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ENVIRONMENTAL ASSESSMENT OF RESIDENTIAL BUILDING RENOVATIONS

ENVIRONMENTÁLNÍ HODNOCENÍ REKONSTRUKCÍ OBYTNÝCH BUDOV

DISERTAČNÍ PRÁCE
DOCTORAL THESIS

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Abstract

One of the methods utilized for quantification of environmental impacts of human activities is Life-Cycle Assessment (LCA). This dissertation applies the method on renovations of residential buildings in the Czech Republic. The reason is high potential for environmental savings in existing building stock and lack of such works in the Czech conditions. Therefore the dissertation deals with LCA of building renovations to increase the knowledge in this field. Moreover it also questions and evaluates accuracy of building LCA in general to increase understanding of differences and inaccuracies that are often admitted, but seldom analysed in literature.

The dissertation includes five LCAs of two case studies: a block-of-flats in Brno and a terraced house in a nearby village. First case study includes LCAs of the original state and renovation of the block-of-flats. The second case study describes LCAs of the original state, partial reconstruction or demolition and new construction of the terraced house. The LCAs are performed in two software tools: Eco-Bat 4.0 and GaBi 4. Detailed models of the evaluated buildings are based on available designs. Environmental impacts are calculated in four impact categories predefined in Eco-Bat 4.0 to enable comparison of results: Ecological Scarcity, Cumulative Energy Demand (or Primary Energy in GaBi 4), Non-Renewable Energy and Global Warming Potential. The accuracy of the performed LCAs is tested in up to 324 different scenario combinations considering variable service life of building materials, construction waste quantities, waste management and transport distances.

Generally, the results confirm environmental efficiency of building renovations. The renovation of block-of-flats results in 17.39% average reduction of total environmental impacts. Demolition and new construction of the terraced house result in 76.83% average savings. However, the variation of results is rather high due to tested scenario combinations: up to 56.06%. Further research is necessary to improve this issue.

Keywords

Building Renovation, Environmental Impacts, Life-Cycle Assessment, Residential Building, Sustainability, Sustainable Development

Abstrakt

Jednou z metod využívaných pro hodnocení dopadů lidských činností na životní prostředí je Life-Cycle Assessment (LCA). V této disertační práci je metoda LCA aplikována na renovace obytných budov v České Republice. Důvodem je velký potenciál pro snížení dopadů na životní prostředí v rámci existujícího bytového fondu. Cílem této práce ale není jen kvantifikace potenciálních úspor. Práce se také zabývá přesností zvolené hodnotící metody a vhodnosti její aplikace pro zvolené cíle, což jsou témata v literatuře většinou opomíjená.

V práci jsou hodnoceny dvě případové studie – bytový dům v Brně a řadový rodinný dům v jedné z okolních obcí – hodnotící dopady životního cyklu budov na životní prostředí. První obsahuje dvě LCA studie hodnotící původní a renovovaný stav bytového domu. Druhá obsahuje tři LCA studie hodnotící původní stav rodinného domu, nerealizovaný návrh jeho rekonstrukce a realizovanou demolici a novostavbu. Dopady na životní prostředí jsou hodnoceny ve čtyřech kategoriích: Ecological Scarcity, Cumulative Energy Demand (Primary Energy), Non-Renewable Energy a Global Warming Potential. Přesnost LCA studií je v práci ověřována zavedením čtyř proměnných a použitím dvou různých softwarů (až 324 různých výpočetních kombinací).

Výsledky práce potvrzují, že renovace mají za následek snížení dopadů staveb na životní prostředí. V případě bytového domu dosáhla průměrná úspora až 17,39 %. V případě rodinného domu dokonce až 76,83 %. Nicméně se také projevil značný vliv ověřovaných proměnných. Rozdíly mezi výsledky jednotlivých výpočetních kombinací dosáhly až 56,06 %. Před širší aplikací metody LCA v oblasti renovací obytných budov je tedy nutný další výzkum, který by zvýšil její přesnost.

Klíčová slova

Environmentální dopady, obytné budovy, posuzování životního cyklu, renovace staveb, udržitelnost, udržitelná výstavba

Bibliographic reference

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Declaration

I hereby declare that I have worked on this dissertation on “Environmental Assessment of Residential Building Renovations” independently and that I have provided references to all information sources I used.

In Brno on 10th January 2019

………………………………

Ing. Karel Struhala

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Table of content

1. Introduction

This section introduces issues of sustainability and environmental impacts of human activities. It also describes key role of the construction industry in mankind's strive towards sustainable society and introduces several options that could lead to increased efficiency of buildings: from legal regulation to voluntary certification. Lastly, this section briefly mentions the need for precise quantification of environmental impacts and introduces Life-Cycle Assessment (LCA) as a method commonly utilized for this purpose.

1.1. Challenges We Face

Technological advance combined with population growth (UN, 2017) causes that mankind can more than ever before affect Earth's ecosystems. Full scale of mankind's involvement in the ongoing climate change is hard to measure or predict. There are authors that belittle or even deny mankind`s responsibility, e.g. (Klaus, 2007). Other authors go as far as to compare the impacts of mankind's accelerating development with prehistoric extinction events, (Nee, 2004). In her book The Sixth Extinction, An Unnatural History journalist Elisabeth Kolbert describes that the biodiversity is diminishing ever since mankind started to spread from its African cradle, (Kolbert, 2014). Scientific evidence seems to confirm this latter opinion.

The latest IPCC report states that "*Human influence on the climate system is clear, and recent anthropogenic emissions of GHGs are the highest in history. Recent climate changes have had widespread impacts on human and natural systems*", (Pachauri, 2014). Measurements presented in the report show that concentration of GHGs in the atmosphere is steadily rising since the industrial revolution. In particular the CO_2 (probably the most well-known GHG) levels increased from approximately 280 ppm around 1850 (Pachauri, 2014) to more than 400 ppm in 2017 (NOAA-ESRL, 2017). The relation between GHG concentrations and the global warming is well known to general public. Knowledge about threats to other parts of the environment is not so widespread. Therefore general public in Europe and North America was shocked by recent reports showing the most remote islands in the Pacific Ocean littered with plastic waste. The reports show that even microparticles of plastic waste significantly influence marine fauna and flora, (Klein, 2017). The situation on the land is no different. Local ecosystems are endangered by deforestation, agriculture or construction works. R. Bailis et al. presented a study (Bailis, 2015) showing unsustainability of current levels of wood harvesting and deforestation. Struhala et al. (Struhala, 2012) mention that approximately 250 km^2 of forests or agricultural lands were covered by new residential buildings in the Czech Republic between 1997 and 2009. This may seem insignificant compared with global statistics (e.g. (UNEP, 2003)), however it almost equals the area of the second largest city in the country. Above mentioned information illustrate the need for social and technological changes that would guarantee sustainability of mankind on Earth.

1.2. Global Response

Discussion about the impacts of human activities on the Earth’s ecosystems is going on since the second half of the 20th century. United Nations Conference on the Human Environment in Stockholm (also known as Stockholm Conference) in 1972 can be considered one of the first steps in mankind’s strive for *“… the preservation and improvement of the human environment, for the benefit of all the people and their posterity”*, as defined in the resulting declaration (UN, 1972).

Despite initial hopes, mankind was unable to fulfil the principles defined during the Stockholm Conference in the following decade. This lead to establishment of WCED in 1983, (Borowy, 2014). The results of WCED`s work include a report entitled Our common Future from 1987. This report summarized the issues related with what we now describe as “sustainable development”. Actually, the (currently well-known) definition of the sustainable development was used in the report for the first time. It defined it as *“… development that meets the needs of the present without compromising the ability of future generations to meet their own needs”*, (WCED, 1987).

Other major events, conferences and documents followed. Vienna Convention for the Protection of the Ozone Layer in 1985 and subsequent Montreal Protocol in 1987 meant the beginning of the efforts for the restoration of ozone layer that was significantly damaged by release of specific carbon compounds (e.g. hydrocarbons) into the atmosphere, (WMO, 2014).

United Nations Conference on Environment and Development in Rio de Janeiro in 1992 resulted in release of Agenda 21 and ratification of United Nations Framework Convention on Climate Change. The former is a voluntary document addressing sustainable human development, (UN, 1992a). The latter is an international treaty focusing on the impact of GHG on climate change. The treaty should help *"… stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"*, (UN, 1992b). The treaty entered into force in 1994, after the ratification in 50th UN member state.

The ratifiers of the UNFCCC treaty hold annual conferences to assess the progress in dealing with the climate change since 1995. The 1997 conference in Japan resulted in adoption of the well-known Kyoto Protocol. This treaty further extends the original UNFCCC. It sets limits to the production of GHG emissions for the developed countries, because the ratifiers agree that *"… the developed countries have the major share on emissions of greenhouse gases…"*, (UN, 1997). Most of the affected countries promised to reduce their GHG production by 20% till 2020 compared with the state in 1990. Fulfilling of the Kyoto Protocol is closely monitored by scientists, politicians and general public alike.

The Kyoto Protocol has some temporal, legal and scientific limitations. The greatest is that some countries have not adopted it (e.g. USA) and others withdrawn later (e.g. Canada in 2012). Another problem is that some GHGs remain in the atmosphere for long time. IPCC simulations show (see Figure 1) that atmospheric GHG concentrations would rise by at least 10% till 2100, even if mankind would stop producing GHGs altogether, (IPCC, 2014). Therefore new treaties followed in the wake of the Kyoto Protocol as the knowledge about the climate change increased. Most recently it was the Paris Agreement adopted in December 2015. The treaty binds the ratifiers to take measures *"… holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change"*, (UNFCCC, 2015). With this target the Paris Agreement reflects complexity of the climate-change-related problems better than any previous international treaty. On the other hand it should be highlighted that neither the Paris Agreement nor the preceding treaties specify the means to reach the defined targets. This could be considered as an opportunity for new research and development of suitable methods and technologies.

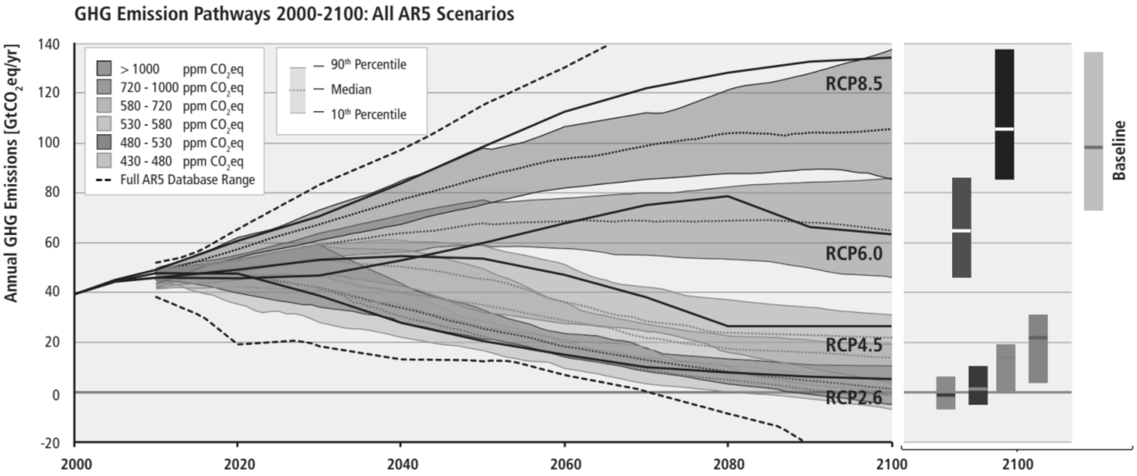


Figure 1. Possible scenarios of global GHG emissions and atmospheric GHG concentrations (represented by CO_2 equivalents) according to ICPP. (IPCC, 2014)

1.3. What's Happening in the EU?

Previously mentioned pledges and treaties are being implemented into international and national laws, ordinances and standards. In the EU it is i. a. the Green Paper on Energy Efficiency or Doing More with Less. This document released by the EC in 2005 says that *"… there would be very good reasons for the European Union to make a strong push towards a re-invigorated programme promoting energy efficiency at all levels of European society…",* (EC, 2005). The reasons included: increased competitiveness of the EU, increased employment rates in all member states, environment protection and security of energy supply. EC further pursued the energy efficiency in Action Plan for Energy Efficiency in 2006. There the EC highlighted significant potential for energy savings in several sectors of the industry and society, namely: *"… residential and commercial buildings with savings potentials estimated at 27 % and 30 % respectively, the manufacturing industry, with the potential for a 25 % reduction, and transport, with the potential for a 26 % reduction in energy consumption"*, (EC, 2006). The document presented general guidelines for achieving such savings, e.g. improving energy performance of buildings or changing the consumer behaviour.

More recently the EC published EUROPE 2020 A strategy for smart, sustainable and inclusive growth (EC, 2010) and A Roadmap for moving to a competitive low carbon economy in 2050, (EC, 2011). Both acts confirm EU`s will to pursue the goal of sustainability through increased investments in research and development, implementation of new technologies or changes of citizen behaviour. Especially the reduction of GHG emissions is emphasised. The “roadmap” (EC, 2011) says that EU could achieve 80% reduction of CO_2 emissions in 2050 compared to the 1990 baseline – see Figure 2. The highest reduction of CO_2 emissions is expected in energy production and distribution. Up to 99% savings should be achieved i. a. by replacing the traditional energy sources (like coal and oil) by RES. The least savings (up to 49%) are expected in agriculture.

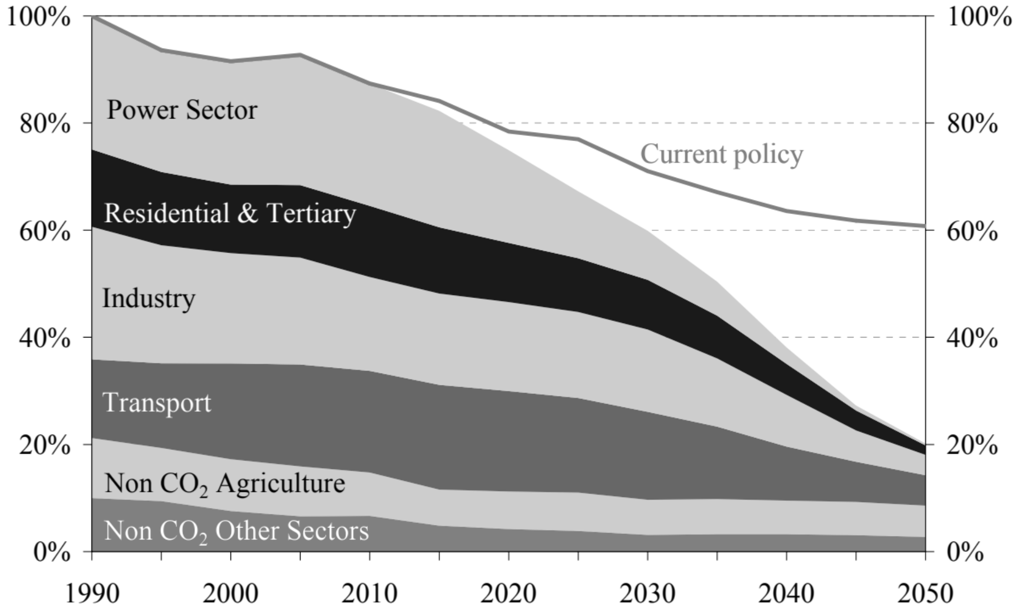


Figure 2. Plan for 80% reduction of CO_2 emissions in the EU till 2050. (EC, 2011)

Progress in pursuit of the declared environmental goals is closely monitored and periodically published by the EC. Latest report (EC, 2015) estimates that average GHG emissions in the whole EU are 23% below the 1990 levels. *“The EU is therefore currently on track towards meeting its Europe 2020 greenhouse gas reduction target as well as its Kyoto Protocol targets”*, (EC, 2015). Such significant reduction of the total GHG emissions is achieved despite the fact that some of the minor member states achieved only little or none GHG emissions reduction. For example GHG emissions in Luxembourg are 21% higher than in

1990 due to increased traffic. Thus the report is rather sceptical in projections and simulations of future development. It states that current measures and policies are *"… insufficient to meet the agreed 2030 GHG target of an emission reduction…"*, (EC, 2015). This means that further tightening of the adopted measures is necessary to meet the 2030 and 2050 efficiency and emission goals. For this purpose the EC prepared proposals for updates of key directives like the Energy Efficiency Directive or EED (EC, 2016a) and Energy Performance of Buildings Directive or EPBD (EC, 2016b) as well as changes in the EU`s budget. Efficiency of the new measures is yet to be seen.

1.4. Why are (Residential) Buildings so Important?

Literature states that the building sector has approx. 40% share on total energy consumption, approx. 40% share on total waste production and approx. 24% share on GHG emissions in the EU, (Fraunhofer-ISI, 2009), (D'Agostino, 2015). The role of the residential buildings should be highlighted in this regard. The reason is the fact that they represent major part of the existing building stock. Statistics show that for example in the Czech Republic there were 1 766 046 residential and only 600 567 non-residential buildings in 2011, (Antonín, 2014). Moreover the non-residential buildings in these statistics include agricultural buildings, parking lots, etc. with minimal energy and water consumption or maintenance.

Considering the information above it is no surprise that the residential (building) sector has major role for example in the EU's plan for low-carbon economy (see Figure 2). This plan expects up to 91% savings of GHG emissions in "Residential and Tertiary" sector (EC, 2011). Execution of this plan as well as other treaties, acts and directives mentioned in Sections 1.2 and 1.3 is already influencing the building regulations in the EU. A prime example is the EU's EPBD (see Section 1.5.1). This directive provides general guidelines and sets target levels for energy performance (and savings) of buildings across the EU.

Main issue connected with achieving the declared energy and emission targets is final implementation of specific measures. For example in case of the EPBD the measures are set by individual EU member states (D'Agostino, 2015). This process is rather slow. Only 15 member states (including the Czech Republic) had fully adopted the proposed nZEB requirements for new construction between 2010 and 2015. Moreover, only 8 member states adopted the nZEB requirements for renovations of existing buildings at the same time, (BPIE, 2015). Such underrating of the renovation measures further aggravates the issue: Modern building concepts (e.g. passive buildings) have rather low energy consumption (and other environmental impacts) during their life cycle. In comparison, approx. 75% of the existing buildings in the EU could be considered inefficient in this regard, (EC, 2016b) (see Figure 3, (Feist, 1997)).

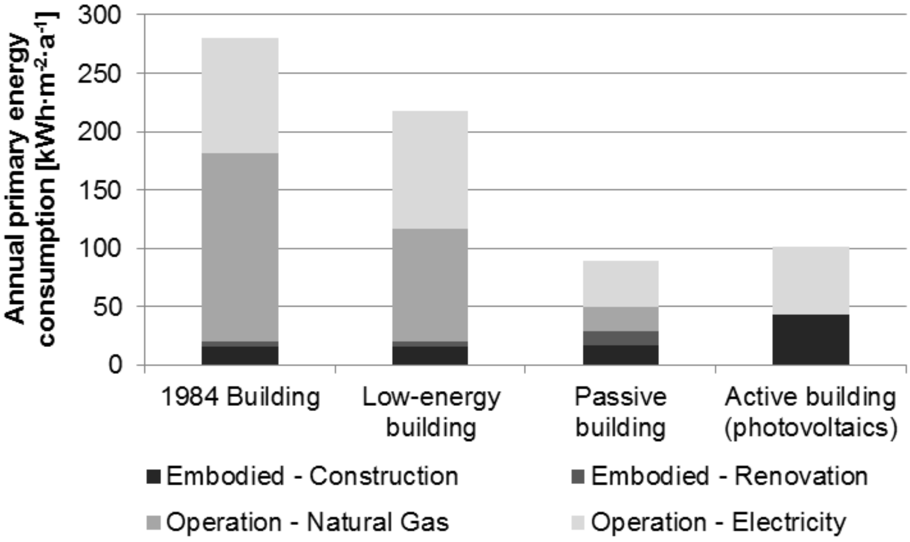


Figure 3. Primary energy (see explanation in Section 2.2.3.1) consumption of buildings with different energy efficiency. (Feist, 1997)

Currently only 0.4 to 1.2% buildings are renovated or modernized in the EU each year. Such low rate of modernization is insufficient for achieving the declared 2030 and 2050 energy and environmental targets. Situation in the Czech Republic could be used to illustrate the problem (MRDCR, 2015): Ordinance No. 78/2013 Coll. (MITCR, 2013) introducing the requirements of EPBD into Czech legal system was adopted in 2013. Next year there were 4 181 648 inhabited flats in the Czech Republic. Only 23 811 out of these were newly completed flats and 9 428 flats were renovated in this year. This is approximately 0.6% and 0.2% respectively of all inhabited flats in the Czech Republic at that time. At this rate it would take decades to modernize residential building stock according to the EPBD requirements. Therefore if the Czech Republic (as well as the rest of EU) is to meet the declared 2030 or 2050 targets it is necessary to implement further measures, especially to accelerate (cost-effective) modernization of existing residential building stock.

1.5. Ways to Influence the Efficiency of Buildings

Section 1.4 summed the reasons for the acceleration of the rate of efficient renovations of existing buildings. Suitable strategies are developed both in government agencies, private companies and international organizations. Many proposals are also published in original research papers like (Kamari, 2017). The results of the development vary. Some documents propose legal changes and tightening of technical standards followed by subsidy programmes. Others highlight the need for dissemination of the state-of-art knowledge to the owners and users of the buildings. They expect that the owners and users of buildings would willingly renovate their property to achieve monetary savings or increase the prestige and value of their property.

Evaluation of the efficiency of implemented measures is inseparable part of the ongoing strive for more efficient and sustainable (residential) buildings. Generally speaking, more complex methods provide more accurate information and solutions. Single- or double-criteria methods like the energy certification based on the EPBD are easy to apply. This is compensated by a level of bias or distortion of the results. It is possible that for example a significant part of the environmental impacts would remain out of scope of such methods. A prime example in this regard is application of biofuels to reduce the transport-related carbon emissions. The carbon emissions really decreased, however at the cost of significant increase of NOx emissions, (Hoekman, 2012). On the other hand, complex multi-criteria methods require large quantities of input data and processing time. Also the possibility of error could be higher due to the quantity of input data. Following Sections briefly introduce several examples of existing assessment methods and strategies.

1.5.1. EPBD and the 2016 Proposal Amending the EPBD

The EPBD was already introduced in previous sections. It asks EU member states to prepare and enforce minimum energy requirements that would ensure achieving cost-optimal balance between the investment and operational energy costs of buildings. It encourages member states to promote the concept of nearly zero-energy buildings (nZEB), (EC, 2010): buildings that require minimum or none energy supply during their operation, (Kurnitski, 2011). In this regard the EPBD says that

> *“(a) by 31 December 2020, all new buildings are nearly zero-energy buildings; and*
>
> *(b) after 31 December 2018, all new buildings occupied and owned by public authorities are nearly zero-energy buildings.” (EC, 2010)*

Environmental impacts related with buildings are also addressed in the EPBD. It introduces primary energy (see Section 2.2.3.1) as an indicator of environmental performance. Compliance of buildings with the EPBD (and following national regulations) is proven by energy performance certificates, (EC, 2010).

The disadvantage of the EPBD is that it provides only general framework for achieving the defined targets. It is up to individual member states to introduce suitable legal and technical requirements (as mentioned in Section 1.4), like the Czech ordinance No. 78/2013 Coll. The ordinance focuses on the operation efficiency of buildings. It defines the calculation methods and specifies energy performance requirements and primary energy requirements that new buildings and renovations in the Czech Republic have to fulfil. The environmental performance of buildings (represented by non-renewable primary energy) is included in the ordinance as a supplement to the dominant energy performance. The role of the ordinance is rather restrictive. Also the cost-optimization is described insufficiently. The ordinance just states that fulfilling the required energy performance parameters would ensure cost-optimality, (MITCR, 2013). Such generalizations can be misleading, which proves for example a report by Ministry of Industry and Trade of the Czech Republic (MITCR, 2013). More information regarding the application of the EPBD in the EU is available for example in (D'Agostino, 2015) or (EC, 2015).

The experience with application of the EPBD as well as latest technological advance led the EC to propose an update of the directive. The proposal (EC, 2016b) confirms the will to achieve 60 to 80 Mtoe energy savings till 2020 compared with 2007 baseline through the implementation of the EPBD. It states that 48.9 Mtoe energy savings were already achieved in 2014. However the proposal confirms that the EPBD and its implementation in individual member states is lacking especially regarding to the EU`s 2050 pledges (see Section 1.3). Thus the proposal recommends:

- *"Integrating long term building renovation strategies (Article of 4 Energy Efficiency Directive), supporting the mobilisation of financing and creating a clear vision for a decarbonised building stock by 2050;*
- *encouraging the use of ICT and smart technologies to ensure buildings operate efficiently; and*
- *streamlining provisions where they have not delivered the expected results." (EC, 2016b)*

The efficiency of the proposed changes is yet to be seen. The success of the EPBD has potential for global impact as the EU is one of three biggest economies in the world (along with China and USA) compared by GDP, (IMF, 2017).

