. SimaPro.
Ruggeri, M., Pantini, S., Rigamonti, L., 2019. Assessing the impact of selective demolition techniques on C&D waste management. IOP Conf. Ser.: Earth Environ. Sci. 296, 12005. https://doi.org/10.1088/1755–1315/296/1/012005.
Schiller, G., Ortlepp, R., Krauß, N., 2015. Mapping of the Anthropogenic Stockpile in Germany for the Optimization of Secondary Raw Materials Management (Kartierung des Anthropogenen Lagers in Deutschland zur Optimierung der Sekundärrohstoffwirtschaft). Environmental Research Plan of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Umweltforschungsplan des Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit). Dessau-Roßlau.
Seit, H., 2015. Waste and disposal law for construction and expansion - Bavaria (Abfall- und Entsorgungsrecht für Bau und Ausbau - Bayern), 2nd ed. VOB-Verlag Ernst Vögel, Stamsried.
Thibodeau, C., Bataille, A., Sié, M., 2019. Building rehabilitation life cycle assessment methodology–state of the art. Renew. Sustain. Energy Rev. 103, 408–422. https://doi.org/10.1016/j.rser.2018.12.037
United Nations General Assembly, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. United Nations. 〈https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E〉 (Accessed 13 January 2021).
Vares, S., Hradil, P., Sansom, M., Ungureanu, V., 2020. Economic potential and environmental impacts of reused steel structures. Struct. Infrastruct. Eng. 16, 750–761. https://doi.org/10.1080/15732479.2019.1662064
Weidema, B.P., Pizzol, M., Schmidt, J., Thoma, G., 2018. Attributional or consequential life cycle assessment: a matter of social responsibility. J. Clean. Prod. 174, 305–314. https://doi.org/10.1016/j.jclepro.2017.10.340
Weidema, B.P., Simas, M.S., Schmidt, J., Pizzol, M., Løkke, S., Brancoli, P.L., 2020. Relevance of attributional and consequential information for environmental product labelling. Int J. Life Cycle Assess. 25, 900–904. https://doi.org/10.1007/s11367-019-01628-4
Wouterszoon Jansen, B., van Stijn, A., Gruis, V., van Bortel, G., 2020. A circular economy life cycle costing model (CE-LCC) for building components. Resour., Conserv. Recycl. 161, 104857. https://doi.org/10.1016/j.resconrec.2020.104857
Xia, B., Ding, T., Xiao, J., 2020. Life cycle assessment of concrete structures with reuse and recycling strategies: a novel framework and case study. Waste Manag. 105, 268–278. https://doi.org/10.1016/j.wasman.2020.02.015
Zhang, C., Hu, M., Di Maio, F., Sprecher, B., Yang, X., Tukker, A., 2022. An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. Sci. Total Environ. 803, 149892. https://doi.org/10.1016/j.scitotenv.2021.149892