1.5.2. IEA-EBC Annex 56

The research in the field of sustainable development is supported by many non-governmental agencies. One of them is IEA, established in 1974 under OECD. The aim of IEA is *"… to foster international cooperation among the 28 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources",* (Ott, 2017) IEA-EBC programme covers one of the key fields of interest of IEA: building sector. The goal of the programme is integration of new technologies, promoting of low-emission, efficient and sustainable buildings and communities. IEA-EBC works through individual projects (called Annexes). (Ott, 2017)

One of the recently completed IEA-EBC projects is known as Annex 56. Its full title is Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation. The project ran between 2011 and 2017. 23 organizations from 12 countries (including Faculty of Civil Engineering, Brno University of Technology) have participated in the project. The aim of the project was to:

- *“Define a methodology for the establishment of cost optimized targets for energy use and carbon emissions in building renovation;*
- *Clarify the relationship between the emissions and the energy targets and their eventual hierarchy;*
- *Determine cost effective combinations of energy efficiency measures and renewable energy based measures;*
- *Highlight the relevance of co-benefits achieved in the renovation process;*
- *Develop and/or adapt tools to support the decision makers in accordance with the methodology developed;*
- *Select exemplary case-studies to encourage decision makers to promote efficient and cost effective renovations in accordance with the objectives of the project.”* (Ott, 2017)

The resulting methodology and supplementary documents are based on more than 20 case studies across Europe, as well as consultations with experts, scholars and general public. The case studies were mostly residential buildings. Two exceptions were an office building in Austria (Höfler, 2017) and an elementary school in Czech Republic (Sedlák, 2017). These case studies included not only in situ measurements or computer simulations, but also socio-cultural surveys among owners and users of the buildings as well as general public, (Ott, 2017). The project also included multiple workshops, public meetings and conferences, where the methodology was presented and discussed. The ongoing work was presented in journal papers, like (Sedlák, 2015) or (Mørck, 2017) to further spread the knowledge.

Final version of the methodology (Ott, 2017) was released in 2017. It highlights the need for truly multidisciplinary approach in building renovations. The case studies evaluated during the development of the methodology confirmed that achieving extreme efficiency in one of the evaluated indicators causes inefficiency in others. For example the most energy-efficient and environmentally-friendly renovation is seldom cost-effective. Another conclusion is that building renovations have great potential for application of RES.

Especially because there are often limits for implementation of passive (energy-saving) measures like ETICS in building renovations, (Almeida, 2017).

It could be said that the scope of Annex 56 is similar to previously mentioned EPBD. However there are several differences in approach to the building renovations. The most obvious difference is the level of details in both the EPBD and Annex 56 methodologies. EPBD provides just a framework that has to be further developed before application. Annex 56 methodology is complete and ready-to-use. The most significant difference is that Annex 56 puts cost-optimality in the first place. The methodology should motivate the owners of buildings to carry out the renovations and achieve monetary savings without need for any legal restrictions or subsidies. This emphasis of cost-efficiency is connected with the fact that every citizen of the EU has to follow the laws, ordinances and standards based on the EPBD, while the Annex 56 methodology is voluntary. The success of Annex 56 project depends purely on the acceptance by experts and general public.

1.5.3. (Voluntary) Building Certification Schemes

Building certification is another way for promoting sustainability and efficiency. The principle is that more efficient, environmentally- and user-friendly buildings receive higher level certificates. Building certificates can be mandatory, like the energy performance certificates issued in compliance with the EPBD in EU (see Section 1.5.1) or the complex multi-criteria Green Mark in Singapore, (Bozovic-Stamenovic, 2016). However the majority of building certification schemes is voluntary. Some certification schemes are even offered by private organizations for a fee. The stakeholders are willing to pay the fee knowing that a renowned certificate will significantly increase the market price of their property. The increased efficiency of these buildings can be considered a desirable side effect of efforts to maximize the profit, (Awadh, 2017).

One of the most wide-spread voluntary certification schemes is BREEAM. It is a British certification scheme, originally introduced in 1990. Similarly to other certifications BREEAM evaluates the quality of buildings in several dozens of criteria in ten categories: Energy, Health and Wellbeing, Innovation, Land Use, Materials, Management, Pollution, Transport, Waste and Water, (BRE, 2017). Such multi-criteria approach gives the users a complex overview of a building`s efficiency and sustainability. In this regard it can be considered more precise than the EPBD-based energy certification. On the other hand it should be noted that the multi-criteria approach is considerably more time consuming and expensive than the energy performance certification. Specific BREEAM methodologies are currently available for planned buildings, new construction, in-use buildings and refurbishments with sub-methodologies covering broad range of building types from residential to industrial. More than 560 000 individual certificates in 78 countries were issued since its introduction. 13 294 of these were issued in the EU member states (8 867 in the United Kingdom), 127 in the Czech Republic, (BRE, 2017).

There are many other voluntary certifications schemes similar to BREEAM. One of them is LEED developed in the USA. It is available for wide range of building types. There are more than 90 000 certified commercial building projects and more than 400 000 certified residential building projects worldwide. In the EU there are only 1 312 LEED certified buildings according to (USGBC, 2017). This is probably caused by availability of local certification tools like German DGNB, French HQE or Czech SBToolCZ.

Generally speaking, the number of issued building certificates is increasing; however it is still much lower than the number of existing buildings. Therefore the certified buildings should be rather considered examples of state-of-art knowledge and technologies than a new quality standard. For example there are only 184.78 BREEAM, DGNB and LEED certificates per million citizens in Luxembourg according to (GBIG, 2017). This is the highest per capita number of certificates in the whole EU. In comparison there are only 15.36 BREEAM, DGNB and LEED certificates per one million citizens in the Czech Republic. Still, such relatively low number of certificates (see Figure 4) is the highest in the Eastern and Central Europe and seventh in the EU, (GBIG, 2017).

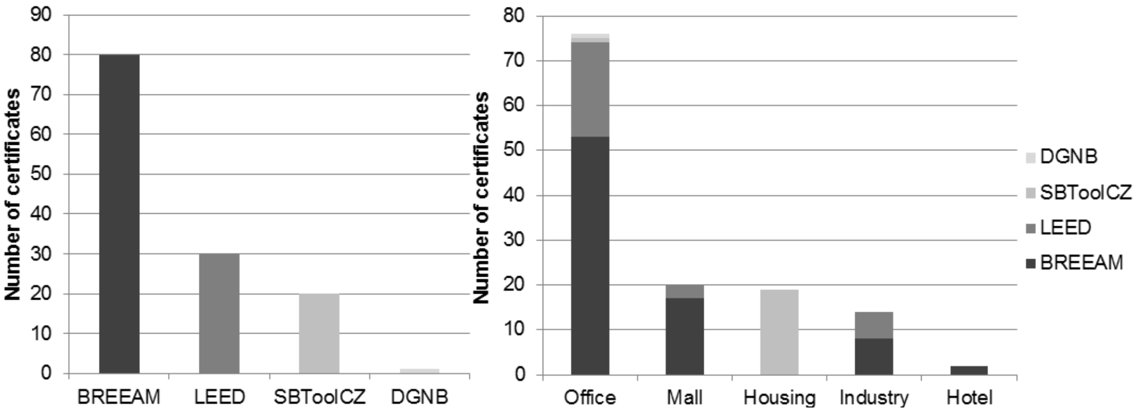


Figure 4. Building certificates in the Czech Republic in June 2017 based on data from (GBIG, 2017) and (SBToolCZ, 2017).

One of the barriers that hinder faster spreading of the mentioned buildings certification schemes is relatively high price of the certificates. The fact that the individual certifications are not compatible with each other is also a problem sometimes. This is the reasons for initiatives that try to create free-of-charge harmonized all-encompassing evaluation methodologies. One such initiative is an ongoing study of EC`s JRC: Efficient Buildings. The aim of the study is to develop a common EU framework of indicators to assess the environmental performance of buildings. The study started in 2015. First version of the proposed methodology (entitled Level(s)) was released in August 2017, (Dodd, 2017). It contains:

- *“Macro-objectives: An overarching set of six macro-objectives for the Level(s) framework that contribute to EU and Member State policy objectives in areas such as energy, material use and waste, water and indoor air quality.*
- *Core Indicators: A set of 9 common indicators for measuring the performance of buildings which contribute to achieving each macro-objective.*
- *Life cycle tools: A set of 4 scenario tools and 1 data collection tool, together with a simplified Life Cycle Assessment (LCA) methodology, that are designed to support a more holistic analysis of the performance of buildings based on whole life cycle thinking.*

- *Value and risk rating: A checklist and rating system provides information on the reliability of performance assessments made using the Level(s) framework." (Dodd, 2017)*

The Level(s) methodology is available for both new construction and major renovations of residential and office buildings. The methodology covers a wide range of building-related issues: GHG emissions, resource (materials and water) efficiency, indoor climate, resilience to climate change and cost optimization, (Dodd, 2017). Similarly to other multi-criteria certifications the Level(s) emphasizes complexity of interactions between buildings and the environment. The life cycle of buildings is evaluated from the acquisition of raw materials through construction, use of the building and demolition to waste management. This complexity is desirable from the point of view of both the environment and the end user, because it will help optimize the efficiency of buildings. However it may prove to be a disadvantage, because Level(s) is entering a well-established market with strong competition.

1.6. Quantification of Sustainability and Environmental Impacts

Previous sub-sections have briefly described possibilities for reduction of environmental impacts in building sector. Different approaches supporting more efficient (residential) buildings were introduced. All these approaches share the need for quantification of environmental impacts; either in a single all-encompassing criterion or in a set of multiple complementary criteria. The calculation methods applied to quantify the environmental impacts are commonly based on principles of the Life-Cycle Assessment (LCA).

LCA is developed since the second half of the 20th century. As the title suggests, LCA highlights the need for considering the whole life cycle of the assessed product. It is applicable in all aspects of human activities from agriculture to marketing. The applications are not limited to environmental issues. LCA can be applied for calculations of economic or cultural impacts as well. Common applications include:

- **Product and/or production technology development.** LCA could be used for comparisons of products, transport options etc. Conscious end users could utilize LCA to identify the most suitable product. Producers could apply LCA in supporting role during design of new products as well as a basis for optimization of existing products or facilities (e.g. reduction of energy and material demand). This approach to design of products with regard to their environmental performance is also known as “ecodesign”. (Baumann, 2004)

- **Strategic planning and policy-making.** LCA could be applied as a decision-making tool in risk management, sustainability assessment, EIA and other fields, (ISO, 2006a). Example of such application could be long-term state energy policy.
- **Marketing and Eco-labelling.** Changes in consumer preferences have turned the LCA into a tool for specific type of communication with public: green marketing. Large production companies often utilize LCA to obtain certificates of environmental performance (e.g. building certificates mentioned in Section 1.5.3) for their products. Such certificates give them advantage over the competition. Spreading use of various certificates lead to standardization of eco-labelling and environmental marketing in ISO 14020 standard series to prevent misbehaviour, (Baumann, 2004).

Basic LCA framework is described in ISO 14040 (ISO, 2006a) and following ISO standards. The framework provided by the ISO standards is purposefully general. Therefore some situations require more specific guidelines. Prime example of such situation is building LCA, particularly building renovation LCA with all the imaginable problems. Even though many research projects (e.g. the Annex 56 mentioned in Section 1.5.2) and standards already dealt with this topic, there are still uncertainties that limit the accuracy of the LCA studies in this field (see Section 2.4).

1.7. Section Summary

This section briefly introduces the issues that contemporary society is facing in the context of construction industry. It also described why building renovations are a key part of the strive towards sustainable construction and society (which is why this dissertation deals with building renovations instead of new construction). Major part of this section focuses on examples of legal and voluntary options that should motivate the owners and users to improve the efficiency of buildings. In this context the section also introduces the need for quantification of environmental impacts of buildings (or other human activities) and a method commonly utilized for this purpose: Life-Cycle Assessment. This method is the cornerstone of the dissertation. As such it is described in detail in following Section 2.

2. Life-Cycle Assessment

"Increased awareness of the importance of environmental protection and the possible impacts associated with products, both manufactured and consumed, has increased interest in the development of methods to better understand and address these impacts. One of the techniques being developed for this purpose is Life Cycle Assessment." (ISO, 2006a)

This section describes the LCA as a method for evaluation of environmental impacts, It introduces the origins of the method as well as its standardized framework. Individual sub-sections briefly describe the steps of any LCA study to provide sufficient scientific background for following sections. Later sub-sections also describe available software tools, databases and applications of LCA in construction industry. They also identify issues that limit the accuracy of the method and hamper its wide-spread utilization (in the construction industry).

2.1. History and Development

Efforts to quantify environmental impacts of human activities quoted above started in the second half of the 20th century, particularly during the 60s and 70s. One of the original stimuli was the concern for massive spreading of disposable packages. It initiated the discussion about wasting of natural resources. This discussion was further supported by the global oil crisis in the 70s. The obvious problem of limited resources was described for example in (Meadows, 1972).

The framework that later became the basis of LCA was probably conceived by Harry E. Teasley, Jr. in 1969 in a packaging study for The Coca-Cola Company. At that time the company was looking for the best available packaging for their beverages. Teasley Jr. and his colleagues created a complex model quantifying the energy, material and environmental impacts related with the life cycle of different types of packaging, (Hunt, 1997). This particular study was confidential, so the methodology remained unknown to others. However the authors continued to work in the field and published some of their later works, e.g. (Frankling, 1972). The released studies came to attention of scientists in other countries like United Kingdom, Germany, Denmark and Sweden, who were working on similar research at the same time, (Oberbacher, 1996), (Boustead, 1996).

By the end of 80s there were already hundreds of environmental studies, especially in the USA and Europe. They were known as REPAs, LCAs, ecobalances, environmental profiles, etc. In the 90s the SETAC have started organizing LCA conferences that served as a meeting place for researchers, industry representatives and policy-makers. The discussion confirmed that LCA (overall term selected at one of these conferences as a representative) is a great method for optimization of products. However it also pinpointed many issues connected with accuracy and objectivity of individual studies. It was clear that a level of standardization is necessary. (Baumann, 2004)

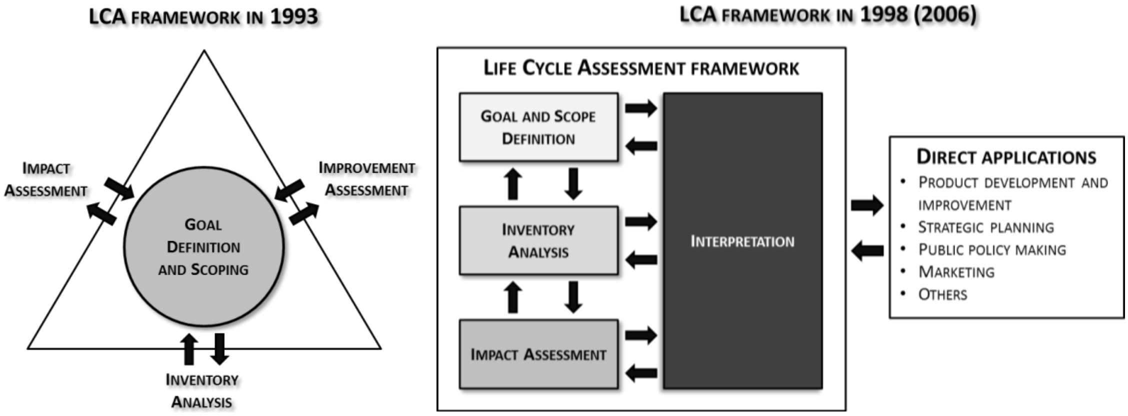


Figure 5. Comparison of (SETAC, 1993) LCA framework from 1993 (left) with **(ISO, 2006a)** LCA framework from 1998 (still valid in 2006).

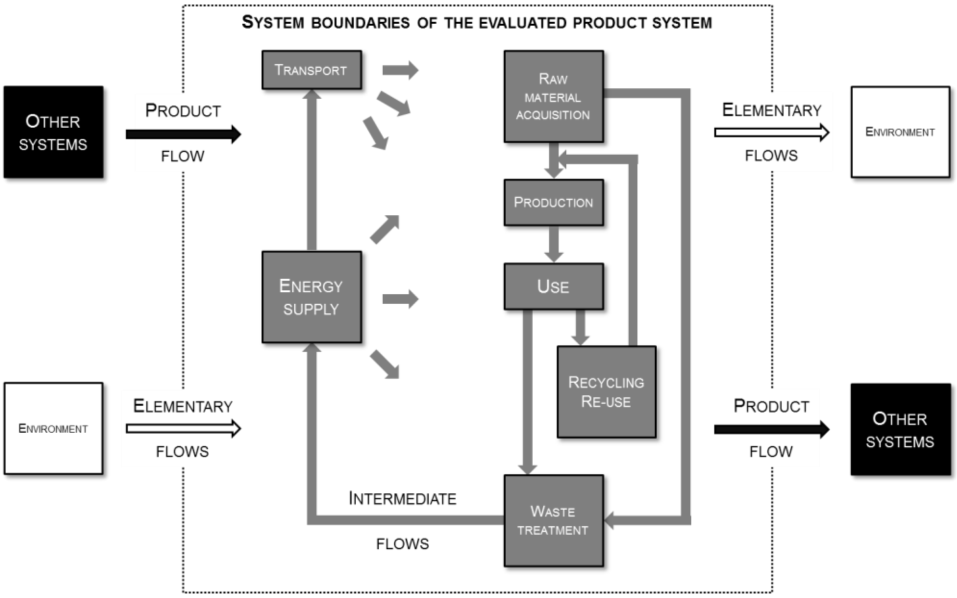


Figure 6. Sample product system model based on ISO 14040. White boxes represent the environment. Grey boxes represent individual parts of the product's life cycle (called processes) evaluated during the particular LCA. Black boxes represent parts of the product's life cycle that are not considered in the particular LCA. Arrows represent interactions (called flows) between

individual processes: materials, intermediate products, waste, etc. (ISO, 2006) See Section 2.2.1 for details.

First universal guidelines for the LCA (SETAC, 1993) were published as a result of the SETAC conference in 1993. First LCA related standard, ISO 14040 (ISO, 1997) was released in 1997. The standard defined LCA as *"… a technique for assessing the environmental aspects and potential impacts associated with a product…",* (ISO, 1997). ISO 14040 was followed by other standards, which combined previous sources and described the LCA as it is currently known. These standards were reissued into ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) in 2006.

The ISO 14040 and ISO 14044 now provide general framework (see Figure 5) for LCA of any product or "product system" in the standardized terminology. A simplified scheme of a product system based on ISO 14040 is shown in Figure 6.The key LCA principles according to ISO 14040 are listed below:

- *"Life cycle perspective;*
- *Environmental focus;*
- *Relative approach and functional unit;*
- *Iterative approach;*
- *Transparency;*
- *Comprehensiveness;*
- *Priority of scientific approach." (ISO, 2006a)*

The standardized framework can be considered (purposefully) vague sometimes. ISO 14040 admits that *"…the depth of detail and time frame of an LCA may vary to a large extent, depending on the goal and scope definition…"*, (ISO, 2006a). Therefore agencies like CEN started to release supplementary standards for specific purposes and industry sectors. For example the key standard for building sector is the EN 15978 (CEN, 2011) introduced in the EU in 2011 (see Section 2.3 for details).

The standardization helped with further spreading of the LCA. Nowadays it is a well-established method applied in a wide range of situations. This is confirmed for example by increasing number of published research works (see Figure 7).

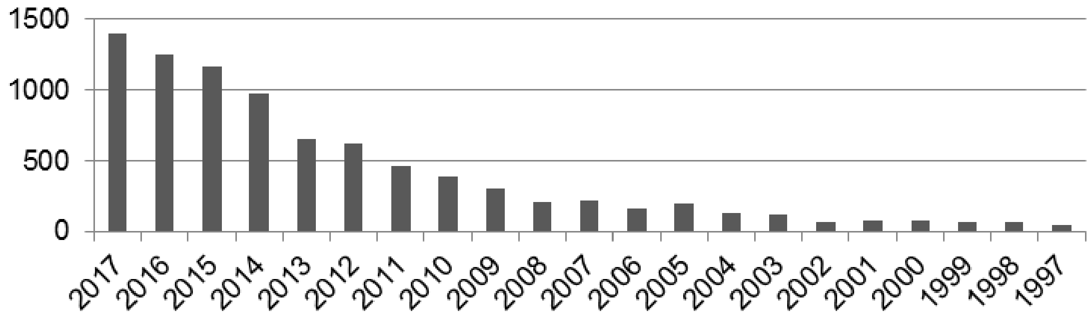


Figure 7. Number of research papers with "Life Cycle Assessment" or "LCA" in their title, abstract or keywords indexed in ScienceDirect database since the release of ISO 14040 standard in 1997. (Elsevier B.V., 2017)

2.2. Basic LCA framework according to ISO 14040

ISO 14040 was adopted by many national standardization agencies. For example in the Czech Republic it was introduced as the (bilingual) ČSN EN ISO 14040 in 1998 (CNI, 1998). The standard was updated in 2006 (ÚNMZ, 2006) in line with the update of the original ISO standard. According to this standard the LCA comprises of four interconnected stages (see Figure 5, right) described in the following sections.

2.2.1. Goal and Scope Definition

Defining the goal and scope is the initial stage of any LCA study. Ideally, all choices and specifications of the boundary conditions are made during this stage. The need for changes may arise during later stages due to iterative nature of the LCA. However it is desirable to foresee and avoid such changes if possible. (Baumann, 2004)

The goals and background of the study have to be established at the beginning of this stage. Both depend on the intended application and audience of the study. Cooperation between authors and commissioners of the study is crucial at this point. Only close cooperation would ensure that the extent and style of presentation of the study corresponds with its purpose. It is clear that for example a report for policymakers would differ from a comparative research study.

The scope of the study is also defined during this stage. It is necessary to define the assessed product system, its inputs, outputs and connections between individual parts of the system. For the purpose of the LCA the evaluated product system is simplified to a set of individual processes and interconnecting flows (see Figure 6), where:

- **Process** or unit process is *"… a set of interrelated or interacting activities that transform inputs into outputs"*, (ISO, 2006). Depending on the scope of the study, level of details and available data a process can represent anything from a single machine to whole manufacturing facility.
- **Flow** represents a single input or output of individual processes: energy, material, waste, manpower, etc. Flows (or intermediate flows) are used to indicate interactions between processes within the boundaries of the assessed product system. Other flows indicate interactions between the product system and its surroundings. (ISO, 2006)
- **Product flow** represents Interaction between the assessed product system and other product systems outside of the system boundaries. Example of a product flow is a pack of hollow ceramic blocks that is sent from a manufacturer to a construction site. (ISO, 2006)
- **Elementary flow** indicates direct interaction between the assessed product system and the environment. Emissions of GHG during the production of electricity can be considered as example of elementary flow. (ISO, 2006)

Establishment of the product system model is supplemented by definition of its function(s). A product system may have a number of different functions. It is necessary to define one of them as the representative of the performance of the product system in a particular LCA study. For example a local waste incineration plant can be viewed as the means for elimination of municipal waste as well as co-generation of electricity and heat. LCA of the municipal waste management would probably consider the amount of disposed (burnt) waste as the function representing the whole facility. LCA quantifying environmental impacts of district heating would use heat as the function. Lastly, LCA of the electricity mix in the country would use electricity as the function. For the purpose of a LCA the function of the product system is represented by:

- **Functional unit** (or functional equivalent). Functional unit quantifies the function of the assessed system. It serves as *"… a reference to which the inputs and outputs of the product system are related"*, (ISO, 2006a). Such reference may be insignificant in stand-alone studies. However its importance increases when there is the need for comparison of results between different LCA studies. In some cases the functional unit can be even standardized to ensure clarity and comparability of the LCA results. Such standardization can be seen for example in EPD certification of construction materials. EPD certification method is standardized in EN 15804 (CEN, 2013). Functional unit and boundary conditions for LCAs of particular materials are further specified in later standards and documents: e.g. the LCAs of thermal insulation materials should use thermal resistance as the functional unit according to EN 16783 (CEN, 2017).

- **Reference flow**. Reference flow is an irreplaceable complement of the functional unit. It describes the way in which the function of the product system is fulfilled, *"… i.e. the amount of products needed to fulfil the function…"* (ISO, 2006a)It could be for example the amount of polystyrene (or mineral wool, etc.) necessary to provide specific thermal resistance in case of previously mentioned thermal insulation materials.

2.2.1.1. System boundaries of assessed product system(s)

Definition of appropriate system boundaries is another necessary step of this LCA stage. System boundaries define which processes will be included in the assessed product system (see Figure 6). This doesn't mean only the physical parameters of the assessed product system. Geographical, temporal, social and other boundaries could be considered too. (Tillman, 1993)

The need for system boundaries is related with the scope and precision of a particular LCA study. Therefore, different types of system boundaries are used to optimize the extent of the LCA. Below are three examples of commonly applied system boundaries based on literature (e.g. (Baumann, 2004)):

- **Cradle-to-grave** system boundaries (see Figure 8) could be considered ideal, as they could provide most accurate results. The assessment with these system boundaries follows the whole life cycle of the assessed product. Flow of resources is modelled from the acquisition of all raw materials in a “cradle” (e.g. a mine) through their processing and use in a product to their final disposal in a “grave” (e.g. a landfill). This means that only elementary flows cross the system boundaries. Cradle-to-grave system boundaries are recommended for example in building certification schemes (e.g BREEAM, see Section 1.5.3).

- **Cradle-to-cradle** system boundaries (see Figure 9) are hypothetical evolution of common cradle-to-grave system boundaries. They expect that remains and waste of one product system will be completely recycled or reused. Such behavior is one of the goals of the sustainable development and therefore a lot of effort is currently focused on development of new and more efficient recycling technologies.

- **Cradle-to-gate** system boundaries (see Figure 10) follow the life cycle of the assessed product from acquisition of raw materials to the end of the production process. The “gate” represents shipping of the completed product off the production facility. Cradle-to-gate system boundaries are applied for example during the EPD certification of various products. The reason for this is simple: Producers have little control over the actual use of their products. It would be needlessly demanding to assess all possible uses of a product in a single LCA study.

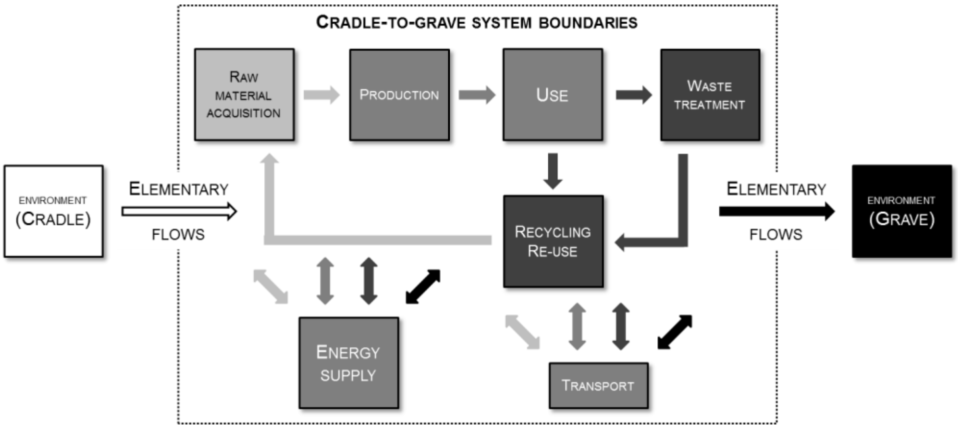


Figure 8. Scheme of cradle-to-grave system boundaries.

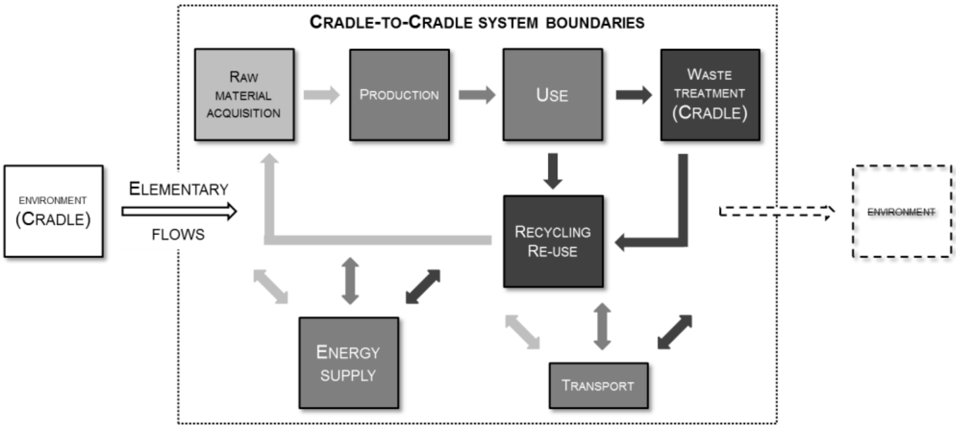


Figure 9. Scheme of cradle-to-cradle system boundaries. Dashed lines and crossed text indicate parts that are omitted compared to cradle-to-grave system boundaries.

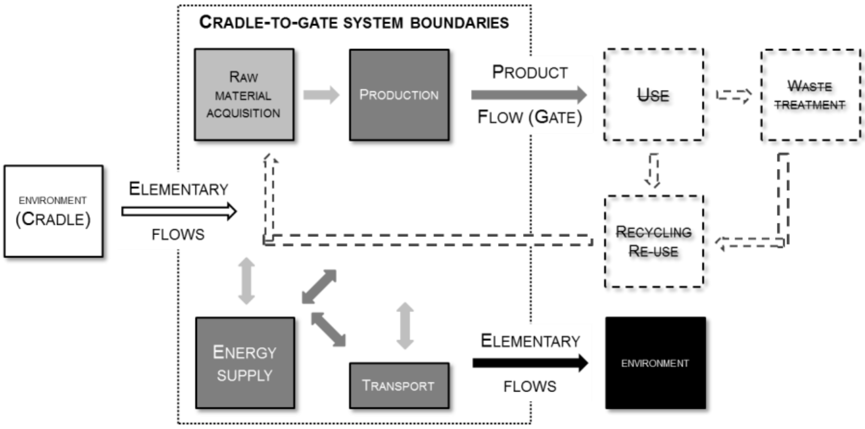


Figure 10. Scheme of cradle-to-gate system boundaries. Dashed lines and crossed text indicate parts that are omitted compared to cradle-to-grave system boundaries.

2.2.1.2. Allocation of (environmental) impacts between different product systems

Sometimes it is not possible (or necessary) to follow the whole life cycle of a product. Sometimes the system boundaries of one product system interfere with system boundaries of another product system. Such situations require allocation of (environmental) impacts between the affected product systems (and the environment). Allocation should reflect real interactions between the systems. It should be based on physical parameters of the assessed inputs and outputs. Allocation could be also based on other parameters (e.g. monetary flows), if “physical” boundaries between the systems are not clear. Three basic cases when allocation should be considered (Baumann, 2004) are:

- **Multi-output process** produces multiple different products. Brickworks producing different types of ceramic bricks are an example of such situation. In this situation the LCA results can be divided between individual product systems (bricks) based on the amount of raw materials, operating times of the production line, etc.

- **Multi-input process** allocation is similar to multi-output allocation. This allocation can be encountered e.g. in LCAs focused on waste management (e.g. landfill for different wastes).
- **Open-loop recycling** is the most challenging type of allocation. It is a situation when a product is (at least partially) recycled and used as a secondary raw material in another product system. Therefore the (environmental) impacts connected with one material should be allocated between multiple product systems. There are different approaches to this type of allocation depending on the available data, type of the product, etc. One approach (allocation based on number of uses) considers all the subsequent products equal. This means that total impacts could be simply divided by the number of production cycles (see Figure 11). Such approach is suitable especially for materials that can be fully recycled or re-used (e.g. glass bottles). Another approach (allocation based on the quality of raw materials) considers the fact that recycling degrades the quality of the original material. Environmental impacts related with the material are be divided using a specific ratio (see Figure 12). This approach is suitable for LCAs of materials that cannot be fully re-used or recycled: e.g. concrete that can be recycled into aggregate. Another approach (cut-off allocation) considers all the product systems separately (see Figure 13). This means that impacts related with acquisition (e.g. mining) of raw materials are incorporated only in the LCA of the first product system. LCAs of intermediate product systems focus on the recycling and re-use of the material. Finally, impacts related with the waste management are incorporated only in the LCA of the last product system.

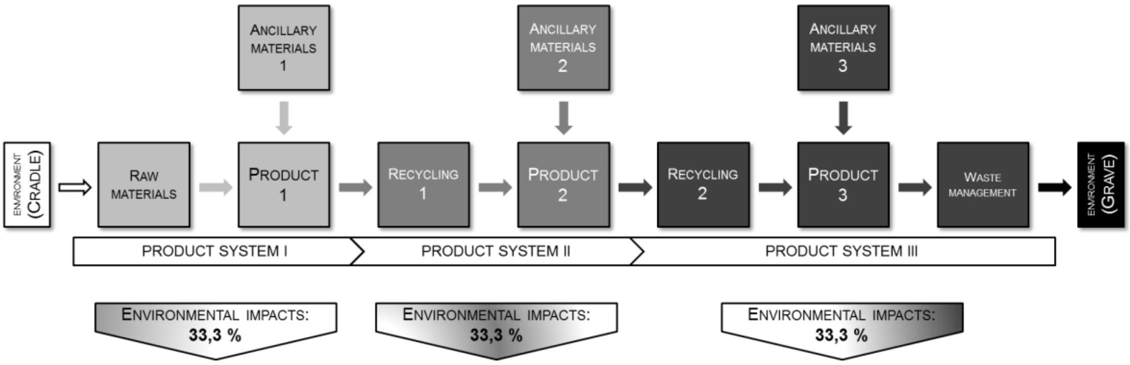


Figure 11. Example of allocation based on number of uses. Life cycle of the assessed material interacts with three product systems. Environmental impacts related to the original raw materials are (for the purpose of the assessment) evenly distributed between all three product systems.

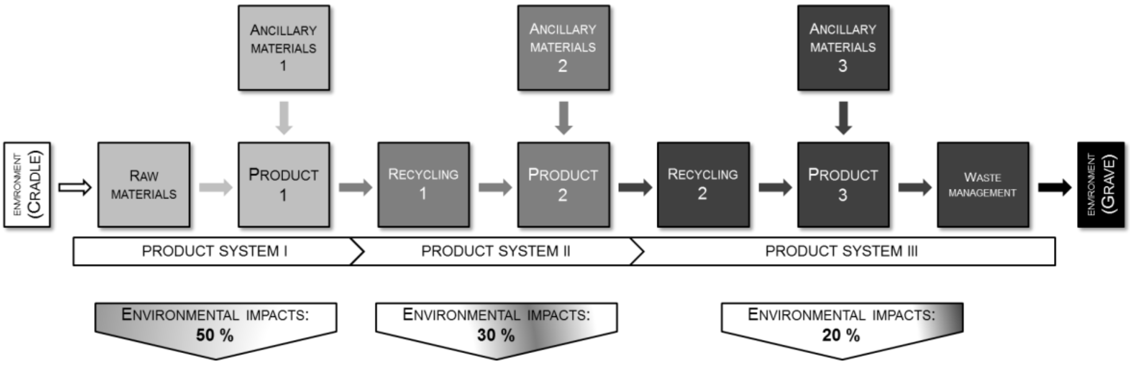


Figure 12. Example of allocation based on the “quality” of the original raw materials. Most environmental impacts related with the original raw materials are (for the purpose of the assessment) assigned to the first production cycle. Quality of the original raw materials degrades during the later production cycles. This is reflected by the lower share on the total impacts.

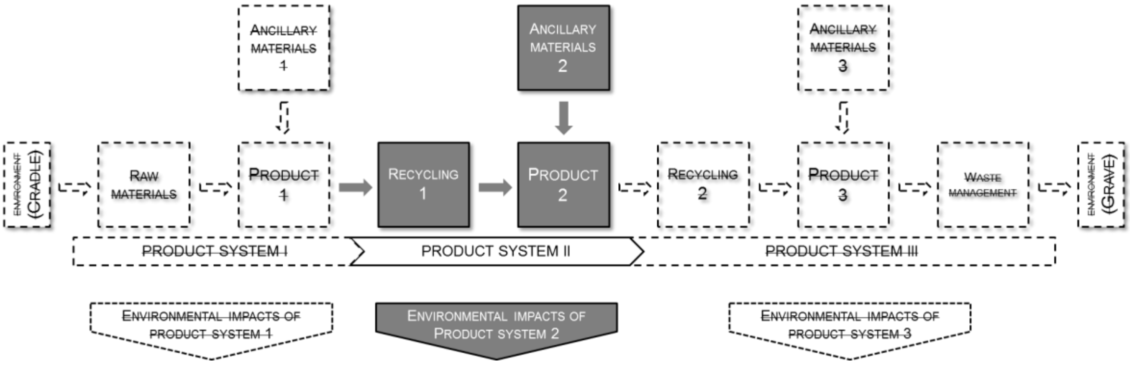


Figure 13. Example of cut-off allocation. Only one part of the life cycle of the original raw materials is assessed. Parts of the material life cycle that are not considered in the assessment are indicated by dashed lines and crossed texts.

Generally, allocation should be avoided in LCA; especially the cut-off allocation that significantly narrows the system boundaries of the assessment. It may result in omitting of important parts of the assessed product system. Such distortions of results are undesirable. However there are situations when cutting-off unimportant parts of the assessed product system is beneficial. EPD certification could be used as an example again. The EN 15804 standard says that *"… processes generating a very low contribution to the overall revenue may be neglected"*, (CEN, 2013). This very low contribution is later specified as *"Contribution to the overall revenue of the order of 1% or less..."*, (CEN, 2013). This approach simplifies LCAs of complex product systems with hundreds of inputs and outputs of varying importance. The reduction of accuracy is considered justifiable by speeding of the assessment process.

2.2.1.3. Input Data and their Processing

The accuracy of all LCA studies depends on the quality of input data and chosen calculation procedure. These also significantly influence the amount of work behind a particular LCA study. Specification of the data sources and calculation procedure (based on the intended goal and scope) is therefore another necessary activity at the beginning of any LCA study.

The input data should provide sufficient information about natural resources (e.g. metal ores), emissions to air, emissions to soil, emissions to water, etc. related with the assessed product system. The input data are gathered during second stage of the LCA, called Life-Cycle Inventory (LCI) or Inventory Analysis (see Section 2.2.2) According to ISO 14044 these data *"… may be collected from the production sites associated with the unit processes within the system boundary, or they may be obtained or calculated from other sources. In practice, all data may include a mixture of measured, calculated or estimated data"*, (ISO, 2006b).

Ideally the input data would be based on detailed monitoring of the assessed product system. Such level of precision is often impossible. Parts of the input data are commonly based on computer simulations, calculations or other sources (see Section 2.2.2.1). Therefore it is necessary that all the input data are consistent and verifiable. ISO 14044 specifically requires that the input data should have suitable:

- *"Time coverage;*
- *Geographical coverage;*

- *Technology coverage;*
- *Precision and completeness;*
- *Representativeness;*
- *Consistency;*
- *Reproducibility;*
- *Sources;*
- *Level of uncertainty." (ISO, 2006b)*

The quality and origin of input data should be recorded for later reference. It is necessary for the processing and reviewing of the LCA study during the final stages of the assessment (see Section 2.2.4) as well as for any future use of the LCI data Influence of the quality and suitability of input data on the results of the LCA is further discussed in Section 6.

The quality and amount of necessary input data directly depends on the intended calculation procedure; or Life-Cycle Impact Assessment (LCIA) as standards (ISO, 2006a) define it. During LCIA the environmental impacts of the assessed product system within selected impact categories are calculated (see Section 2.2.3.). It is desirable to (at least preliminarily) define the method of calculation and impact categories as part of goal and scope LCA stage to make data gathering more efficient.

2.2.2. Life-Cycle Inventory

LCI is the stage where necessary qualitative and quantitative data about the assessed product system (and its interactions with the environment or other product systems) are collected. The data are incorporated into the model of the assessed product system as individual flows and processes (as specified in goal and scope stage of the LCA). This iterative work (see scheme in Figure 14) often results in refining of the initial boundary conditions. (ISO, 2006b)

Data collection during LCI is crucial phase of a LCA study. The quality of the acquired information directly influences the results of the assessment. Section 2.2.1.3 mentioned that LCA data could origin in direct measurements, calculations or estimations. It should be noted that the same methods should be applied for all calculations, measurements or simulations during a particular LCI. Otherwise, the consistency of the study may be compromised and the accuracy of results reduced. (Baumann, 2004)

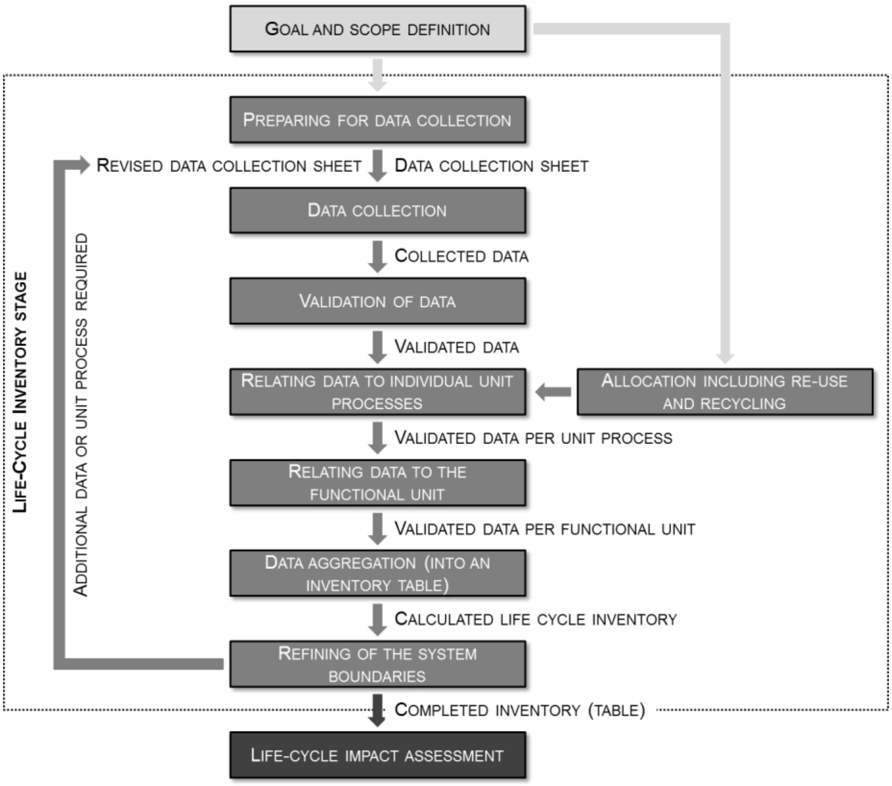


Figure 14. Order of the LCI steps recommended by ISO 14044. (ISO, 2006b)

The requirements on the quality of LCI data are recommended in ISO 14044 (ISO, 2006b). The list of the requirements is presented in Section 2.2.1.3 above. The main reason for these requirements is that the authors of the LCA are rarely the authors of all the data processed during the LCI stage. The necessary data may be acquired by different professionals in various locations. Therefore it is important to record not only the LCI data itself, but also uniform and consistent supplementary information about their origin. Examples describing how the information should be recorded are included i. a. in Annex A of ISO 14044, (ISO, 2006b). Detailed recording of the LCI process would minimize the chance for incorrect application of the data and increase clarity and credibility of the assessment. Moreover it would provide invaluable for anyone who would like to use the LCI data later.

Result of the LCI stage is a model of the product system supplemented with a list of the necessary inputs and outputs. These data serve as the basis for the actual assessment of (environmental) impacts. The list of inputs and outputs is also known as the “Inventory table”. (Tukker, 2000)

2.2.2.1. LCI Databases

Accuracy-wise, it could be expected that the best data are those measured or calculated directly for the purpose of the particular LCA study. Acquisition of such data would require cooperation of specialists in ecology, toxicology, environmental chemistry and other fields. It would be time consuming and costly. It is also common that acquisition of some data is outright impossible. Therefore, LCA practitioners often rely on other information sources: statistical data, previously published LCA studies or LCI databases. (Baumann, 2004)

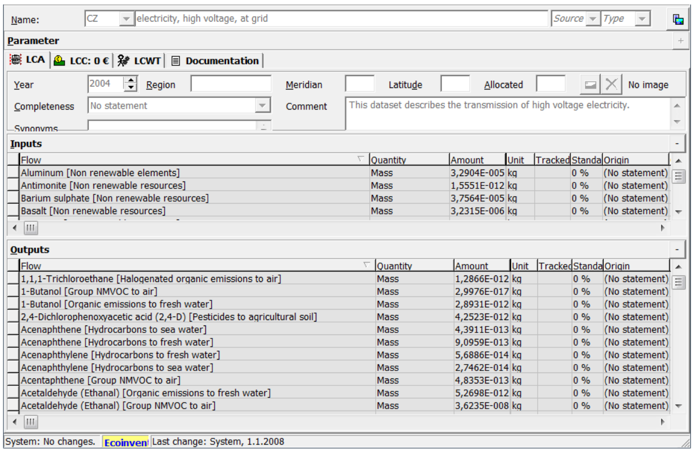
Currently there are dozens of LCI databases available either as part of LCA software tools or separately. Extent of these databases varies. Some contain only a handful of datasets (see example in Figure 15), while others contain thousands of datasets describing various processes in multiple fields of human activities. 20 examples of such databases are listed in Table 1.

The databases acquire datasets from different sources: government agencies, research institutes or private organizations; see e.g. (Hirschier, 2012) for more information. Therefore the quality of the datasets varies greatly. Some of them are based on extensive research, while others are just rough estimates. Some describe only one particular production facility; others provide national, regional or even global averages. Also the age of the datasets could be a limiting factor. Some databases still use datasets from 1990. Such aged data may needlessly distort accuracy of the assessment. (Reap, 2008), (Martínez-Rocamora, 2016)

Suitability of a dataset for particular LCA study is a crucial issue. Their authors should therefore provide sufficient supplementary information for each dataset to help LCA practitioners select datasets that best suits their needs. (Reap, 2008)

Database	Datasets	Primary data	Cost	Dataset focus	Description	Reference
BEAT	> 50	Industry	Free*	United Kingdom	Database included in the BEAT LCA tool. The tool focused on assessment of biomass processing in the UK. Discontinued in 2011.	(AEA Energy & Environment, 2017)
CCaLC database	> 2000	Literature	Free*	Global	Database collecting multidisciplinary LCI data (carbon-emissions-related only) for CCaLC LCA tool.	(UoM, 2017)
CPM LCA Database	748	Industry	Free	Sweden	Database collecting multidisciplinary LCI data from Sweden.	(CPM, 2017)
CRMD	17	Industry	Free	Canada	Database based on 1998 LCI data from Canadian industry. Creation of the database was a one-time project without further updates.	(UoW, 2017)
Eco-Bat	325	Other databases	Fee*	Switzerland	Database included in the Eco-Bat building LCA tool providing building-related data. Based on ecoinvent and KBOB data. Discontinued in 2015.	(LESBAT, 2017)
ecoinvent	> 13300	Industry	Fee	Global	One of the most extensive multidisciplinary LCI databases.	(ecoinvent, 2017)
ELCD	584	Literature	Free	EU	JRC database collecting LCI data from the EU.	(JRC, 2017)
envimat	296	Other databases	Free	Czechia	Database collecting LCI data related to CZ construction industry. Most of the data originates in ecoinvent database.	(CTU Prague, 2017)
EPD database	> 770	Industry	Free	Global	Database presenting EPD certificates. Information in the EPDs differ, but the certificates could still be used similarly to other LCI datasets.	(Environdec, 2017)
ESU database	> 1700	Other databases	Fee	Global	Database providing multidisciplinary LCI data. It is based on ecoinvent data combined with other sources (databases, literature, industry).	(ESU services, 2017)
GEMIS database	> 10900	Literature	Free*	Global	Database included in GEMIS LCA tool. The database includes multidisciplinary global LCI data.	(IINAS, 2017)
Environmental Profiles	1745	Industry	Free	EU, USA, UAE	Environmental Profiles database collects LCI data on construction materials, primarily meant as a source of data for BREEAM certification.	(BRE, 2017)
GREET	> 1500	Industry	Free*	USA	Database included in GREET transport LCA tool. The database contains multidisciplinary LCI data supporting the aim of the tool.	(ANL, 2017)
IBO	> 500	Industry	Free	Austria	Database collecting LCI data from Austrian construction industry.	(IBO, 2017)
IDEA	> 3800	Industry	Fee	Japan	Database collecting multidisciplinary LCI data from Japan.	(JEMAI, 2017)
LCA Food Database	27	Industry	Free	Denmark	Database collecting LCI data from Danish food industry. The database was last updated in 2007.	(2.-0 LCA Consultants, 2007)
LCDN	2360	Other databases	Free	EU	JRC database aggregating data from other existing databases like Plastic Europe or Professional Database	
Plastics Europe	90	Industry	Free	EU	Database collecting LCI data of European Association of Plastics Manufacturers.	(PleasticsEurope, 2017)
Professional Database	> 3560	Industry	Fee	Global	Database collecting multidisciplinary LCI data. It is available as a part of GaBi LCA tool. Multiple extensions for different industries exist.	(thinkstep, 2017a)
USLCI	5530	Industry	Free	USA	Database collecting multidisciplinary LCI data in the USA.	(NREL, 2017)

Table 1. Illustrative list of 20 available LCI databases. Asterisk in Cost indicates that the database is available only with a specific software.



Name: CZ electricity, high voltage, at grid
Source
Type
Year 2004
Region
Meridian
Latitude
Allocated
Completeness No statement
Comment This dataset describes the transmission of high voltage electricity.

Inputs

Flow	Quantity	Amount	Unit	Tracked	Standa	Origin
Aluminum [Non renewable elements]	Mass	3,2904E-005	kg		0 %	(No statement)
Antimonite [Non renewable resources]	Mass	1,5551E-012	kg		0 %	(No statement)
Barium sulphate [Non renewable resources]	Mass	3,7564E-005	kg		0 %	(No statement)
Basalt [Non renewable resources]	Mass	3,2315E-006	kg		0 %	(No statement)

Outputs

Flow	Quantity	Amount	Unit	Tracked	Standa	Origin
1,1,1-Trichloroethane [Halogenated organic emissions to air]	Mass	1,2866E-012	kg		0 %	(No statement)
1-Butanol [Group NMVOC to air]	Mass	2,9976E-017	kg		0 %	(No statement)
1-Butanol [Organic emissions to fresh water]	Mass	2,8931E-012	kg		0 %	(No statement)
2,4-Dichlorophenoxyacetic acid (2,4-D) [Pesticides to agricultural soil]	Mass	4,2523E-012	kg		0 %	(No statement)
Acenaphthene [Hydrocarbons to sea water]	Mass	4,3911E-013	kg		0 %	(No statement)
Acenaphthene [Hydrocarbons to fresh water]	Mass	9,0959E-013	kg		0 %	(No statement)
Acenaphthylene [Hydrocarbons to fresh water]	Mass	5,6886E-014	kg		0 %	(No statement)
Acenaphthylene [Hydrocarbons to sea water]	Mass	2,7462E-014	kg		0 %	(No statement)
Acentaphthene [Group NMVOC to air]	Mass	4,8353E-013	kg		0 %	(No statement)
Acetaldehyde (Ethanal) [Organic emissions to fresh water]	Mass	5,2698E-012	kg		0 %	(No statement)
Acetaldehyde (Ethanal) [Group NMVOC to air]	Mass	3,6235E-008	kg		0 %	(No statement)

System: No changes. Ecoinvent Last change: System, 1.1.2008

Figure 15. Part of the dataset (equivalent to inventory table) describing Czech energy mix in GaBi 4 software using the ecoinvent 2.0 database, (Hirschier, 2012). It shows not only the elementary flows, but also supplementary information describing the content and origins of the dataset.

2.2.3. Life-Cycle Impact Assessment

LCIA is the phase where the (environmental) impacts of the assessed product system are calculated. Basically the *"… impact assessment is achieved by "translating" the environmental loads from the inventory results into environmental impacts, such as acidification, ozone depletion …"*, (Baumann, 2004). LCIA comprises of three mandatory and three optional steps or "elements" according to ISO 14040 (see scheme in Figure 16).

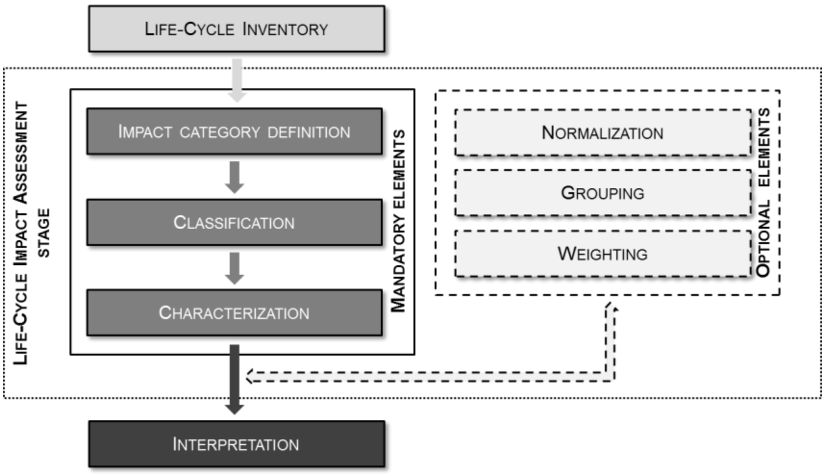


Figure 16. Steps of the LCIA ordered according to ISO 14040. (ISO, 2006a), (Baumann, 2004)

2.2.3.1. Mandatory LCIA steps and LCA impact categories

LCIA begins with definition of impact categories according to the goal and scope of the assessment. An impact category represents specific environmental issue affected by the assessed product system, e.g. global warming. Selection of impact categories therefore influences the informative value of the LCA. (Dong, 2017)

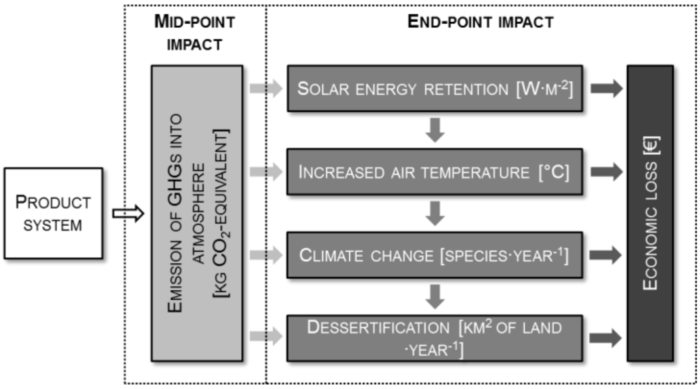


Figure 17. Part of the cause-effect impact chain of GHG emissions based on (Kočí, 2009) and (Baumann, 2004). Examples of available category indicators are shown in square brackets.

The effect of assessed product system in specific impact category is quantified by so called impact category indicator. It could be quantified on multiple levels in a cause-reaction chain (Kočí, 2009), therefore any impact category can have multiple category indicators (and vice versa one indicator could be applied in multiple impact categories). These category indicators could be divided into two groups depending on how the environmental impacts are calculated:

- **Mid-point category indicators.** These indicators quantify the damage to the environment (caused by the product system) indirectly through a reference substance. The damage potential of the assessed elementary flows is expressed using “equivalent quantity” of the reference substance. The equivalent quantity describes what amount of the reference substance would have to be released to the environment to do the same damage as the assessed elementary flow. For example impact of GHG emissions could be evaluated using kg of CO_2-equivalent as impact category indicator. This approach is rather simple due to the fact that emissions could be directly quantified by measurements. (Kočí, 2009)

- **End-point category indicators.** These indicators quantify the actual damage to the environment. For example the impact of GHG emissions could be represented by number of extinct species in a particular ecosystem. It should be noted that accuracy of end-point approach is limited by lack of knowledge regarding the complex interconnections within the environment (Kočí, 2009)

Dozens of individual impact categories and their indicators exist, (Dong, 2017). It was already mentioned (see Section 2.2.1.3) that a preliminary selection of impact categories and indicators should be part of the goal and scope LCA stage. The reason is that the quality and quantity of LCI data depends on it. The selection could be based on common practice, state-of-art or (where available) standardized requirements. Following list describes seven well-known mid-point impact categories that are applied for example in building LCAs in the EU, (CEN, 2011):

- **Global Warming Potential** (GWP). The impacts of the “greenhouse effect” are illustrated by Figure 17. In mid-point context GWP represents the ability of GHG molecules to absorb infrared radiation (i.e. enhance radiative forcing). As mentioned previously, GWP is expressed with equivalent emissions of CO_2 [kg CO_2-eq.] in mid-point context. Scientific basis behind this impact category is further described in (Houghton, 1992).

- **Stratospheric Ozone Layer Depletion Potential** (ODP). Stratospheric ozone naturally protects Earth from ultraviolet radiation. Its depletion causes more radiation to penetrate the atmosphere and cause damage to the environment (plants, animals, people, etc.), (WMO, 2014). In mid-point context ODP is commonly expressed through equivalent emissions of a chlorofluorocarbon Trichlorofluoromethane [kg R-11-eq.] or [kg CFC-11-eq.]. Information regarding the scientific background for this category could be found in (Guinée, 2002).

- **Acidification Potential of Land and Water** (AP). Acid rains that damage plants and degrade soil quality are prime example of acidification. It is caused by acidifying H^+ ions. Acidification is (in mid-point context) therefore expressed by the number of H^+ ions produced per kg of a reference substance – Sulphur dioxide [kg SO_2-eq.]. Further information can be found in (Huijbregts, 1999).

- **Eutrophication Potential** (EP). Eutrophication or nutrification is a phenomenon which could influence land and water ecosystems. It is related with presence of excess nutrients (like phosphor or nitrogen) in the environment. It causes e.g. excessive growth of algae in the water, which consume oxygen necessary for growth of other organisms. In mid-point context the potential damage is described through equivalent mass of phosphates [kg PO_4^{3-}-eq.]. Background information regarding EP impact category can be found in (Huijbregts, 1999).

- **Formation potential of tropospheric ozone photochemical oxidants** (POCP). Excess of ozone and other photo-oxidants in lower levels of the atmosphere is poisonous to living organisms. It is related with human activities (e.g. traffic), however it also depends on local climate (e.g. wind). In mid-point context it is commonly expressed by equivalent emissions of ethane [kg C_2H_4–eq.]. More information could be found in e.g. in (Guinée, 2002).

- **Abiotic Resource Depletion Potential for Elements** (ADP-elements) and **Abiotic Resource Depletion Potential for Fossil Fuels** (ADP-fossil fuels). Both impact categories describe the loss of natural resources and related harm to the environment (e.g. loss of biodiversity). As the titles suggest, first impact category describes depletion of resources like metals, wood, stone, etc. Its common mid-point indicator is equivalent mass of antimony [kg Sb-eq.]. Second impact category focuses solely on extraction of fossil fuels. It uses energy consumption [MJ] as mid-point indicator. Both categories were originally presented together. They were separated to better reflect different aspects of human activities. Further information and overview of scientific background regarding resource depletion could be found in (Heijungs, 1997).

The impact categories listed above are commonly presented together to provide context for the results. However there are also stand-alone impact categories which could be used to describe overall environmental impacts. Examples of such impact categories are:

- **Ecological Scarcity** (UBP). This mid-point impact category originally developed in Switzerland presents environmental impacts of evaluated product system in so called “scarcity points” or “eco-points” [Pts]. The point characteristic is based on aggregated results of multiple impact categories, including those listed previously. (Frischknecht, 2013)
- **Cumulative Energy Demand** (CED). This impact category utilizes energy [MJ] or equivalent energy [MJ-oil eq.] as the means for presenting environmental impacts. In CED the environmental impacts of the product system are made equal to the amount of the (potential) energy contained in the raw materials interacting with the product system. Many similar impact categories such as Primary Energy (PE) or Non-Renewable Energy (NRE) exist. The difference between the impact categories is basically the type of energy which is included in the evaluation. For example NRE impact category considers only energy in non-renewable resources. (Frischknecht, 2015)

Definition of impact categories is followed by classification. At this point all elementary flows have to be assigned (grouped) to the individual impact categories. For example CH_4 emissions could be classified as a cause of global warming.

Classification of all elementary flows is followed by the actual quantification of the environmental impacts. This procedure is commonly described as “Characterization” and the applied mathematical formulae as “Characterization model”. According to (Kočí, 2009) a characterization model could be described by equation

$$EI_{i,X} = CF_{i,X} \times \sum_{r} m_i \tag{1}$$

Where:

$EI_{i,x}$ = resulting value of the impact category indicator for substance (elementary flow) i in impact category X

$CF_{i,x}$ = characterization factor for substance i in impact category X

m_i = assessed amount of substance i, commonly quantified by mass [kg] or volume [m^3]

2.2.3.2. Ready-to-use characterization methods

Above mentioned information illustrate that characterization factors necessary for quantification of environmental impacts are result of multi-disciplinary research in the fields of chemistry, ecology, etc. Any LCA study could be based on such broad scientific foundations. However LCA practitioners often prefer pre-defined characterization factors instead (to save time). For this purpose they can utilize various existing characterization methods providing models for a number of impact categories. Selection of a suitable method depends on the goal and scope of the particular LCA study. There are mid-point (e.g. CML; (Guinée, 2002)) and end-point (e.g. LIME; (Itsubo, 2004)) oriented characterization methods, as well as methods combining both end-point and mid-point approach (e.g. ReCiPe (Goedkoop, 2009) or ILCD (JRC, 2012)). Overview of the available characterization methods can be found in (Guinée, 2002), (Peuportier, 2010) or (Hauschild, 2013).

Characterization methods mentioned in this section are often related. Newer ones (e.g. ILCD) are commonly based on older ones (e.g. CML). Nevertheless, each method represents different scientific view (e.g. focus on a specific region) of the interactions within the environment that surrounds us, (Hauschild, 2013). Therefore the resulting environmental impacts differ even if the methods share the same impact categories, due to different distribution of elementary flows among these categories (see examples in Table 3). For this reason it is advisable to present results in individual impact categories together to provide the necessary context.

Due to continuous development the differences are common even between older and newer versions of the same characterization method. New characterization methods are emerging and the existing ones are updated as our knowledge about the environment will grow.

Table 2. Illustrative list of available characterization methods based on (Hauschild, 2013). If a method has more variants, the table shows the maximum number of impact categories out of all the variants. It should be noted that only “baseline” impact categories are counted in the number. For example Eco-indicator 99 method has 12 impact categories repeating in each of its three assessed “archetypes” (Goedkoop, 2000), which means 36 impact categories in total.

Characterization method	Baseline imp. categories	Localization	Mid-point / End-point	Reference
CML-IA (i. a. CML 96, CML	11	Global	Mid-point	(Guinée, 2002)
Eco-indicator (Eco-indicator 95, Eco-indicator 99)	12	Europe	End-point	(Goedkoop, 2000)
Ecological Scarcity (i. a. Ecofactors 2006, Ecofactors 2013)	14 (turned into 1 overall result)	Switzerland	Combined	(Frischknecht, 2013)
EDIP (EDIP 1997, EDIP	12	Europe	Mid-point	(Hauschild, 2005)
EPS 2000	17	Global	End-point	(Steen, 1999)
Impact 2002+	18	Europe	Combined	(Jolliet, 2003)
LIME (LIME, LIME2)	27	Japan	End-point	(Itsubo, 2004)
LUCAS	10	Canada	Mid-point (Combined)	(Toffoletto, 2007)
MEEuP	21	Europe	Mid-point	(Kemna, 2005)
ReCiPe	21	Global	Mid-point	(Goedkoop, 2009)
TRACI (i. a. TRACI, TRACI 2.0, TRACI 2.1)	12	USA	Mid-point	(Bare, 2011)
USEtox (i. a. USEtox 1.01 or USEtox 2.0)	6	Global / Sweden	Combined	(Rosenbaum, 2008)

Table 3. Comparison of mid-point environmental impacts related with production of cement mortar (calculated in GaBi 4 software) in GWP and ODP impact categories according to different characterization methods.

Characterization method	GWP [kg CO_2-eq.]	ODP [kg R11-eq.]
CML 96	1.945E-01	6.759E-09
CML 2001 (original)	1.948E-01	8.003E-09
CML 2001 (November 2010)	1.952E-01	8.103E-09
EDIP 1997	1.956E-01	7.875E-09
EDIP 2003	1.956E-01	7.875E-09
Impact 2002+ (2.1)	1.923E-01	8.103E-09
TRACI	1.948E-01	8.102E-09
TRACI 2.0	1.952E-01	1.060E-08

2.2.3.3. Optional LCIA Steps

Characterization results are a set of absolute values representing individual impact category indicators. The values are often incomparable as these impact category indicators have different units. Therefore there are the optional LCIA steps, which help with subsequent interpretation of the characterization results to the intended audience: normalization, grouping and weighting.

Using normalization helps with understanding of the LCIA result in a wider (global, regional, state, etc.) context. The characterization results are related to specific reference information (= normalized), for example to the overall environmental impacts of human activities in the same region, (Baumann, 2004). This is done through multiplication of characterization results with pre-defined normalization factors (available in ready-to-use characterization methods):

$$NI_X = NF_X \times \sum EI_{i,X} \ [-] \tag{2}$$

Where:

NI_x = normalized value of the impact category indicator in impact category *X*

NF_x = normalization factor for impact category indicator in impact category *X*

$EI_{i,x}$ = value of the impact category indicator for substance (elementary flow) *i* in impact category *X* calculated according to equation (1)

As mentioned before, normalized environmental impacts show the magnitude of impact category indicator results in the specific context (e.g. region or state). Moreover, it should be highlighted that normalization turns the impact category indicator values into dimensionless quantities. These quantities could be potentially compared or stacked together to a single value (see Figure 18).

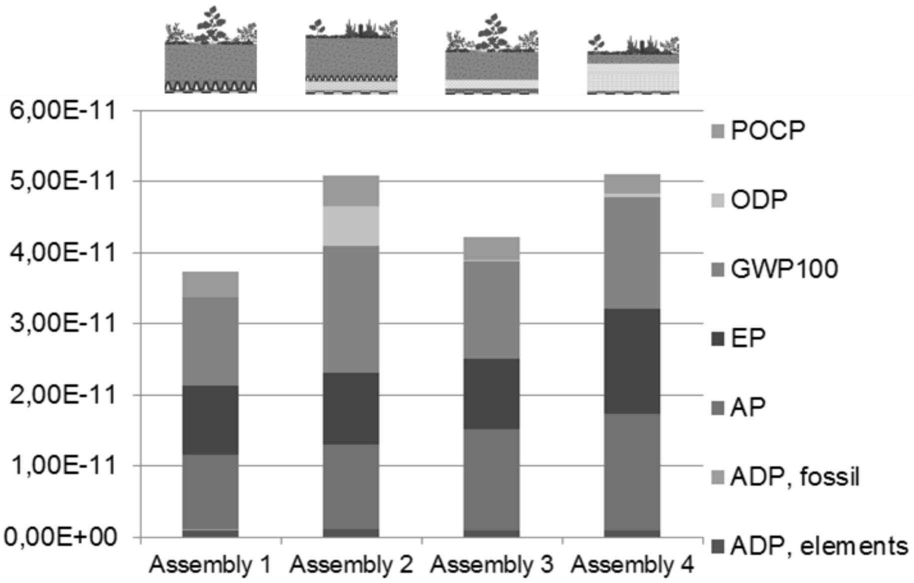


Figure 18. Illustrative example of stacking of normalized results. The chart shows comparison of normalized LCA results of four different green roof assemblies. The results were calculated using CML 2001 (version November 2010) characterization method and normalized with EU-localized normalization factors. Colours represent share of individual impact categories on the stacked result. (Vacek, 2017)

Grouping of the characterization results is similar to grouping in LCI. It is basically sorting of the individual characterization results by scale, localization, type of emissions, etc. The reason is increased clarity, especially when there are many different impact categories. For example Eco-indicator characterization method sorts environmental impacts into three groups (Ecosystem quality, Human health and Resources) according to their role. (Baumann, 2004) (Frischknecht, 2013)

Weighting could be used to highlight relative importance of specific characterization results. It is achieved through multiplication of the characterization results by a specific weighting factor, (Baumann, 2004). Weighting is used for example in building certification schemes like BREEAM that evaluate otherwise incomparable parameters, such as water consumption or indoor air quality, (BRE, 2017). It should be noted that such intentional “distorting” of results should be avoided in general LCA practice.

2.2.4. Interpretation

LCIA provides large quantities of data that could be hard to understand and interpret. Therefore interpretation is the penultimate phase of any LCA study, where “*the findings from the inventory analysis and the impact assessment* *are…"* (ISO, 2006a) analyzed and further processed according to defined goal and scope of the particular LCA. Important findings have to be identified and properly evaluated in this phase. The evaluation should include the following steps according to (Kočí, 2009):

- **Consistency check** validating suitability of used methods for the particular assessment. It includes review of the system boundaries, characterization methods, etc.
- **Completeness check** proving that the amount of LCI data and their level of detail are sufficient for the particular LCA.
- **Evaluation of the quality of input data** focusing on the influence of data gathering methods on the accuracy of the LCI data.
- **Uncertainty analysis** following completeness check and evaluation of the quality of LCI data. It evaluates influence of the input data uncertainties on the LCA results.
- **Sensitivity analysis** evaluating impact of identified problems and variables (e.g. influence of the composition of electricity supply mix) on the overall LCA results.
- **Analysis of variations** evaluating to what extend are the LCA results affected by changes in the modelled scenarios (e.g. application of different production technologies).

The listed evaluations should be part of an inner review of any LCA study. Problems identified during this review should be addressed by subsequent revisions. The inner review should be repeated after the revisions. Sometimes (e.g. in case of product or building certifications) the inner review is followed by a critical review by an independent expert. The critical review results in a report that should verify the findings of the LCA in question, thus increasing its credibility. (Kočí, 2009)

After the evaluation and critical review the Interpretation continues with completion of the LCA report. The report should describe results and the way in which they were achieved. It should explain boundary conditions and other limitations. It should also highlight the conclusions of the assessment and provide recommendations relevant to the intended audience. (Baumann, 2004)

The report is the last step of any LCA study. It is followed by application and dissemination of results that are beyond the authors' influence (see Figure 5).

2.2.5. LCA Tools

Processing of large quantities of data is part of any LCA. First LCA practitioners were significantly limited by the lack of sufficient hardware and software. Currently (thanks to the advances in information technologies) it is possible to process previously unimaginable quantities of data. Still, LCA is rather demanding task and practitioners utilize various software tools to increase their workflow. Development of such tools follows development of standards, LCI databases and LCIA characterization methods.

Currently there are many tools of varying complexity. They could be roughly divided into two groups:

- **General LCA tools** are complex, robust and versatile. They contain extensive databases of LCI data and multiple LCIA characterization models. Some of them even enable creation of new databases and characterizations. Well-known examples of the general tools are GaBi, SimaPro, GEMIS or openLCA.
- **Specialized LCA tools** are employed in specific industries. They do not provide such robustness and freedom as general tools. The databases and modelling options are often limited. These shortcomings are redeemed by faster workflow and result processing corresponding with the aim of the study. For example One Click LCA provides results ready to use in supplementary documents for BREEAM certification. Other building-specific LCA software tools are Eco-Bat, LEGEP, Elodie or Athena.

2.3. LCA Applications in the Building Sector

Section 1 introduced enough reasons for application of LCA in the building industry. First works in this field were published in 1990s (see Figure 7). Nowadays LCA is well-established in the building sector worldwide. It is applied in various situations from evaluation of individual construction materials to assessment of whole buildings or even urban complexes. The increasing importance of LCA is supported by releasing of new standards. The leading role of EU (or CEN) should be highlighted in this regard. This is due to release of two interconnected standards specifying boundary conditions for building LCA: EN 15804 (CEN, 2013) and EN 15978 (CEN, 2011). The former standard focuses on LCAs of construction materials and products, the later on LCAs of whole buildings. Most notable improvement over the general ISO 14040 standard is definition of the individual parts of the product (building) life cycle and their respective boundary conditions. It divides building life cycle into five stages and 17 modules (see Figure 19). Modules A1 to A5 represent the construction of the original building. Modules B1 to B7 represent use of the building. Modules C1 to C4 represent the end the building's life cycle. Module D represents potential positive impacts of the building's life cycle exceeding the standard boundary conditions. The standards also specify impact categories (see Section 2.2.3.1) that should provide complex overview of environmental impacts related with evaluated products.

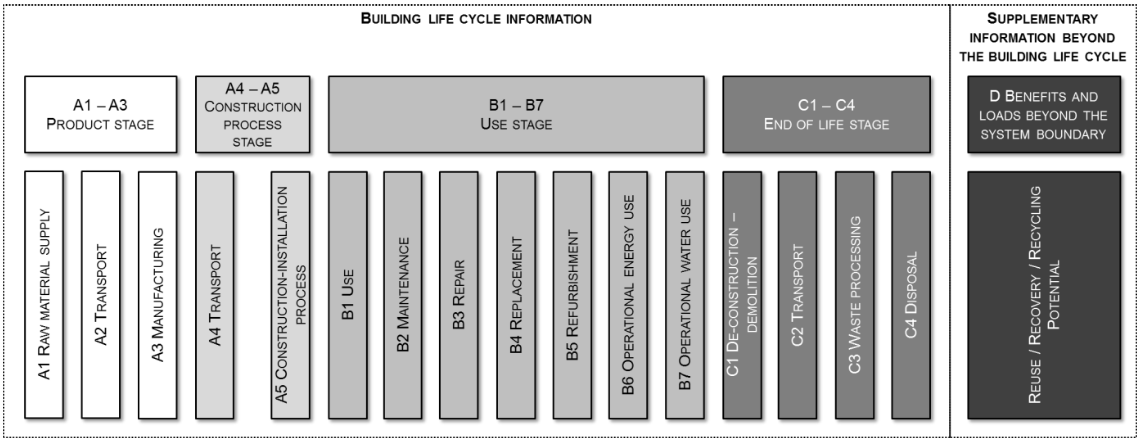


Figure 19. Scheme of the five stages and 17 modules forming the life cycle of a building material (or whole building) according to EN 15804 (CEN, 2013) and EN 15978 (CEN, 2011).

Other national and international standards also exist; e.g. ISO 15868 series of 11 standards describing service life planning and calculation procedures, (ISO, 2011). Moreover there are many methods and guidelines proposed by researchers, government agencies, etc. to provide framework for accurate building (or product) LCA, (Cabeza, 2014). It should be noted that the sheer amount of different methods could be one of the reasons limiting practical application of LCA (in building sector). It indicates that the development of LCA is far from over, which makes specialists such as building designers hesitant to use it. Another reason could be the limited number of LCA specialists. Average knowledge about LCA in many countries (including the Czech Republic) is rather low and there is only a handful of professionals. This also causes high costs of LCA studies (similar to building certifications described in Section 1.5.3).

2.3.1. LCA of Building Materials, Elements, Production and Construction Processes

There are various reasons for LCA of construction materials and other products. The most obvious is the effort to obtain a quality certificate, like the EPD. However LCA is also advantageously utilized for optimization of material composition or production facility operation. Example of such LCA could be found in (Struhala K., 2014). This paper describes LCA of the product stage (modules A1-A3 according to EN 15978 (CEN, 2013)) of experimental thermal insulation composite material using CML2001 characterization model and ecoinvent 2.0 LCI database. The study focuses on evaluation of two types of production line, but it also includes general comparison with other existing insulation materials.

Another reason for application of LCA could be the need for optimization of a specific structure. For example Vacek et al. prepared such LCA to compare environmental impacts of four semi-intensive green roof assemblies. The results were calculated per 1m^2 of the assemblies and 1 year (20-year life cycle) in the impact categories defined by EN 15804 using CML2001 characterization. The study has shown (see Figure 18) that application of novel materials (hydrophilic mineral wool, XPS) does not improve the environmental performance of semi-intensive green roofs. (Vacek, 2017) Similarly, Struhala et al. applied general LCA framework defined in ISO 14040 (ISO, 2006a) to identify the best solution for elimination of the thermal bridge in the parapet wall around flat roof. LCA was the basis of a multi-criteria assessment in this study. It combined thermal efficiency, environmental impacts (AP, EP, GWP, PE) and costs of multiple parapet wall variants. The study evaluated environmental impacts per 1m of the parapet wall and 1 year (20-year life cycle). Results confirmed that energy savings during the operation of the structure are the key for selection of the optimal solution of this structural detail (see Figure 20). (Struhala K., 2014)

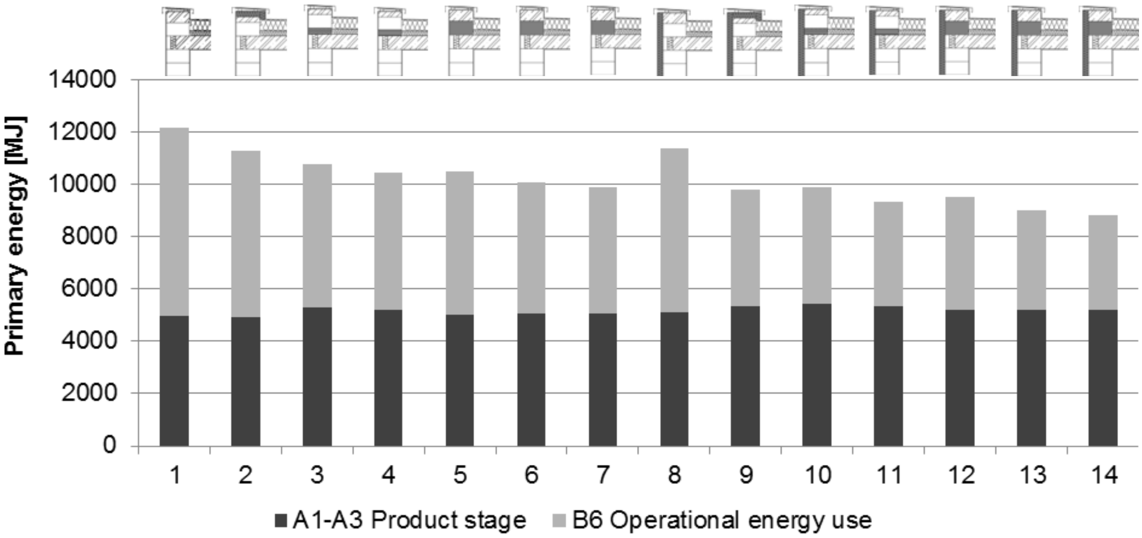


Figure 20. Example of utilization of LCA as a decision-making tool in building design. The chart shows primary energy of fourteen evaluated variants of parapet wall around flat roof. The aim of the study was finding the optimal variant of thermal bridge elimination. (Struhala K., 2014)

Application of LCA is not limited to materials and structures. LCA framework could be successfully applied to construction processes as well. These processes are often simplified or outright omitted in building LCA due to presumable low environmental impacts, (Bilec, 2010). Delem et al. investigated construction of an office building in Belgium. Their study followed the system boundaries set by EN 15978 (CEN, 2011) standard. Ecoinvent 2.2 LCI database was utilized as the basis of environmental data, which were calculated using ReCiPe characterization model. The total environmental impacts presented in the study suggest that the highest environmental impacts are related with construction waste (estimated 5% of supplied materials). (Delem, 2013)

Examples in this section indicate that LCA could be successfully utilized as a decision-making tool for evaluation of individual materials or products and their installation in buildings. It could be also utilized for evaluation of production processes or production facilities. Knowledge acquired through LCA could provide new insight for the building designers and other specialists and thus improve the efficiency of the (building) sector.

2.3.2. LCA of Whole Buildings

LCA enables complex evaluation on different levels: municipalities, buildings, individual building elements or processes taking place during construction. Therefore it could be invaluable for building designers, construction managers and policymakers alike. There are already many building LCA studies. The aim of this section is not a complete list. Instead the following paragraphs introduce several examples of good practise in building LCA.

The most complex studies focus on whole buildings or even urban complexes. For example Chau et al. performed a research on EEIs of high-rise buildings in Hong Kong. They evaluated 18 office buildings, four retail centres and three hotels using Eco-indicator 99 characterization method. The results were calculated per $1m^2$ of construction floor area and 1 year of building operation (during 50-year life cycle). The extensive LCI included not only the construction materials, but also different transport options and construction processes. The study identified 10 materials (e.g. concrete and steel) and technical systems (e.g. electric wiring) with the highest share on embodied environmental impacts (EEIs) of the evaluated buildings. According to the study these materials and systems are responsible for 87.6% of EEIs. The study also suggests that one third of EEIs is related with repairs and replacement of materials and systems with service life shorter than the modelled 50-year life cycle of the buildings. (Chau, 2007) Similar studies dealing with office buildings in other countries were published e.g. by Junnila et al. (Junnila, 2006), Gustafsson et al. (Gustafsson, 2017) or Augustsson (Augustsson, 2014).

Good practise in LCA of residential buildings could be illustrated by Famuyibo et al. They performed extensive research of the life cycle performance of Irish housing stock. The research identified 13 residential building archetypes in Ireland and evaluated their (primary) energy consumption and CO_2 emissions per $1m^2$ of heated floor area and 1 year of operation (during 50-year life cycle). Extent of the LCI and the characterization method were not defined in the published paper. The results indicated that most of the environmental impacts are related with the operation of the evaluated existing buildings. Based on this the authors suggested that modernization of Irish housing stock according to requirements valid in 2012 would bring at least 41% reduction of environmental impacts depending on the particular archetype. Modernization according to passive house requirements would reduce the environmental impacts by up to 82%. Modelled application of renovation measures would increase total environmental impacts only slightly. Operation of the building would still have between 87%.0 and 99.7% share on overall results even after renovation. (Famuyibo, 2013)

Most of the building LCA studies do not cover large samples of buildings like those cited above. They are commonly evaluating individual buildings or a sample of a few similar buildings. For example Struhala and Stránská evaluated environmental impacts of single detached family house in the Czech Republic. The study followed LCA framework defined in EN 15978 (CEN, 2011). The environmental impacts were calculated using CML2001 characterization method. The unit of the assessment was 1m^2 of the treated floor area and 1 year of operation. However the study differed from most by dynamic model of occupancy and related environmental impacts. It also evaluated impact of various length of the service life (50 to 100 years) on the results. The most important result of the study was that dynamic model of occupancy could reduce modelled environmental impacts by almost one fifth compared to the steady-state occupancy model based on maximum design values. Effect of other tested issues on the results was negligible. (Struhala, 2016)

Building LCAs mentioned in this section (except partially Famuyibo et al.) focused simply on evaluation of environmental impacts of new buildings. However LCA could be also utilized in building renovations and modernizations. For example Becalli et al. evaluated the efficiency of renovation of a detached family house in Italy using CED, GWP, ODP, AP, EP and POCP impact categories to quantify the environmental impacts. The study was based on combination of measured data, simulations and LCI database entries. The results are presented per whole building and 1 year of its operation (50-year life cycle). Results indicate that renovation increased embodied energy by 27%. This lead to 74% decrease of operational energy consumption and the resulting CED of the renovation was 58% lower compared to the original state. (Becalli, 2013) Other examples of renovation-related LCA could be found e.g. in (Lesvaux, 2015) or the outcomes of IEA EBC Annex 56 project mentioned in Section 1.5.2. LCA approach was applied throughout the project to identify the optimal solutions for renovation of residential buildings. However the project didn’t aim at accurate building LCA. The system boundaries applied in the project are significantly reduced compared e.g. to the EN 15978 (CEN, 2011). The authors of the Annex 56 methodology justify the reduction by speeding and simplification of the evaluation process. (Ott, 2017) The impact of this on the resulting LCA calculations is not precisely quantified.

2.4. Inaccuracies and Limitations of Building-Related LCA

Previous sections indicate diversity of published LCA studies. It could be argued that the number of different approaches to LCA is necessary to identify and develop the best practise. On the other hand it limits comparison of results between different studies, which is one of the main reasons for LCAs.

One of the common shortcomings of the reviewed building LCA studies is lack of information regarding building construction. Environmental impacts related with the construction itself are commonly omitted as negligible or unquantifiable. Also the information regarding the construction material losses are vague. The LCA studies commonly do not specify what (if any) construction losses are included. When specified, the amount of construction losses differs between studies. E.g. Augustsson in her LCA of Swedish office building considered 10% (by weight) material losses for building elements constructed on-site and 0% for prefabricated building elements, (Augustsson, 2014). Kleeman and Laner measured less than 5% (by weight) material losses during construction of a prefabricated house made of OSB-based structural insulated panels, (Kleeman, 2017). Even such relatively small difference could potentionally influence LCA of a contemporary energy efficient building.

Another issue where the cited LCA studies differ is transport distance. Some studies like Becalli et al. (Becalli, 2013) omit transport as unimportant. Famuyibo et al. (Famuyibo, 2013) consider approximate transport distance of 50km. Other approximations (e.g. 100km) are also common. Such generalization helps with comparison of different studies, but at the same time it reduces the accuracy of the results. On the other hand, there are studies like Augustsson’s (Augustsson, 2014) that consider real-life transport distances in their calculations. This approach ensures accurate results, but also reduces accuracy of comparisons with studies from different geographical regions.

Results suggest that transport has only little share (less than 10%) on the overall LCA results of a building. However this situation may change with centralized production of hi-end materials and components necessary in modern buildings.

There are also several issues related with (construction) waste management in building LCA. First of all is the fact that waste management options differ between countries and regions, (Fischer, 2009). Another related issue is that many countries recently introduced ambitious plans for waste recovery and recycling. In the EU it is the Waste Framework Directive and following local legislation, (MoE, 2014). Accurate modelling of waste management in building LCA therefore limits the applicability the LCA results to a specific geographical region (similarly to transport modelling).

There are several traits common for large number of the published studies, such as 50-year length of estimated building service life. Other traits, such as using floor area as part of the functional equivalent differ only slightly depending on particular study: total floor area, treated floor area, heated floor area, gross, net floor area, etc. are applied. This slight difference often allows at least approximate comparison. However there are differences such as varying system boundaries, characterization methods or utilized LCI databases, which make comparison outright impossible. The problem is illustrated in the study on semi-intensive green roofs by Vacek et al. (Vacek, 2017) mentioned in Section 2.3.1. Its authors claim that they found many studies dealing with the similar topic. However only two studies shared the same characterization model and none shared the same boundary conditions with their study. Another example of such limitations is provided by Silva et al. (Silva, 2017) who performed LCA study on particle board with several different software tools. They concluded that the differences in final environmental impacts could reach up to 66.7% (in POCP impact category).

Described lack of unification currently limits practical use of LCA in the building sector. This is rather unfortunate, as researchers like Kiss and Szalay (Kiss, 2016) suggest that application of LCA in early stages of building design could significantly reduce the environmental impacts related with the life cycle of buildings.

2.5. Section Summary

This section describes the LCA as a method for quantification of environmental impacts of human activities. Most of the section focuses on the method's boundary conditions, steps, available tools or software. The end of this section describes various applications of LCA in the construction industry and connected issues and limitations often encountered in literature. The evaluation of the influence of these issues on the accuracy of LCA is later defined as one of the aims of the dissertation (see Section **Chyba! Nenalezen zdroj odkazů.**) nd thoroughly tested (see Section 6).

3. Aims of the Dissertation

Previous sections summed the reasons for evaluation of environmental impacts of human activities as well as contemporary state-of-art in this field. The LCA was introduced as a promising method for such evaluations. The method is undergoing rapid development. There are still several issues that have to be addressed to support widespread application of accurate environmental impact evaluations.

The general aim of the dissertation is expanding of knowledge of LCA in the building sector in the Czech Republic. Based on the literature review and authors experience with IEA EBC Annex 56 project the dissertation analyses the issues related to building LCA (see Section 2.4) on the renovations of residential buildings. The reasons are: 1) the cited issues are seldom analysed in existing literature, 2) it is necessary to accurately evaluate potential environmental savings to maximize the potential of building renovations and modernizations.

The dissertation aims to:

- Analyse environmental efficiency of renovations (or modernizations) of different types of residential buildings in the Czech Republic,
- analyse impact of the accuracy of input data on the overall results of LCA of residential building (renovation or modernization),
- analyse impact of specific boundary conditions, calculation methods, software and databases on the overall results of LCA of residential building (renovation or modernization).

To fulfil the aims of the dissertation it is necessary to:

- Perform a literature review regarding sustainable construction, LCA in general and applications of LCA in the building industry to identify the state-of-art,
- develop case studies evaluating environmental impacts of renovation of an apartment building and single-family house in the Czech Republic,
- develop variants to the case studies that would allow analysis of the impact of inaccuracies and variations in input data, boundary conditions or calculation methods. These variants should include:

  - different software, calculation methods and databases of input data,
  - different rates of material losses during construction,
  - different material transport distances,
  - different waste management scenarios,
- analyze and compare the results of both case studies to evaluate the impacts of the analyzed inaccuracies and variations on LCA of buildings of different size.

4. Methods and Tools

This section introduces the methods and tools utilized in the dissertation. Most importantly it provides overview of the case studies that are further described in Section 5. It also introduces two software tools utilized for the calculations (Gabi 4 and Eco-Bat 4.0) and describes their limitations.

4.1. Literature Review

Literature review serves as the basis for specification of aims of this dissertation. Reviewed sources include standards, books, journal and conference papers in the fields of sustainable development, LCA in general and LCA in construction industry. The sources are available online, in the Moravian Library or library of the Faculty of Civil Engineering, Brno University of Technology. Part of the online sources (especially journal papers) is available only for a fee. These were accessed thanks to subscriptions of Brno University of Technology or the Moravian Library. Results of the literature review are presented as Sections 1 and 2 of this dissertation.

4.2. Case Studies: Overview

Two case studies located in South Moravian Region of the Czech Republic are evaluated in accordance with the aims of the dissertation. Both case studies are selected because they represent building archetypes common in the region. This fact improves potential application of the results of the dissertation.

First case study is a block-of-flats located at Koniklecová Street in Brno-Nový Lískovec. It is an example of collective housing project from the 1980s. Similar prefabricated concrete buildings were constructed in large quantities between 1950s and 1990s in the Czech Republic, (Skřivánková, 2017). Most of these buildings are characterized by significant heating energy demand and other defects. Therefore they are being renovated and modernized during last two decades, (Drápalová, 2006). Selected block-of-flats Koniklecová 4 was renovated in 2010. The reason for selection of this particular building is that the data regarding the state of the building before and after the renovation are available to the author thanks to participation in IEA EBC Annex 56 project. The building was presented as one of the “shining examples” of good practise in the project, (Mørck, 2017).

Second case study is a terraced single-family house in Přibice, ca 35 km south of Brno. The original building represented archetypical South Moravian terraced house with living quarters, barns and storages. Similar buildings can be encountered in rural areas all across the region as well as in bordering regions in Slovakia and Austria. This particular building was selected due to rather complicated refurbishment design process. Originally the owner planned only basic maintenance and necessary replacement of specific building elements (e.g. windows). Building survey found several structural defects. Thus the owner requested for partial demolition and reconstruction. However further building surveys found more defects. This resulted in demolition of the original building and construction of a new building in its place between 2012 and 2014. Design documentation of all three "stages" of the building design (refurbishment, partial demolition and reconstruction, complete demolition and new construction) is available to the author of the dissertation. This provides opportunity for three separate LCA studies within one case study.

Figure 21. Photographs of both case studies after renovation (construction). Koniklecová 4 block-of-flats is on the left, Přibice 442 single-family house is on the right, (Mapy.cz, 2017).

4.2.1. System Boundaries of the Case Studies

This dissertation contains five LCA studies in total:

- **KO-1** evaluating environmental impacts related with Koniklecová 4 block-of-flats in its original state,
- **KO-2** evaluating environmental impacts related with Koniklecová 4 block-of-flats after the 2010 renovation,
- **PB-1** evaluating environmental impacts related with original single-family terraced house Přibice 275,

- **PB-2** evaluating environmental impacts related with Přibice 275 single-family terraced house after partial demolition and reconstruction of the original building proposed by the owner.
- **PB-3** evaluating environmental impacts related with the new single-family terraced house Přibice 442 built after demolition of the original building no. 275 between 2012 and 2014.

All five LCA studies follow guidelines of ISO 14040 (ISO, 2006a) and EN 15978 (CEN, 2011). It should be noted that the latter standard and the cradle-to-grave system boundaries it introduces (see Figure 19) focus on new construction. Application of these system boundaries on LCA of building renovations can be difficult due to lack of data (designs, energy bills, etc.). Reviewed literature (e.g. (Almeida, 2017) or (Becalli, 2013)) suggests that the parts of the building life cycle prior to the evaluated renovation (parts of modules A1 to B7) and possible co-benefits (stage D) could be excluded from the system boundaries. Such allocation reduces chances for introduction of inaccuracies and highlights the environmental impacts embodied in the renovation itself. Therefore the system boundaries of the LCA studies in this dissertation exclude parts of building life cycle preceding the described renovations (or new construction). This means that LCA modules A1 to A5 in KO-1, KO-2, PB-1 and PB-2 LCA studies describe the renovation (or reconstruction) itself, instead of the original construction of the buildings. In PB-3 LCA study the A1 to A5 modules describe demolition of the original building and new construction. Modules B1 to C4 describe only the use of the buildings after renovation (or new construction) and the final demolition in all five LCA studies. Co-benefits (stage D) are not considered in the LCA studies.

The inventory tables (LCI result) necessary for calculations of environmental impacts focus solely on the buildings themselves. Service lines and pipelines beyond the building envelope, landscaping, access roads, etc. are not considered in the LCA studies. Also, any materials and equipment not permanently attached to the building (e.g. washing machine) are not considered in the LCA studies. This cut-off allocation is applied to avoid uncertainties, such estimates of future development on site.

Parts of the inventory tables describing construction materials, energy consumption, waste management, transport, etc. related with the renovation (construction) are based on available designs, building surveys and information provided by the owners and also producers of the materials. Parts of inventory tables describing use of the buildings after renovation are based on data provided by the users (only KO-1, KO-2), energy certificates (all cases) and estimates based on author’s previous work, (Struhala, 2016). Based on this work the modelling of the use of the buildings also considers full occupancy and no changes in occupant behaviour.

Further description of the buildings, the renovation (construction) process, etc. considered for creation of inventory tables during LCI is presented in Section 5. That section also describes all variations to the basic LCA boundaries considered in this dissertation. The inventory tables are available in Appendix A. The inventory tables structure processes (materials, energy, etc.) considered in the LCA studies into individual modules according to EN 15978 (CEN, 2011). Construction materials (e.g. in modules A1-A3) are further grouped based on the particular building elements to increase clarity of the inventory tables: Foundations, load-bearing walls, floor structures, staircase, roof truss, non-bearing walls and partitions, suspended ceiling, roofing, façade, interior plasters and tiling, flooring, doors and windows, chimneys and BITS. This grouping into building elements is based on literature review, EN 15978 (CEN, 2011) and Annex 56 (Ott, 2017) guidelines and author’s previous experience with building LCA.

4.2.1.1. Reference Service Life

The reference service life of the buildings after renovation (construction) is 60 years in this dissertation. The value is based on Annex B of ISO 15686-1 (ISO, 2011). 50-year reference service life commonly seen in literature (see Section 2.3.2) is considered in several variants of the LCA studies (see Table 4) for comparison purposes.

Detailed information about the service life of all construction materials identified during LCI and included in the inventory tables is not available at this time. Therefore it is necessary to estimate it to provide basis for modelling of maintenance, repairs and replacements. Four scenarios of these estimates are included in the LCA studies in this dissertation. Description of the material service life variants is in Section 5.3.2 and inventory tables in Appendix A.

Table 4. Variants of building service life considered in individual LCA studies.

Service life data origin	KO-1	KO-2	PB-1	PB-2	PB-3
ISO 15686-1 v1	---	---	60 years	---	60 years
ISO 15686-1 v2	---	---	60 years	---	60 years
IEA EBC Annex 56	50 years 60 years	50 years 60 years	50 years 60 years	50 years 60 years	50 years 60 years

4.2.1.2. Functional equivalent and reference unit

Literature review shows that building LCA results are presented in various ways. Some studies present total values, other present environmental impacts per tenant (or user), volume or floor area of the building. The results are presented in two ways in this dissertation:

- **Total results** are presented in comparisons of individual variants within both case studies to highlight the differences,
- **results per 1m^2 of treated floor area and year of operation** are calculated in order to enable comparison between case studies and with literature. This decision is based on literature review. The reason is that treated floor area is commonly the least affected value during building renovation. Therefore it should enable the most accurate comparison of different buildings before and after renovation. Other functional equivalents and reference units suggested by literature unnecessarily distort the results. For example the volume of a building could increase through application of ETICS on the façade and the number of tenants fluctuates in time. (Becalli, 2013), (Lesvaux, 2015), (Almeida, 2017).

4.2.1.3. Impact Categories and Characterization Model(s)

LCA studies in this dissertation do not present environmental impacts in impact categories recommended in EN 15978 (CEN, 2011). The results are calculated in UBP, CED (PE), NRE and GWP impact categories instead (see Section 2.2.3.1). The reason is the limitations of one of the LCA software tools utilized for the calculations (see Section 4.2.2.1). The UBP could be considered as equivalent to normalized environmental impacts provided by other characterization methods, such as CML (see Section 2.2.3.2). It even incorporates the CED, NRE and GWP impact categories. UBP impact category is therefore utilized to present overall results in Section 6 almost exclusively to avoid confusion. Other impact category results are presented only occasionally to highlight specific issues. Results of the calculations in all four impact categories are provided in Appendix D and Appendix E.

4.2.2. Software, Calculation Methods and Databases

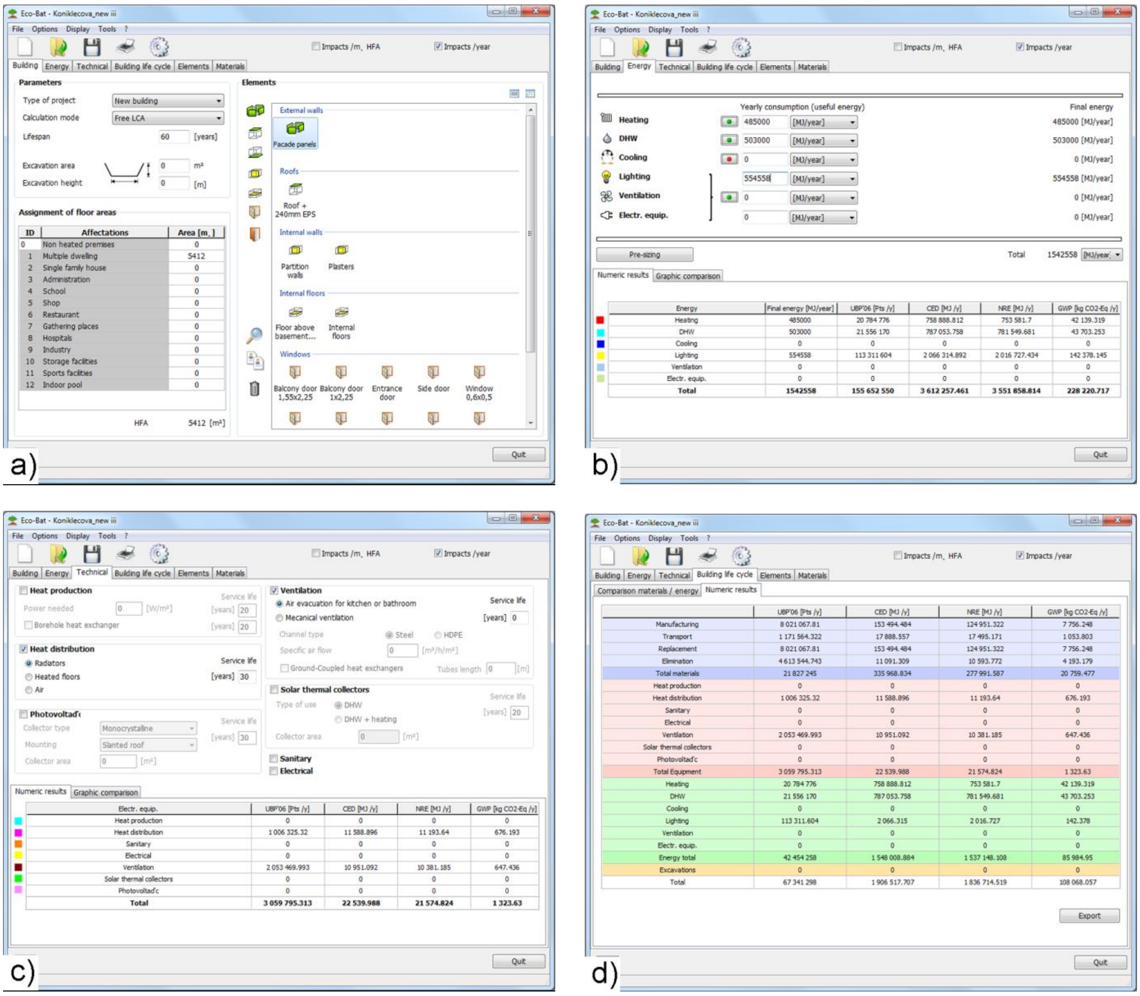
Calculations of environmental impacts in this dissertation are performed using two LCA tools: Eco-Bat 4.0 and GaBi 4. Both tools are available at the Institute of Building Structures, Faculty of Civil Engineering, Brno University of Technology. Eco-Bat 4.0 is utilized in all LCA studies. GaBi 4 is utilized only in PB-1 and PB-3 LCA studies. Reason is the fact that evaluation in GaBi 4 requires more input data (e.g. for description of technical systems) than Eco-Bat 4.0. Such data were not available for KO-1, KO-2 and PB-2 LCA studies. Thus, GaBi 4 is utilized mainly for comparative assessment of the LCA results. Purpose of the comparison is quantification of differences originating in utilization of different characterization models and LCI databases. GaBi 4 is also utilized for detailed assessment of some variations (e.g. waste management scenarios) that is impossible in Eco-Bat 4.0. Detailed description of the variants is in Section 5.3. Following sections introduce basic information about both tools.

4.2.2.1. Eco-Bat 4.0

Eco-Bat 4.0 is a tool for quick and simple building LCA developed in LESBAT laboratories belonging to University of Applied Sciences of Western Switzerland, (LESBAT, 2013). It is meant primarily as a support tool for building designers. For this reason it sacrifices some level of complexity and precision (compared to robust LCA tools like GaBi 4) in favour of ease-of-use and fast workflow. Thanks to this “user-friendliness” it was recommended as the basic LCA tool utilized in IEA EBC Annex 56 project and translated into five languages (English, German, Italian, French and Czech). There are three main reasons for utilizing Eco-Bat 4.0 in this dissertation:

- Availability of the tool at the Institute of Building Structures,

- possibility for comparison of the dissertation results with results of IEA EBC Annex 56 case studies,
- detailed understanding of the advantages and limitations of the tool. This is based on the fact that author of the dissertation worked with developers on Czech and English translation of the tool.



☐ Impacts /m₋ HFA
☑ Impacts /year

Parameters

Type of project: New building
Calculation mode: Free LCA
Lifespan: 60 [years]
Excavation area: 0 m²
Excavation height: 0 [m]

Assignment of floor areas

ID	Affectations	Area [m₋]
0	Non heated premises	0
1	Multiple dwelling	5412
2	Single family house	0
3	Administration	0
4	School	0
5	Shop	0
6	Restaurant	0
7	Gathering places	0
8	Hospitals	0
9	Industry	0
10	Storage facilities	0
11	Sports facilities	0
12	Indoor pool	0

HFA 5412 [m²]

	Yearly consumption (useful energy)		Final energy
Heating	485000	[MJ/year]	485000 [MJ/year]
DHW	503000	[MJ/year]	503000 [MJ/year]
Cooling	0	[MJ/year]	0 [MJ/year]
Lighting	554558	[MJ/year]	554558 [MJ/year]
Ventilation	0	[MJ/year]	0 [MJ/year]
Electr. equip.	0	[MJ/year]	0 [MJ/year]

Total 1542558 [MJ/year]

	Energy	Final energy [MJ/year]	UBP'06 [Pts /y]	CED [MJ /y]	NRE [MJ /y]	GWP [kg CO2-Eq /y]
🟥	Heating	485000	20 784 776	758 888.812	753 581.7	42 139.319
🟦	DHW	503000	21 556 170	787 053.758	781 549.681	43 703.253
🟦	Cooling	0	0	0	0	0
🟨	Lighting	554558	113 311 604	2 066 314.892	2 016 727.434	142 378.145
🟦	Ventilation	0	0	0	0	0
🟩	Electr. equip.	0	0	0	0	0
	Total	**1542558**	**155 652 550**	**3 612 257.461**	**3 551 858.814**	**228 220.717**

☐ **Heat production**
Power needed: 0 [W/m²]; Service life [years] 20
☐ Borehole heat exchanger [years] 20

☑ **Heat distribution**
● Radiators
○ Heated floors
○ Air
Service life [years] 30

☐ **Photovoltaďc**
Collector type: Monocrystalline
Mounting: Slanted roof
Collector area: 0 [m²]
Service life [years] 30

☑ **Ventilation**
● Air evacuation for kitchen or bathroom
○ Mecanical ventilation
Service life [years] 0
Channel type: ● Steel ○ HDPE
Specific air flow: 0 [m³/h/m²]
☐ Ground-Coupled heat exchangers; Tubes length 0 [m]

☐ **Solar thermal collectors**
Type of use: ● DHW ○ DHW + heating
Collector area: 0 [m²]
Service life [years] 20

☐ **Sanitary**
☐ **Electrical**

	Electr. equip.	UBP'06 [Pts /y]	CED [MJ /y]	NRE [MJ /y]	GWP [kg CO2-Eq /y]
🟦	Heat production	0	0	0	0
🟪	Heat distribution	1 006 325.32	11 588.896	11 193.64	676.193
🟧	Sanitary	0	0	0	0
🟨	Electrical	0	0	0	0
🟥	Ventilation	2 053 469.993	10 951.092	10 381.185	647.436
🟩	Solar thermal collectors	0	0	0	0
🟪	Photovoltaďc	0	0	0	0
	Total	**3 059 795.313**	**22 539.988**	**21 574.824**	**1 323.63**

	UBP'06 [Pts /y]	CED [MJ /y]	NRE [MJ /y]	GWP [kg CO2-Eq /y]
Manufacturing	8 021 067.81	153 494.484	124 951.322	7 756.248
Transport	1 171 564.322	17 888.557	17 495.171	1 053.803
Replacement	8 021 067.81	153 494.484	124 951.322	7 756.248
Elimination	4 613 544.743	11 091.309	10 593.772	4 193.179
Total materials	21 827 245	335 968.834	277 991.587	20 759.477
Heat production	0	0	0	0
Heat distribution	1 006 325.32	11 588.896	11 193.64	676.193
Sanitary	0	0	0	0
Electrical	0	0	0	0
Ventilation	2 053 469.993	10 951.092	10 381.185	647.436
Solar thermal collectors	0	0	0	0
Photovoltaďc	0	0	0	0
Total Equipment	3 059 795.313	22 539.988	21 574.824	1 323.63
Heating	20 784 776	758 888.812	753 581.7	42 139.319
DHW	21 556 170	787 053.758	781 549.681	43 703.253
Cooling	0	0	0	0
Lighting	113 311.604	2 066.315	2 016.727	142.378
Ventilation	0	0	0	0
Electr. equip.	0	0	0	0
Energy total	42 454 258	1 548 008.884	1 537 148.108	85 984.95
Excavations	0	0	0	0
Total	67 341 298	1 906 517.707	1 836 714.519	108 068.057

Figure 22. Screenshots of the Eco-Bat 4.0 interface: a) specification of building structures and materials; b) specification of the energy sources and consumption, c) specification of building integrated technical systems (BITS), d) total results.

Figure 22 shows the user interface of Eco-Bat 4.0. Three screens (parts a, b and c of the figure) describe the size of the building, its materials, energy consumption and technical systems. For this purpose the software utilizes in-built LCI database based on ecoinvent 2.2 (Hirschier, 2012) combined with Swiss KBOB statistics (Lesvaux, 2015). The database contains several hundreds of energy and material datasets. It is not possible to modify existing datasets or add new datasets to the database. Therefore some approximations are necessary when modelling the building in the tool (see Section 5.4). Prime example of these approximations is modelling of technical systems (see Figure 22c): There are only several options in the tool, e.g. selection of the type of heating (radiators, heated floors or ventilation). The environmental impacts related with these systems are approximated based on average Swiss KBOB data. Another example is that the tool does not consider waste management of original building parts of a renovated building. Evaluating the impact of these limitations on the results is one of the aims of this dissertation.

Eco-Bat 4.0 utilizes Swiss Eco-factors as characterization method (Frischknecht, 2013) in version 2013 to calculate environmental impacts of the assessed buildings. It should be noted that there's a typo in the tool suggesting that it utilizes previous version of the method. Principle of the method is shown in Figure 23. Its main advantage is that a single result (UBP impact category) represents wide spectrum of environmental impacts. Eco-Bat 4.0 presents environmental impacts not only in the UBP, but also in CED, NRE and GWP impact categories (see Section 2.2.3.1 for details); three latter could be considered parts or sub-categories of UBP.

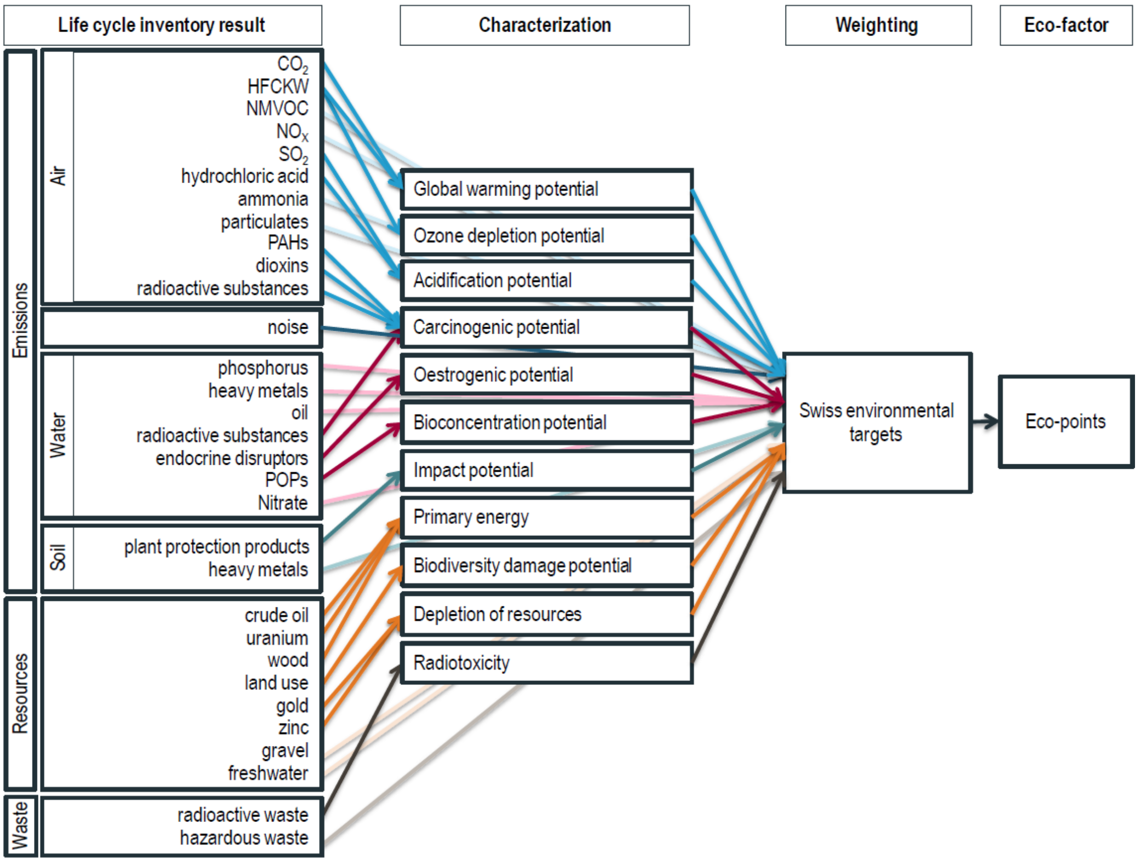


Figure 23. Principle of UBP characterization method. (Frischknecht, 2013)

The results aren't structured according to EN 15978 (CEN, 2011) in Eco-Bat. Instead, they are divided into four groups (with 18 sub-groups): Materials, Equipment, Energy and Excavations (see Figure 22d). These groups correspond with A1 to A3, A4, A5, B4, B6, and C1 to C4 modules defined in EN 15978 (CEN, 2011). Authors of the tool omitted any equivalents of modules C1 and C2 assuming that their environmental impacts would be negligible. Equivalents of modules B1 and B7 are omitted as the authors of the tool assumed that their modelling would be too inaccurate. Finally, equivalents of modules B2, B3 and B5 are omitted as the authors considered them overlapping with equivalent of module B4. Equivalency of individual result groups and standardized building life cycle modules is shown in Table 5. Idealizations necessary to present the results in the form compliant with EN 15978 (CEN, 2011) are described in Section 5.4.1.

Table 5. Assignment of Eco-Bat result groups to equivalent building life cycle modules according to EN 15978 (CEN, 2011).

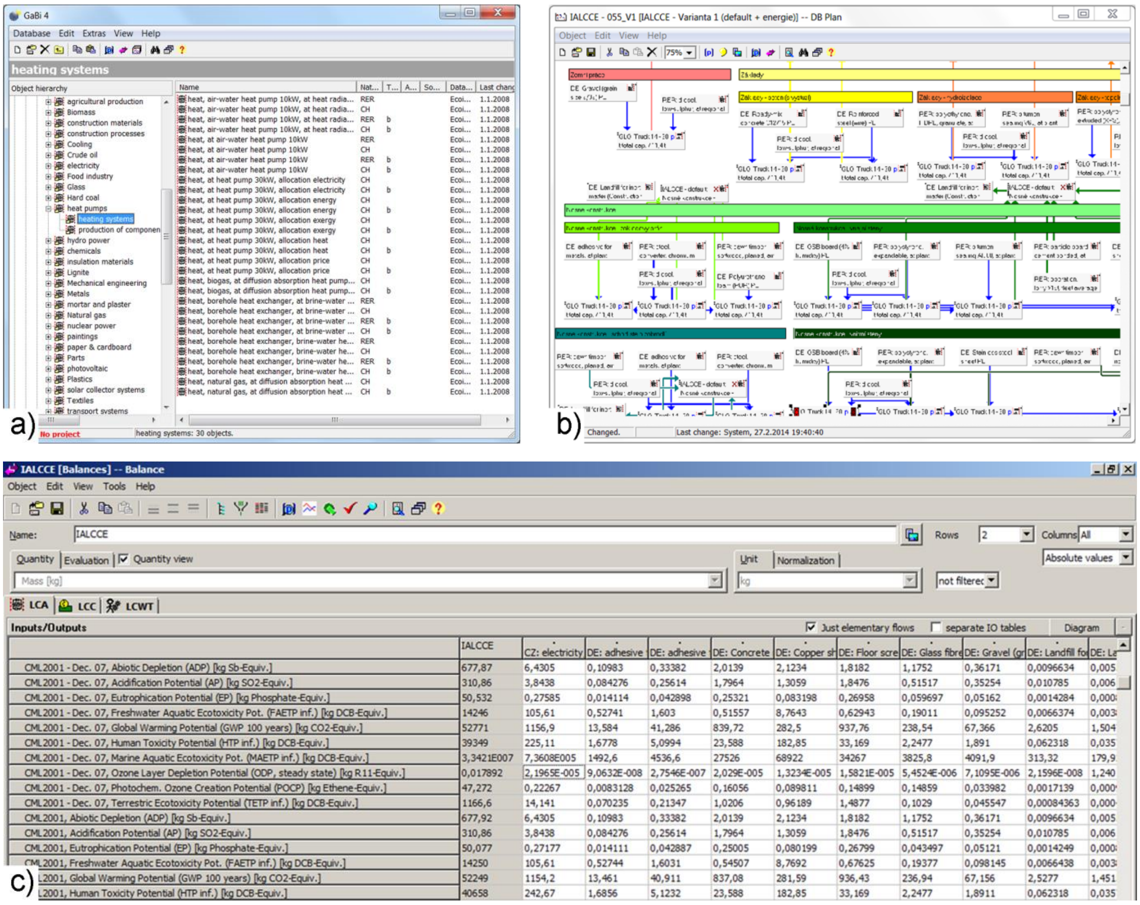
Eco-Bat result grouping		Equivalent EN15978 LCA module
Materials	Manufacturing	A1-A3
	Transport	A4
	Replacement	B4
	Elimination	C1-C4
BITS	Heat production	A1-A3, B4
	Heat distribution	A1-A3, B4
	Sanitary	A1-A3, B4
	Electrical	A1-A3, B4
	Ventilation	A1-A3, B4
	Solar thermal collectors	A1-A3, B4
	Photovoltaics	A1-A3, B4
Energy	Heating	B6
	DHW	B6
	Cooling	B6
	Lighting	B6
	Ventilation	B6
	Electric equipment	B6
Excavations		A5

4.2.2.2. GaBi 4

GaBi 4 is a robust LCA tool developed by thinkstep (previously PE International), (thinkstep, 2017b). It is meant for specialists who could utilize it to perform detailed LCA of any product system. The reasons for utilizing GaBi 4 in this dissertation include:

- Availability of the tool at the Institute of Building Structures,
- open structure enabling modifications of existing datasets and characterization models as well as creation of new ones.

Figure 24 shows the user interface of GaBi 4. All parts of the evaluated product system are modelled in the same way in so called "plans" (Figure 24b). The results are calculated for each plan separately with all characterization models available in the tool at once (Figure 24c).



- agricultural production
- Biomass
- construction materials
- construction processes
- Cooling
- Crude oil
- electricity
- Food industry
- Glass
- Hard coal
- heat pumps
  - heating systems
  - production of componen
- hydro power
- chemicals
- insulation materials
- Lignite
- Mechanical engineering
- Metals
- mortar and plaster
- Natural gas
- nuclear power
- paintings
- paper & cardboard
- Parts
- photovoltaic
- Plastics
- solar collector systems
- Textiles
- transport systems

Name	Nat...	T...	A...	So...	Data...	Last chang
heat, air-water heat pump 10kW, at heat radia...	RER				Ecoi...	1.1.2008
heat, air-water heat pump 10kW, at heat radia...	CH				Ecoi...	1.1.2008
heat, air-water heat pump 10kW, at heat radia...	RER	b			Ecoi...	1.1.2008
heat, air-water heat pump 10kW, at heat radia...	CH	b			Ecoi...	1.1.2008
heat, at air-water heat pump 10kW	RER				Ecoi...	1.1.2008
heat, at air-water heat pump 10kW	CH				Ecoi...	1.1.2008
heat, at air-water heat pump 10kW	RER	b			Ecoi...	1.1.2008
heat, at air-water heat pump 10kW	CH	b			Ecoi...	1.1.2008
heat, at heat pump 30kW, allocation electricity	CH				Ecoi...	1.1.2008
heat, at heat pump 30kW, allocation electricity	CH	b			Ecoi...	1.1.2008
heat, at heat pump 30kW, allocation energy	CH				Ecoi...	1.1.2008
heat, at heat pump 30kW, allocation energy	CH	b			Ecoi...	1.1.2008
heat, at heat pump 30kW, allocation exergy	CH				Ecoi...	1.1.2008
heat, at heat pump 30kW, allocation exergy	CH	b			Ecoi...	1.1.2008
heat, at heat pump 30kW, allocation heat	CH				Ecoi...	1.1.2008
heat, at heat pump 30kW, allocation heat	CH	b			Ecoi...	1.1.2008
heat, at heat pump 30kW, allocation price	CH				Ecoi...	1.1.2008
heat, at heat pump 30kW, allocation price	CH	b			Ecoi...	1.1.2008
heat, biogas, at diffusion absorption heat pump...	CH				Ecoi...	1.1.2008
heat, biogas, at diffusion absorption heat pump...	CH	b			Ecoi...	1.1.2008
heat, borehole heat exchanger, at brine-water ...	RER				Ecoi...	1.1.2008
heat, borehole heat exchanger, at brine-water ...	CH				Ecoi...	1.1.2008
heat, borehole heat exchanger, at brine-water ...	RER	b			Ecoi...	1.1.2008
heat, borehole heat exchanger, at brine-water ...	CH	b			Ecoi...	1.1.2008
heat, borehole heat exchanger, brine-water he...	RER				Ecoi...	1.1.2008
heat, borehole heat exchanger, brine-water he...	CH				Ecoi...	1.1.2008
heat, borehole heat exchanger, brine-water he...	RER	b			Ecoi...	1.1.2008
heat, borehole heat exchanger, brine-water he...	CH	b			Ecoi...	1.1.2008
heat, natural gas, at diffusion absorption heat ...	CH				Ecoi...	1.1.2008
heat, natural gas, at diffusion absorption heat ...	CH	b			Ecoi...	1.1.2008

heating systems: 30 objects.

Name: IALCCE

Inputs/Outputs

	IALCCE	CZ: electricity	DE: adhesive	DE: adhesive	DE: Concrete	DE: Copper sh	DE: Floor scre	DE: Glass fibre	DE: Gravel (gr	DE: Landfill fo	DE: La
CML2001 - Dec. 07, Abiotic Depletion (ADP) [kg Sb-Equiv.]	677,87	6,4305	0,10983	0,33382	2,0139	2,1234	1,8182	1,1752	0,36171	0,0096634	0,005
CML2001 - Dec. 07, Acidification Potential (AP) [kg SO2-Equiv.]	310,86	3,8438	0,084276	0,25614	1,7964	1,3059	1,8476	0,51517	0,35254	0,010785	0,006
CML2001 - Dec. 07, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	50,532	0,27585	0,014114	0,042898	0,25321	0,083198	0,26958	0,059697	0,05162	0,0014284	0,000
CML2001 - Dec. 07, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	14246	105,61	0,52741	1,603	0,51557	8,7643	0,62943	0,19011	0,095252	0,0066374	0,003
CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	52771	1156,9	13,584	41,286	839,72	282,5	937,76	238,54	67,366	2,6205	1,504
CML2001 - Dec. 07, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	39349	225,11	1,6778	5,0994	23,588	182,85	33,169	2,2477	1,891	0,062318	0,035
CML2001 - Dec. 07, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	3,3421E007	7,3608E005	1492,6	4536,6	27526	68922	34267	3825,8	4091,9	313,32	179,9
CML2001 - Dec. 07, Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	0,017892	2,1965E-005	9,0632E-008	2,7546E-007	2,029E-005	1,3234E-005	1,5821E-005	5,4524E-006	7,1095E-006	2,1596E-008	1,240
CML2001 - Dec. 07, Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	47,272	0,22267	0,0083128	0,025265	0,16056	0,089811	0,14899	0,14859	0,033982	0,0017139	0,000
CML2001 - Dec. 07, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	1166,6	14,141	0,070235	0,21347	1,0206	0,96189	1,4877	0,1029	0,045547	0,00084363	0,000
CML2001, Abiotic Depletion (ADP) [kg Sb-Equiv.]	677,92	6,4305	0,10983	0,33382	2,0139	2,1234	1,8182	1,1752	0,36171	0,0096634	0,005
CML2001, Acidification Potential (AP) [kg SO2-Equiv.]	310,86	3,8438	0,084276	0,25614	1,7964	1,3059	1,8476	0,51517	0,35254	0,010785	0,006
CML2001, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	50,077	0,27177	0,014111	0,042887	0,25005	0,080199	0,26799	0,043497	0,05121	0,0014249	0,000
CML2001, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	14250	105,61	0,52744	1,6031	0,54507	8,7692	0,67625	0,19377	0,098145	0,0066438	0,003
L2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	52249	1154,2	13,461	40,911	837,08	281,59	936,43	236,94	67,156	2,5277	1,451
L2001, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	40658	242,67	1,6856	5,1232	23,588	182,85	33,169	2,2477	1,8911	0,062318	0,035

Figure 24. Screenshots of the GaBi 4 interface: a) main interface for accessing individual datasets, characterization models, etc.; b) "plan" where the LCI model is created, c) part of the total results as presented directly in the tool.

Available GaBi 4 version includes two LCI databases: PE Professional and ecoinvent 2.0. The latter is used for the LCA studies in the dissertation as it contains more than 4 000 datasets for individual materials, products, services or processes, (Frischknecht R., 2007).

GaBi 4 provides multiple characterization methods and impact categories for calculations of environmental impacts of the evaluated product system. It is possible to evaluate the whole life cycle of a building corresponding with modules A1 to C4 according to EN 15978 (CEN, 2011).

Four impact categories are selected from the pre-set GaBi 4 database: UBP, PE (equivalent of CED in Eco-Bat 4.0), NRE and GWP. Selection of these impact categories should enable comparison of results with Eco-Bat 4.0. It should be noted that both available tools contain different versions of the characterization models utilized for calculation of results in these impact categories. Eco-Bat 4.0 calculates all environmental impacts with Eco-factors (Frischknecht, 2013) characterization method. GaBi 4 also utilizes this method for calculation of UBP results, although in older version (released in 2006). Results in other three impact categories have to be calculated with different characterization methods. CML2001 (Guinée, 2002) characterization method (version released in November 2010) is selected for calculation of environmental impacts in GWP. The reason is that this is the newest characterization model in the available GaBi 4. Table 3 suggests that there are minimal differences in various characterization methods applied for calculations in GWP impact category. Therefore only minimal impact of this difference on the results is expected. The characterization method applied to calculate primary energy consumption (PE and NRE) is not specified in GaBi 4. Quantification of the impact of various characterization methods on the results is one of the aims of the dissertation.

4.3. Section Summary

This section describes and justifies the methods and tools utilized in the dissertation. It introduces the case studies (described in detail in Section 5), which are the bases of the dissertation and describes their boundary conditions. These are set according to the aims of the thesis (specified in Section **Chyba! enalezen zdroj odkazů.**). The section also provides information on both software tools (GaBi 4 and Eco-Bat 4.0) utilized for calculations of environmental impacts in the individual LCAs, their strengths and weaknesses.

5. Case Studies

This section gives detailed information regarding the case studies (introduced in previous section) evaluated within this dissertation: design, materials, energy and water consumption, etc. It also describes the variables and scenarios intended to test the accuracy of LCA as described within the aims of the thesis (see Section **Chyba! Nenalezen zdroj odkazů.**).

5.1. Block-of-Flats Koniklecová 4

The block-of-flats evaluated in KO-1 and KO-2 LCA studies is property of Brno-Nový Lískovec municipality. The municipality uses it as social housing. It was built in 1983 using the standardized B 70 R/K template. The building has 14 floors in total. Unheated ground floor provides storage facilities and rooms for technical equipment. There are 12 residential floors (five flats per floor; see Figure 25) above it. Last (partial) floor at the top of the building houses the elevator machine room. It also provides access to the building's (cold) flat roof. (Mørck, 2017)

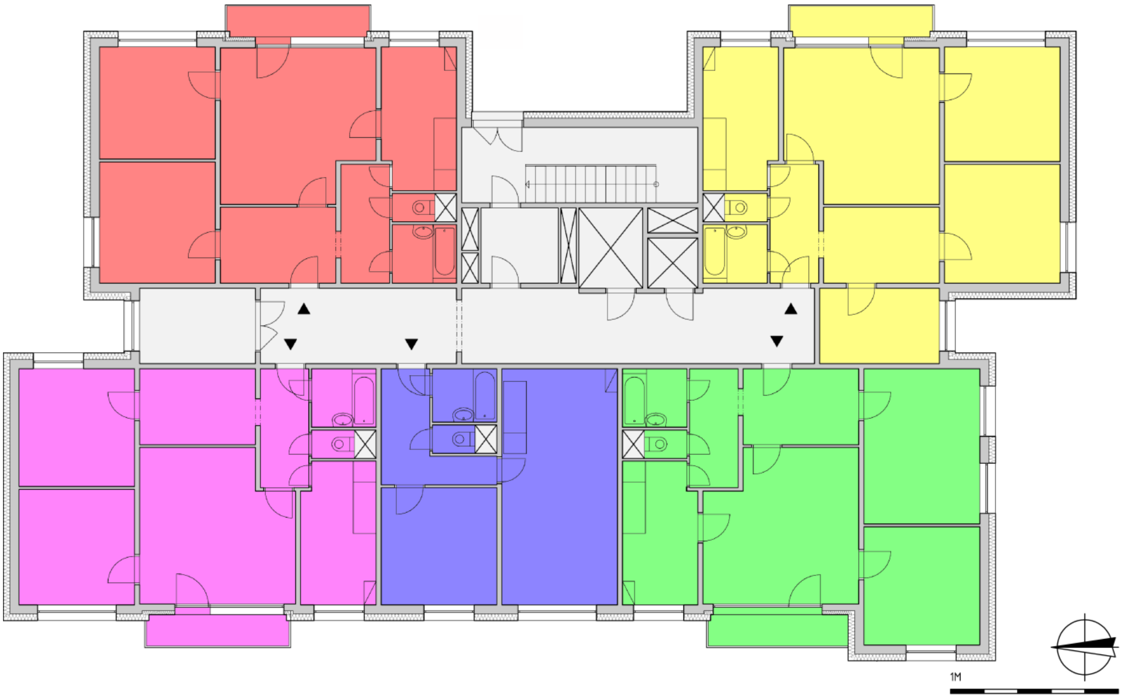


Figure 25. Layout of a residential floor in Koniklecová 4 block-of-flats. Individual flats are highlighted by different colours. (Mørck, 2017)

Sections 5.1.1 and 5.1.2 describe the building before and after renovation. The description is based on renovation designs, author's survey of the building, information from the tenants and municipality. The description was previously published by Mørck et al. (Mørck, 2017) as part of IEA EBC Annex 56 deliverables. In this dissertation the information is utilized for creation of detailed inventory tables (see Appendix A). These tables list quantities of materials and energy related the renovation itself as well as the use of the building before and after the renovation. It should be noted that only limited data regarding the use of the building are available. There is also lack of data regarding BITS, e.g. amount of sanitary ceramics, lengths of pipes or wiring. The environmental impacts of KO-1 and KO-2 LCA studies are therefore evaluated only in Eco-Bat 4.0, where these data are not necessary. This is reflected in the inventory tables describing both LCA studies: they include only data required for evaluation of environmental impacts in Eco-Bat 4.0.

Figure 26. Koniklecová 4 block of flats: Eastern view (left) shows state of the building before the 2010 renovation, Western view (right) shows state of the building after renovation. (Mørck, 2017)

5.1.1. KO-1: Koniklecová 4 before the 2010 Renovation (Mørck, 2017)

Load-bearing structure of the building is made of reinforced concrete wall and floor panels supported by plain concrete foundations slabs and strips. The thickness of the panels varies according to design documentation: floor and interior wall panels are 150mm thick; envelope wall panels are 200 and 270mm thick. Interior partitions are made of reinforced concrete panels, hollow core bricks and particleboard. Partitions dividing storages in the basement are made of wooden latticework.

Thermal protection of the building envelope was provided by 60mm of polystyrene insulation incorporated in the wall panels and 120mm of mineral wool under the roof's air cavity. Waterproofing in basement and on the roof is made of bituminous sheets.

Walls and ceilings were originally covered with 5 to 10mm of cement (or lime-cement) plaster. The façade of the ground floor was originally covered with ceramic tiles. Ceramic tiles were also reported in kitchens and bathrooms. Flooring was made of cast terrazzo, cast concrete or linoleum. Top of the roof parapet walls and other flashing were made of galvanized steel sheets.

Originally there were only windows with wooden frame and double glazing in the building. Some of them were replaced with plastic even before the 2010 renovation. Exterior window sills were made of galvanized steel sheets. Interior window sills were made of ceramics, terrazzo and particleboard. Entrance door and some of the interior doors (in common premises) consisted of steel frame with single safety glazing (with metal reinforcing mesh). Interior door in the flats consisted of metal frame and particleboard wings.

Technical equipment in the building corresponded to the time of construction. The building was heated with steel radiators. Heat was supplied by district heating from nearby (gas burning) heating plant via a water-water heat exchanger connected to underground hot water service pipes. This heat exchanger also heated DHW. Both heating water and drinking water (including DHW) were distributed by metal pipes. Drinking water was supplied with underground metal service pipes. Waste water was discharged via metal sewage pipes. Ventilation of the building was mostly natural. Small electrical ventilators were installed in kitchens, toilets and bathrooms to remove odours and vapours into aluminium and galvanized steel ducts in central ventilation shafts. Lighting equipment consisted of manually operated fluorescent tubes and bulbs. Other electric equipment like the kitchen utensils differed in individual flats. Electricity was supplied with underground service line.

5.1.2. KO-2: Koniklecová 4 after the 2010 Renovation (Mørck, 2017)

The aim of the renovation was achieving significant operational energy savings. Therefore the renovation focused on building envelope and outdated technical systems. Other parts of the building were left in the original state.

Envelope walls were newly insulated with EPS, EPS Perimetr and mineral wool ETICS to reduce heat losses. The thickness of this thermal insulation varies from 120mm to 200mm. Thermal insulation of the roof was increased with 240mm of EPS anchored into the original roof panel. The ventilation openings leading to the air cavity under the roofing were sealed with ETICS and the air cavity remained unventilated. New waterproofing made of m-PVC sheets and Ti-Zn flashing was installed on the roof. Original waterproofing of basement walls was repaired with new layer of bituminous sheets.

Only the doors and windows in the envelope are replaced with new ones. New windows have plastic frames and double (basement) or triple (elswhere) glazing. New main entrance door are made of aluminium frame with triple glazing. New auxiliary entrance door are made of plastic with no glazing. The balconies are converted to closed loggias with sliding windows (aluminium frame, single glazing) to further reduce the heat losses through the balcony doors and windows. New window sills are made of Ti-Zn sheets or plastic.

Exterior wall finishes are made of ceramic tiles (ground floor) and synthetic plaster (elswhere). Interior finishes (flooring, plasters, etc.) were mostly only repaired after window replacement. The only exception is the ceiling above ground floor. This ceiling was insulated with 140mm of EPS and mineral wool to reduce heat losses of the flats in the first floor. The ceiling was also finished with synthetic plaster.

Technical equipment in the building was partially replaced to increase energy efficiency of the building. Pair of new counter-flow heat exchangers was installed in the boiler room. The heating system was divided into Eastern and Western branch to allow better regulation based on the orientation of flats. The renovation of heating system included replacement of original circulation pumps, valves and heads, etc. Some of the original pipes as well as all radiators were left in place as their replacement was deemed too expensive and time consuming. Ventilation equipment (local ventilators and ducts) in all flats was replaced. New noise silencers and outlets were installed. However the original ducts in the installation shafts were left in place. Lighting equipment was replaced in the common premises during the renovation. New energy-saving components and timer-based regulation was installed.

Table 6. Comparison of the energy consumption of Koniklecová 4 block-of-flats before (KO-1) and after (KO-2) the 2010 renovation.

	Treated floor area [m^2]	**Energy certificate**	**Average U-value of building envelope [W·m^{-2}·K^{-1}]**	**Energy consumption**		
				Heating [GJ·a^{-1}]	**DHW [GJ·a^{-1}]**	**Lighting, etc. [GJ·a^{-1}]**
KO-1	5412	E	1.08	1519	631	555
KO-2	5412	B	0.35	485	503	555

5.2. Single-Family Terraced House Přibice 275 (and 442)

Both the original (no. 275) and newly built (no. 442) house in Přibice are private property. The date of the original construction is unknown. The oldest part of the original building can be found in cadastral map of the village from 1879, (ÚAZK, 2018). The building currently standing on the plot was constructed after demolition of the original between 2012 and 2014. All three evaluated variants are described in Sections 5.2.1 to 5.2.3 Detailed inventory tables (see Appendix A) of these variants are based on the design documentation, owner’s information and building surveys. The content of the inventory tables reflects the level of details necessary for evaluation of environmental impacts in specific LCA tools as defined in Section 5.3.

5.2.1. PB-1: Original Přibice 275 Single-Family Terraced House

Original building (see photographs in Figure 27) was a terraced house typical for the region. It had a ground floor with living quarters, garage, barn and storages (see Figure 28 and Figure **29**). Further storages were in the loft (accessible with ladder) and a small cellar. The building had pitched roofs. There was also unused concrete underground tank in the yard. Its function was unclear.

Figure 27. Street view (left) and yard view (right) of the original single-family house in Přibice.

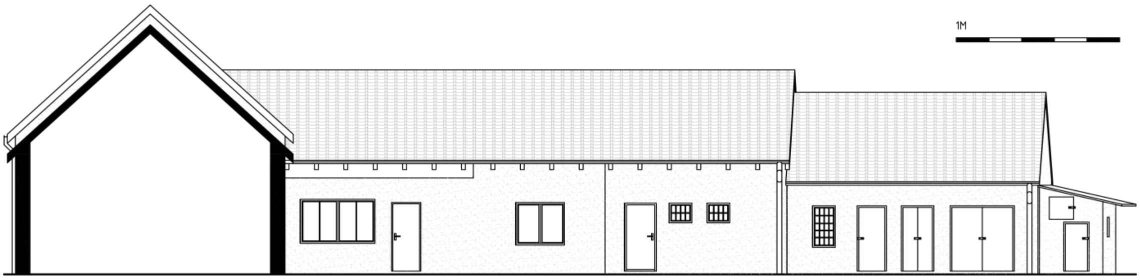


Figure 28. Southern elevation of the original single-family house in Přibice. Black hatching indicates neighbouring building.

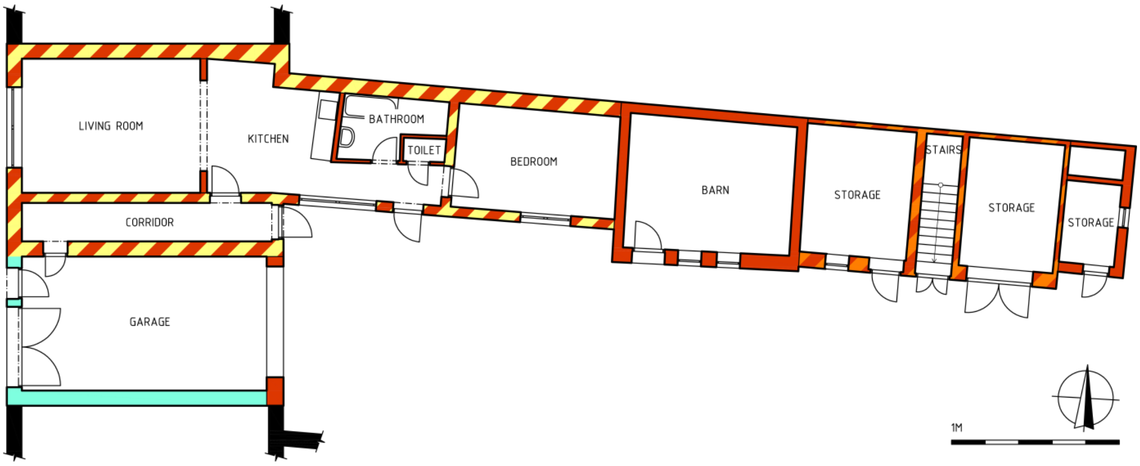


Figure 29. Ground floor plan of the original single-family house in Přibice. Coloured hatching indicates different construction materials identified by the surveys: Black – neighbouring buildings; Red – solid fired ceramic bricks; Blue – aerated concrete blocks; Red-Yellow stripes – mix of solid fired ceramic bricks and adobe bricks; Red-orange stripes – mix of solid fired ceramic bricks and hollow ceramic bricks.

Demolition in 2012 revealed that only part of the original building had foundations. “Foundation strips” found under the walls in the living quarters, barn and storages were made of a layer of sandstone in the ground. Foundation strips under the garage walls as well as the water tank in the yard were made of plain concrete. Walls in the living quarters and the attic were made of a combination of adobe bricks and solid fired ceramic bricks. Walls in other parts of the building were a mix of solid fired ceramic bricks, hollow ceramic bricks and aerated concrete blocks. There were several types of floor structures in the building. Floor structure above garage was made of steel I-profiles and hollow ceramic panels. There was a joist floor above the living quarters. Finally the barn and storages had floors made of steel I-profiles and flat brick vaults.

The building had gabled roofs supported by timber roof truss. The roofing was made of ceramic roof tiles on timber battens. Critical details (valleys, eaves, etc.) were protected by galvanized steel flashing. Other waterproofing was not installed. Rainwater was gathered by galvanized steel gutters and downspouts and released on ground.

Street façade was covered with lime-cement plaster and ceramic tiles. Yard façade as well as interior walls and ceilings were covered predominantly with lime-cement or lime plaster. The plaster was locally reinforced with metal wire mesh. It should be noted that the plaster in the barn, cellar and storages was significantly degraded due to poor maintenance (see Figure 27 – right). Part of the ceilings in the living quarters was made of wooden panelling. Flooring in the garage was made of Terrazzo tiles on a layer of cast concrete. Flooring in the living quarters was made of ceramic tiles and wooden parquets placed on a layer of cast concrete with bituminous waterproofing. Flooring in the rest of the building was made of bricks placed on ground, except the cellar where there was an earthen floor.

The windows in living quarters consisted of wooden frame and double glazing. Windows sills of these windows were made of galvanized steel sheets (exterior) and ceramic tiles (interior) Windows in the rest of the building consisted of metal frame with single glazing. Window sills of these windows were made of the same plaster as the surrounding façade. Garage door were wooden (incl. frame), with single glazing. Other doors in the building were also wooden with wooden or metal frames.

Technical equipment, sanitary equipment, kitchen utensils, etc. in the building were in poor condition and required replacement. Living quarters were heated with electric radiators in individual rooms. The rest of the building was not heated. DHW was heated with electric boiler. Ventilation of the building was natural. The lighting equipment consisted of fluorescent tubes (kitchen) and bulbs. Electricity was supplied with above-ground service line. Water was supplied with underground service pipe. Waste water was discharged into municipal sewage system via steel pipes. Rainwater was gathered by galvanized steel gutters and released on ground.

5.2.2. PB-2: Partial Demolition and Reconstruction of the Original Přibice 275 Single-Family House

This variant describes the hypothetical partial demolition and reconstruction of the building proposed by the owner after initial building survey. Most of the original building should have been demolished according to the owner's requests. The layout and shape of the reconstructed building was based on the original (see Figure 31 to Figure **30**) with changes in the living quarters (expansion to the attic) barn (replacement with a workshop) and stores (demolition and moving to the attic). It should be noted that when the design process of this variant stopped, it required further measures to pass contemporary energy certification. Such measures are not considered in this dissertation. It serves as an example of ad hoc renovations of such residential buildings without proper design documentation and building permits.

The design of the reconstruction considered contemporary building materials and technical equipment to improve the efficiency of the building. The designs included: reinforced concrete foundations and floor structure, new walls (both load-bearing and non-bearing) made of hollow ceramic blocks and timber roof truss supported with steel columns. The attic should have been accessed via wooden staircase. Thermal protection of new envelope structures should have been provided by EPS (ETICS, floating flooring) and mineral wool (attic ceiling) and waterproofing by bituminous sheets (foundations) and plastic membrane (roof).

Surface finishes were designed according to the owner's wishes. Walls should have been finished with synthetic plaster in the exterior, lime and gypsum plasters or ceramic tiles in the interior. The roof should have been covered with ceramic tiles on timber battens (same type as the original). Heavy floating flooring in the ground floor should have been made of terrazzo tiles (garage, workshop and storage), ceramic tiles (wind lobby, kitchen and bathroom) and laminate (living room, bedroom and corridor) on concrete. Light floating flooring in the attic should have been made of ceramic tiles (bathroom and toilet) and laminate (elsewhere in the attic) on OSB boards. The ceiling in the attic should have been made of plasterboard panels (and vapour barrier) supported with timber battens.

Windows with plastic window frames and double glazing were included in the designs. The window sills should have been made of galvanized steel sheets (exterior) and plastic (interior). Entrance door should have been plastic, garage door aluminium (street) and wooden (yard). Interior door should have been made of wood or particleboard. Sliding door should have been encased in aluminium casing with plasterboard cladding.

The building should have been equipped with new technical systems complying with contemporary standards. New plastic service pipes and new electric service lines should have been constructed. Heating should have been provided by radiators supplied by a gas boiler in the attic. Hearth in the living room should have served as an auxiliary heat source. The gas boiler should have also provided DHW. All the piping in the interior should have been made of plastic (gas, DHW), copper or steel (heating). Waste water should have been discharged by new plastic pipes into the municipal sewage system. Rainwater should have been gathered and stored in renovated underground tank in the yard. Natural ventilation of the building should have been supported by local electric ventilators in the kitchen, bathrooms and toilet. Lighting should have been provided by energy saving bulbs.

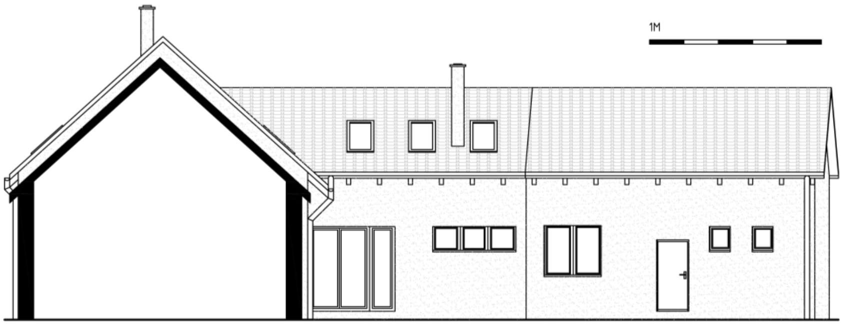


Figure 30. Southern elevation of the hypothetical reconstruction of single-family house in Přibice. Black hatching indicates neighbouring building.

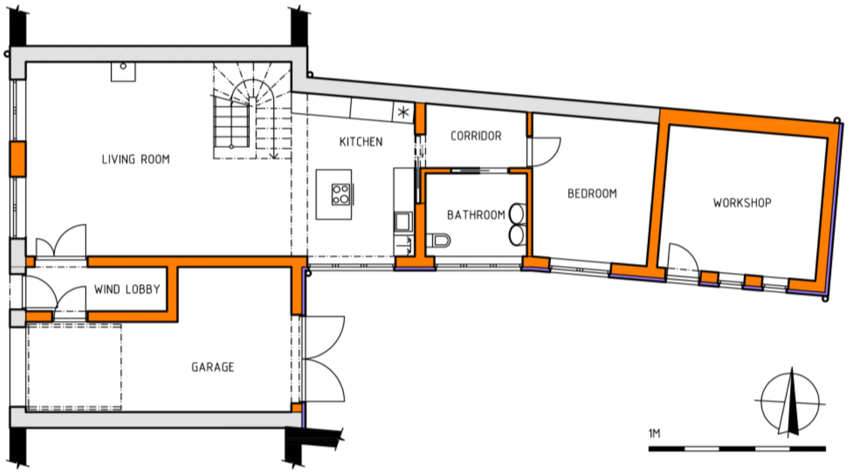


Figure 31. Ground floor plan of the hypothetical reconstruction of single-family house in Přibice. Colours indicate main construction materials: Black – neighbouring buildings; Grey – conserved parts of the original building; Orange – hollow ceramic blocks; purple – additional thermal insulation.

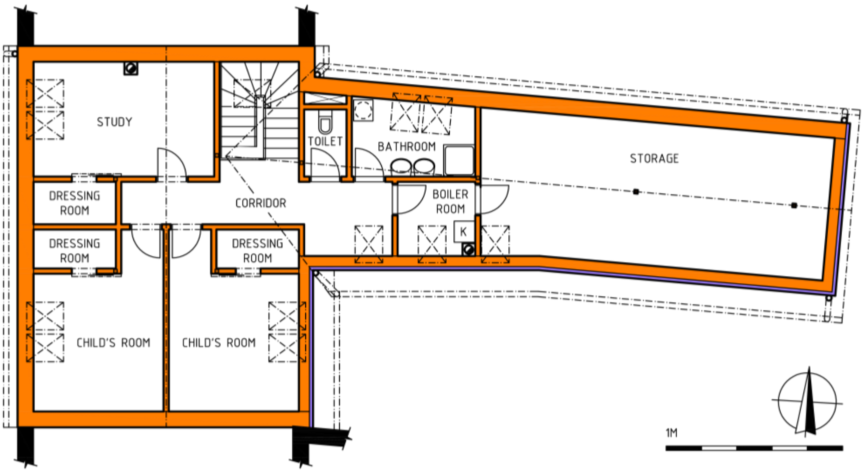


Figure 32. Attic floor plan of the hypothetical reconstruction of single-family house in Přibice. Colours indicate main construction materials: Black – neighbouring buildings; – hollow ceramic blocks; purple – ETICS.

5.2.3. PB-3: Demolition and New Construction of Přibice 442 Single-Family House

PB-3 variant represents the executed real-life scenario. It replaced the original PB-1 single-family house, which was demolished in 2012. New building layout and shape is evolution and simplification of PB-2 design. It comprises only of the living quarters (expanded to the attic) and garage (see Figure 34 to Figure **33**). Original storages, barn and cellar adjoining the living quarters were demolished without replacement. The only original structure left on the plot is the underground tank in the yard, which now serves as rainwater storage.

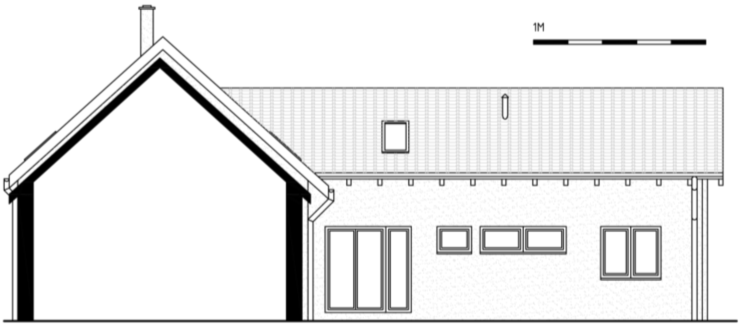


Figure 33. Southern elevation of the new Přibice 442 single-family house. Black hatching indicates neighbouring building.

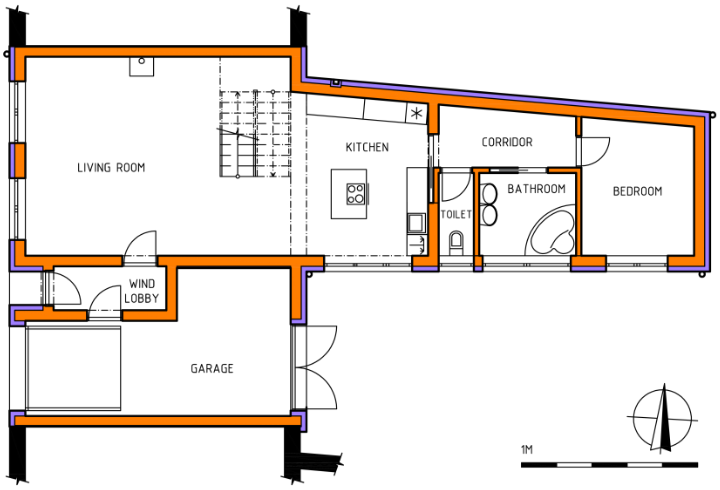


Figure 34. Ground floor plan of the new Přibice 442 single-family house. Colours indicate main construction materials: Black – neighbouring buildings; Orange – hollow ceramic blocks; Purple – ETICS.

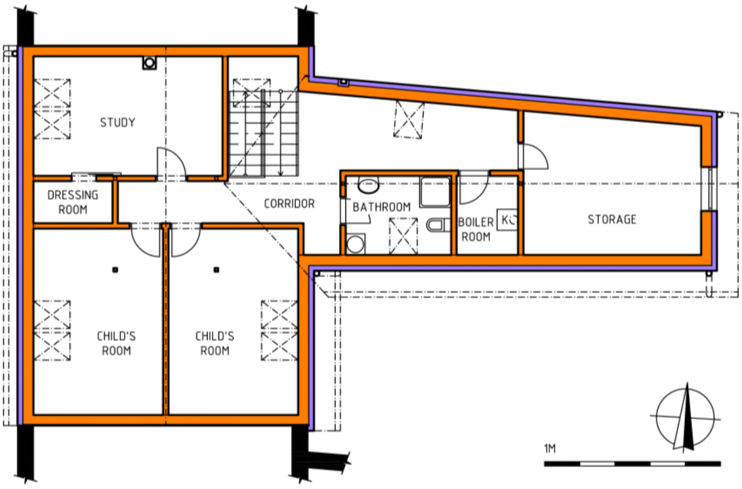


Figure 35. Attic floor plan of the new Přibice 442 single-family house. Colours indicate main construction materials: Black – neighbouring buildings; Orange – hollow ceramic blocks; Purple – ETICS.

The structural and material design as well as design of technical systems of PB-3 is almost identical to PB-2 (see Section 5.2.2). The differences are caused by the fact that no original structures remained in PB-3. Therefore the volume of construction waste (in A5 module) as well as the amount of construction materials (modules A1 to A3 and B4) is larger compared to PB-2. Also the energy efficiency of the building is significantly improved and the building fulfils contemporary energy requirements. Main reason for this improvement is reduced heat loss of the envelope thanks to overall application of hollow ceramic blocks and ETICS (see comparison in Table 7).

Table 7. Comparison of the energy consumption of single-family house in Přibice in original state (PB-1), after the proposed partial demolition and reconstruction (PB-2) and after the executed demolition and new construction (PB-3).

	Treated floor area [m^2]	**Energy certificate**	**Aver. U-value of envelope [W·m^{-2}·K^{-1}]**	**Energy consumption**		
				Heating [GJ·a^{-1}]	**DHW [GJ·a^{-1}]**	**Lighting, etc. [GJ·a^{-1}]**
PB-1	79	G	1.40	171.01	8.33	1.41
PB-2	227	E	0.66	202.30	17.32	2.80
PB-3	259	C	0.34	136.94	7.53	3.31

5.3. Scenarios in the Case Studies

The LCA studies in this dissertation include several variables within the boundary conditions. These are grouped in individual scenarios and scenario combinations. The reason for the variables is author’s previous experience with LCA and lack of unity in the reviewed literature. One of the aims of this dissertation is therefore identification of the impact of these variables on the LCA results. Overview of the application of the variables in the five LCA studies is in Table **8**. It should be noted that the variables are applied for each LCA module separately. The reason is limiting of the number of LCA scenario combinations. Still, the number of scenario combinations varies from six to 324 in each module.

Table 8. List of variables applied in individual LCA studies.

Scenario		**LCA Tool**	
		Eco-Bat 4.0	**GaBi 4**
Material service life	**1**		PB-1, PB-2
	2	KO-1, KO-2, PB-1, PB-2, PB-3	PB-1, PB-2
	3	KO-1, KO-2, PB-1, PB-2, PB-3	PB-1, PB-2
Construction waste quantities	**i**	KO-1, KO-2, PB-1, PB-2, PB-3	PB-1, PB-2
	ii	KO-1, KO-2, PB-1, PB-2, PB-3	PB-1, PB-2
	iii	KO-1, KO-2, PB-1, PB-2, PB-3	PB-1, PB-2
Waste management	**I**		PB-1, PB-2
	II		PB-1, PB-2
	III		PB-1, PB-2
	IV	KO-1, KO-2, PB-1, PB-2, PB-3	
Transport distances	**a**		PB-1, PB-2
	b		PB-1, PB-2
	c		PB-1, PB-2
	d		PB-1, PB-2
	e	KO-1, KO-2, PB-1, PB-2, PB-3	

5.3.1. LCA Tools and Methods

First variable is application of different LCA tools (Eco-Bat 4.0 and GaBi 4) with their in-built LCI databases and characterization methods. Both LCA tools and their limitations are described in Section 4.2.2. Utilization of both tools for quantification of environmental impacts of the same building should provide insight into the accuracy of comparisons of various LCA studies found during the literature review. However, it should be noted that the limitations of the tools also limit applicability of other variables in individual LCA studies (see Table 8).

5.3.2. Number of Replacements – Material Service Life

Section 2.3 introduces differences in specification of service life of buildings. This parameter is interconnected with durability of individual construction elements and materials. Materials with low durability may need replacement during the service life of a building. The number of such replacements increases the quantities of in-built materials and construction waste. This in turn increases EEIs related with the building in question. It may be possible that the EEIs related with the replacements will overshadow environmental impacts of the original construction.

There is currently no unified database specifying service lives of whole buildings or durability of individual construction materials. Three scenarios for modelling the number of replacements of the construction materials and elements are therefore considered in module B4 of the LCA studies to evaluate the variations in EEIs:

(1.) Numbers of replacements are based on the service life values in Appendix B of ISO 15686-1 (ISO, 2011) and rounded down. This scenario is not applicable in Eco-Bat 4.0 due to pre-set service life values. Therefore it is applied only in PB-1 and PB-3 LCA studies performed in GaBi 4.

(2.) Numbers of replacements are based on the service life values in Appendix B of ISO 15686-1 (ISO, 2011) and rounded up. This scenario is applied in all LCA studies in this dissertation.

(3.) Numbers of replacements are based on the IEA EBC Annex 56 methodology (Almeida, 2017). This scenario is applied in all LCA studies in this dissertation.

The numbers of replacements of the construction materials and elements considered in the LCA studies are included in the inventory tables in Appendix A.

5.3.3. Construction Waste Quantification

This variable is based on the fact that the amount of material lost as construction waste during A5 and B4 modules of building life cycle influences EEIs of a building (see Section 2.4). All LCA studies in this dissertation therefore include scenarios with three levels of construction material losses to evaluate the impacts of this variable on the total results. Construction material losses are represented by increased weight of necessary construction materials and waste.

(i.) The amount (weight) of construction materials in the inventory tables is rounded up to individual pieces or packages. E.g. the amount of dry plaster is rounded up to 25kg (the weight of one package).

(ii.) The amount (weight) of construction materials in the inventory tables is increased by 5% and rounded up to individual pieces or packages. The exceptions are the materials in prefabricated elements such as windows or sanitary ceramics. In these cases the material losses should be included in the respective LCI database datasets. Material losses related with the production of prefabricated elements are therefore not considered in this dissertation to avoid possible duplicities.

(iii.) The amount (weight) of construction materials in the inventory tables is increased by 10% and rounded up to individual pieces or packages. Similarly to (ii.), the exceptions are the materials in prefabricated elements.

5.3.4. Waste Management

Four waste management scenarios are considered in the LCA studies in this dissertation. Each represents contemporary waste management options. These scenarios are applied in A5, B1, B2, B4, C1 to C4 modules in the LCA studies:

(I.) Predefined datasets available in ecoinvent 2.0 LCI database are utilized for modelling of waste management.

(II.) Ecoinvent 2.0 datasets are modified to represents a situation when all waste (except waste water) related with the life cycle of the evaluated building is landfilled.

(III.) Ecoinvent 2.0 datasets are modified to represents a situation when all waste (except waste water) related with the life cycle of the evaluated building is recycled.

(IV.) Predefined datasets available in Eco-Bat 4.0 (based on ecoinvent 2.2 datasets) are utilized for modelling of waste management. It should be highlighted that this scenario does not consider demolition waste related with original building due to limitations of the tool.

Scenarios (I.), (II.) and (III.) are applied only in PB-1 and PB-3 LCA studies in GaBi 4. The reason is that individual datasets in Eco-Bat 4.0 include pre-set waste processing. This is represented by scenario (IV.).

Specific datasets (originating in ecoinvent 2.0) representing waste management in scenarios (I.), (II.) and (III.) are listed in inventory tables in Appendix A. List of individual processes representing waste management in Eco-Bat 4.0 datasets in scenario (IV.) is not available.

5.3.5. Transport Distances

Literature review suggests that the impact of this variable on the total results of the LCA studies should be minimal. Five transport distance scenarios are considered to test this presumption:

(a.) 100km transport distance between material producers (or waste processing facilities) and building site is considered.

(b.) 50km transport distance between material producers (or waste processing facilities) and building site is considered.

(c.) Median transport distances between nearest material producers (or waste processing facilities) and municipalities in Brno – Město and Brno – Venkov districts are considered. Producers of ten common building materials were identified for this scenario: Concrete, ceramic roof tiles, hollow ceramic bricks, mineral wool, mortars and plasters, plasterboard, plastic and bituminous waterproofing, plasterboards and sawn timber (and other wood products). Position of production facilities of other materials is not identified due to insufficient data. Therefore the transport distance applied for other materials and services is represented by a median value of the transport distances of the ten listed materials.

(d.) Actual transport distances between nearest material produces identified in scenario (c.) and the building site are considered. The locations of the production facilities of ten common building materials are the same as in scenario (c.). Transport distances applied for other building materials are calculated in the same way as in scenario (c.)

(e.) Transport distances pre-set in Eco-Bat 4.0 are considered.

Transport distances in scenarios (c.) and (d.) are based on positions of the nearest production facilities according to Google maps (Google, 2017) and

Mapy.cz (Seznam.cz, 2017) websites as of June 2017. Positions of these production facilities were identified via publicly available sources (e.g. trade register or producers’ websites). Maps documenting position of the production facilities are in Appendix B. . All transport distances considered in the LCA studies are listed in Appendix C.

Scenarios (a.) to (d.) are applied only in PB-1 and PB-3 case studies in GaBi 4. The reason is that the latest version of Eco-Bat 4.0 does not allow modifications of pre-set values (scenario e.)

5.4. Necessary Idealizations

There are two types of idealizations applied in the LCA studies in this dissertation. First is simplification of the building life cycle framework defined in EN 15978 (CEN, 2011). The reasons include overlapping of the boundaries of specific LCA modules, lack of data describing specific LCA modules and limitations of the utilized LCA tools. The other type of idealization is based on the fact that inventory tables of all LCA studies contain dozens of individual entries. LCI databases in Eco-Bat 4.0 and GaBi 4 do not contain equivalent processes for all of them. Therefore it is necessary to either model the missing processes or replace them with similar processes available in the databases.

5.4.1. Idealization of Building Life Cycle

Level of idealization or simplification of the structure of building life cycle standardized in EN 15978 (CEN, 2011) depends on the specific LCA tool. In Eco-Bat 4 the necessary idealization originates in its pre-defined structure. Table 5 in Section 4.2.2.1 shows how the Eco-Bat 4.0 results could be processed and rearranged into standardized LCA modules A1 to A3, A4, A5, B4, B6 and C1 to C4. This rearrangement is not perfect and results representing Manufacturing (equivalent modules A1 to A3) and Elimination (equivalent modules C1 to C4) in Eco-Bat 4.0 cannot be broken down and assigned to individual standardized modules. Another issue is that original construction materials and equipment cannot be included in the assessment in any way (e.g. as demolition waste at the end of the modelled building life cycle). This allocation reduces total environmental impacts of the renovated buildings life cycle. On the other hand it highlights the impact of any renovations or modernizations compared to maintaining of the original state of the building in question.

Open structure of GaBi 4 enables modelling of whole building life cycle. Still, several idealizations were applied during the calculations in this tool as well. Module B3 is omitted due to lack of data describing future user behaviour. Module B5 is omitted as all works potentially related with it are assigned either to modules A1 to A5 or module B4. Modules A5, B2, B4, C1, C2, C3 and C4 are included with some idealization of individual processes described in following sections.

5.4.2. Idealization of Construction Materials

Idealization and substitutions of one material with another are common issue in LCA studies. Inventory tables in Appendix A provide complete list of materials, elements and process considered in the case studies in this dissertation. The quantities of listed materials (e.g. consumption of mortar) are based on design documentation of individual case studies, description of individual ecoinvent 2.0 datasets and producer specifications. The tables also include list of matching Eco-Bat 4.0 and ecoinvent 2.0 (in GaBi 4) database datasets that are assigned to these materials. Eco-Bat 4.0 allows only matching of inventory table entries with provided datasets. Therefore accuracy of matching some materials is limited: e.g. vapour sealing tapes have to be matched with PE vapour barrier. In contrast GaBi 4 enables modelling of missing datasets. This should provide more accurate basis for the calculation of environmental impacts. Examples of such models are in Figure 36. The models are based on description of individual ecoinvent 2.0 datasets as well as (material) producer data.

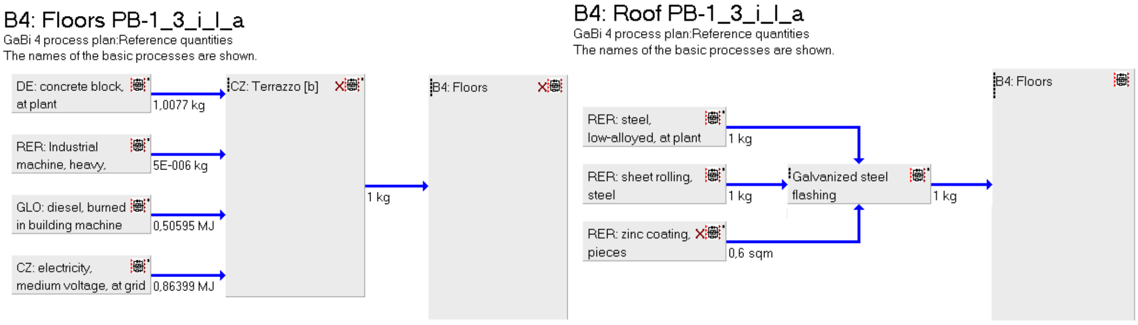


Figure 36. Examples of idealization in the modelling of construction materials. Left: Production of Terrazzo flooring tiles. Right: Production of galvanized steel flashing.

Another issue related only with Eco-Bat 4.0 is modelling of BITS. It was already mentioned in Section 4.2.2.1 that the tool provides only pre-set options for modelling of BITS. For the purpose of this dissertation the options representing Heat distribution (e.g. boiler or radiators), Sanitary equipment (e.g. bathtubs or fresh water pipes) and Ventilation are considered in the individual LCA studies. Electrical equipment is not considered as it does not include only wiring, but also washing machines, televisions, and other appliances, which are out of the set system boundaries. Other options (Heat production, Photovoltaics, Solar thermal collectors) are not considered as they represent systems, which are not installed in the evaluated buildings.

5.4.3. Idealization of Construction Processes

Building construction (LCA module A5) is limited only to excavation works in Eco-Bat 4.0. Therefore this section focuses on modelling in GaBi 4 (LCA studies PB-1 and PB-3). Construction process is represented by on-site use of building machines for mixing and pouring of plasters, mortars and concrete – see Figure 37. Data on energy consumption of the machines are based on the description of their respective ecoinvent 2.0 datasets. Volume of mixing water is calculated based on producer data. Other site equipment like scaffolding is not considered. This decision is based on author’s previous work, where the environmental impacts related with such equipment were negligible compared to on-site energy and water consumption, (Struhala, 2016). Processing of construction waste (see Section 5.4.5) is also included when relevant (especially LCA module B4). Quantities of energy, water, etc. considered during modelling as well as matching ecoinvent 2.0 datasets are included in inventory tables in Appendix A.

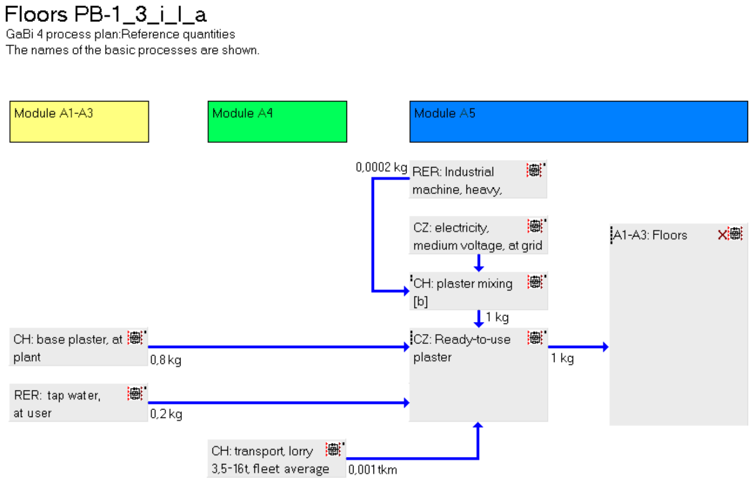


Figure 37. Part of the GaBi 4 model of PB-3 reconstruction showing the datasets utilized to model plaster production and processing.

5.4.4. Idealization of Building Use and Maintenance

It is not possible to model building use (LCA module B1) and maintenance (LCA module B2) in Eco-Bat 4.0. Therefore this section describes modelling in GaBi 4 only (LCA studies PB-1 and PB-3). Building use is represented only by production and processing of municipal waste in this dissertation. The amount of municipal waste is based on author's previous work, (Struhala, 2016). Maintenance is represented by weekly cleaning (wet wiping and vacuuming), annual revisions of technical equipment by a technician and painting of surfaces (e.g. metal door frames) in five to ten year intervals. Electricity, water and detergent consumption during cleaning was estimated based on the treated floor area. Environmental impacts related with the revisions are represented by transport distance travelled by the technician (according to scenarios in Section 5.3.5). The amount of paint is calculated based on the area of the painted surfaces and paint producer data. Quantities of the materials and energy consumption as well as matching ecoinvent 2.0 datasets are listed in inventory tables in Appendix A.

5.4.5. Idealization in Waste Management

Section 5.3.4 introduced four waste management scenarios. These scenarios are included in modules A5, B1, B2, B4 and C1 to C4 in individual LCA studies. In scenarios (I.) and (IV.) the entries in inventory tables are matched with predefined datasets in Eco-Bat 4.0 and GaBi 4 databases respectively. The conversion is automated and connected to specific construction material in Eco-Bat 4.0. Therefore scenario (I.) models only processing of construction and demolition waste. In contrast the in-built ecoinvent 2.0 datasets have to be selected manually in GaBi 4. This enables adding of municipal waste processing and waste water processing in scenario IV. It should be noted that waste transport has to be added to some ecoinvent 2.0 datasets.

Scenarios (II.) and (III.) describe hypothetical situation when all waste (except waste water) is landfilled or recycled respectively. Modelling of these scenarios is possible only in GaBi 4. Therefore these scenarios are considered only for PB-1 and PB-3 LCA studies. Both scenarios are applied on construction and demolition waste and municipal waste alike. The difference between these types of waste is that processing of municipal waste does not include demolition or deconstruction works.

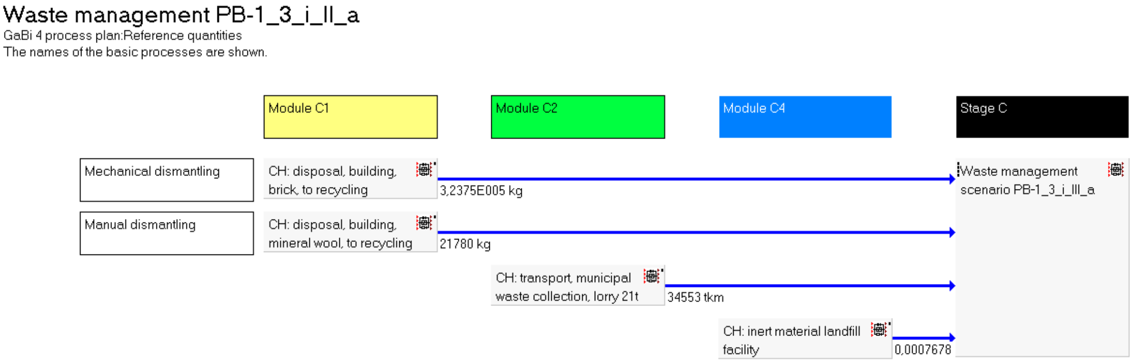


Figure 38. GaBi 4 model of waste management according to scenario (II.).

Waste management in scenario (II.) is modelled based on detailed review of the original ecoinvent 2.0 datasets. The review revealed that various datasets describing construction and demolition waste management share the same basis. There are only two processes representing construction or demolition waste creation (LCA module C1) in the ecoinvent 2.0 database: manual dismantling or mechanized demolition. There is only one process applied in all options of waste transport (LCA modules B1, B4 and C2) and also only one process applied for landfilling of all waste (LCA modules B1, B4 and C4). This enabled modelling of landfilling as an option for all materials in the inventory tables. Figure 38 illustrates how the model is created. Amounts of waste, energy or machinery are calculated based on the information in the original ecoinvent 2.0 datasets and inventory tables (see □). For example the dataset describing the landfill states that the maximum capacity of the modelled facility is 450 000 m^3 of waste. Environmental impacts related with landfilling in scenario (II.) are therefore based on the ratio between the calculated construction waste volume and predefined capacity of the landfill.

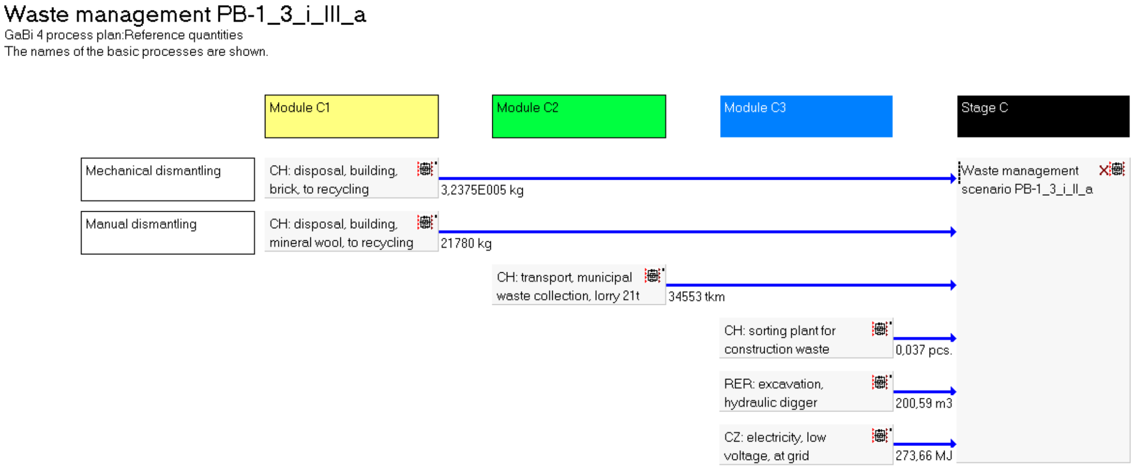


Figure 39. GaBi 4 model of waste management according to scenario (III.).

Waste management scenario (III.) describes situation when all construction and municipal waste is recycled. This scenario shares the processes representing demolition and deconstruction (LCA module C1) and waste transport (LCA modules B1, B4 and C4) with scenario (II.). Waste processing (LCA modules B1, B4 and C3) is represented by a sorting plant and its operation. Module C4 is not considered in this scenario as the sorted waste is a secondary raw material. Environmental impacts related with further processing of such secondary raw material (module D) are not considered in the dissertation. Amounts of waste, energy or machinery necessary for modelling of scenario (III.) are calculated based on the information in the original ecoinvent 2.0 datasets and inventory tables (see □). Modelling of waste management in scenario (III.) is illustrated in Figure 39.

5.5. Section Summary

This section provides detailed information on the case studies of building renovation evaluated in this dissertation: Block-of-flats Koniklecová 4 and single-family house Přibice 275. In total five LCA studies are described based on these buildings. These represent their original state and state after renovation (or demolition and new construction in one case): construction materials, energy consumption, etc. The section also describes all variables and scenarios developed to fulfil the aims of the dissertation in the LCA studies: frequency of replacements (three scenarios), amounts of construction waste (three scenarios), waste management (four scenarios) and transport distances (five scenarios). Lastly this section explains idealizations and simplifications necessary to model the buildings in the selected software tools.

6. Results and Discussion

This section describes environmental impacts of individual LCA studies introduced in Section 5. In KO-1 and PB-1 LCA studies the results represent maintaining of the original state of the evaluated buildings during the modelled 60-year service life and subsequent end-of-life scenarios. In other LCA studies the results include the renovation (or new construction) and maintaining of the buildings in the new state during the 60-year service life as well as end-of-life scenarios.

The results of calculations in Eco-Bat 4.0 and GaBi 4 are presented separately in Sections 6.1 and 6.2. The environmental impacts are described mostly only in UBP impact category in this section to increase clarity of interpretation. Environmental impacts in CED, NRE and GWP impact categories are included only occasionally to provide more detailed information or highlight specific issues. Therefore if the text in this section describes “environmental impacts”, it refers to environmental impacts in the UBP impact category if not stated otherwise. Results in all impact categories are provided in Appendix D and Appendix E.

Generally, the results are grouped according to standardized life cycle structure defined in EN 15978 (CEN, 2011). Detailed results, such as EEIs of individual building elements are grouped in the same way as the individual entries in inventory tables (see Section 4.2.1 and Appendix A) to avoid confusion.

Additionally, Appendix D present Eco-Bat 4.0 results as grouped in the tool. This grouping is not presented in following sections as it is potentially misleading: It divides environmental impacts related with materials in four sub-groups, but environmental impacts related with particular technical systems are provided as one aggregated number for the whole building life cycle.

6.1. Eco-Bat 4.0 Results

This section describes environmental impacts of individual scenarios considered in KO-1, KO-2, PB-1, PB-2 and PB-3 LCA studies as calculated with the Eco-Bat 4.0. In total six scenario combinations are considered in each LCA study. It should be reminded that due to the limitations of the tool the results do not cover environmental impacts related with the original construction or any renovations (or demolitions) preceding those described in Section 5 in any way.

6.1.1. KO-1 and KO-2 LCA Studies

Figure 40 shows total environmental impacts of all the scenario combinations considered in KO-1 and KO-2 LCA studies as defined in Section 5.3. It shows that the highest environmental impacts are achieved by the combination of construction waste scenario (iii.) and replacement scenario (3.) in KO-1 LCA study. This scenario combination has 19.33% higher total environmental impacts than the lowest KO-2 combination of construction waste scenario (i.) and replacement scenario (2.).

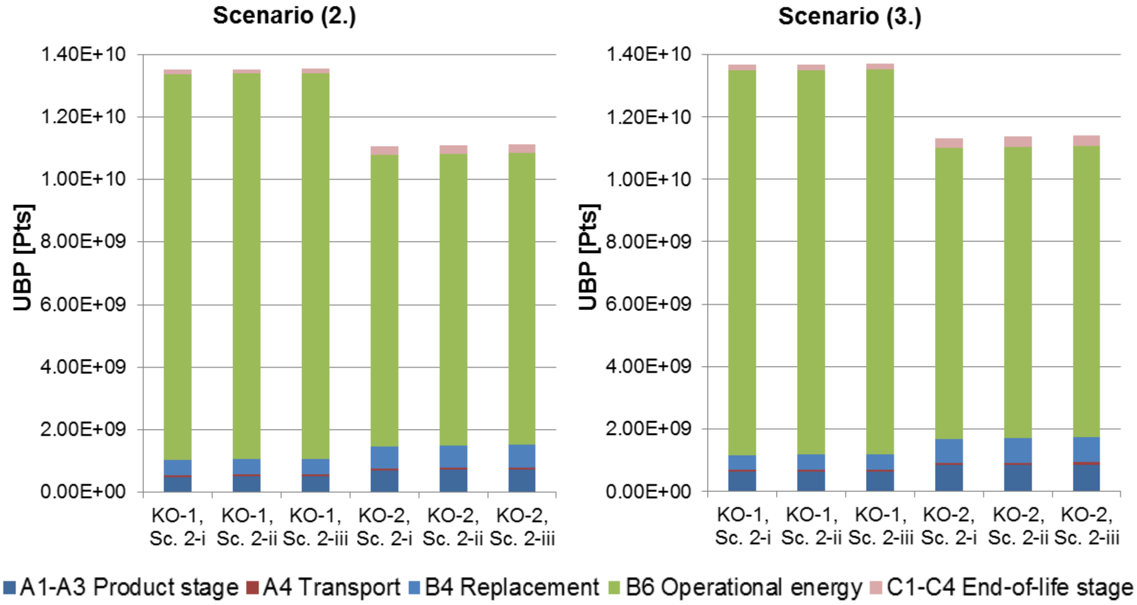


Figure 40 Total environmental impacts related with combination of individual scenarios in KO-1 and KO-2 LCA studies.

Overall the charts confirm positive effect of the renovation in reducing building's environmental impacts (as described in Section 2.3). KO-2 LCA study has on average 17.39% lower total environmental impacts compared to KO-1. The most important reason for the difference are operational energy savings as operational energy is (under set boundary conditions) responsible for most environmental impacts related with the modelled life cycle of KO-1 and KO-2 LCA studies. In fact, operational energy is responsible for at least 89.95% (depending on scenario combination) of total environmental impacts in the UBP impact category in KO-1 (see Figure 42). The share of operational energy on total results is lowered by additional construction works (ETICS, loggias, etc.) in KO-2. Thanks to these works the EEIs (modules A1-A3, A4, B4 and C1-C4) of

KO-2 increased by up to 48.83% compared to KO-1 (see Figure 43). Still, operational energy is responsible for at least 82.00% environmental impacts in KO-2. In contrast module A4 representing transport of construction materials and wastes has only up to 0.64% share on total environmental impacts (up to 5.45% of EEIs). Also the share of waste management in modules C1-C4 is relatively low: up to 2.89% of total environmental impacts (up to 16.05% of EEIs).

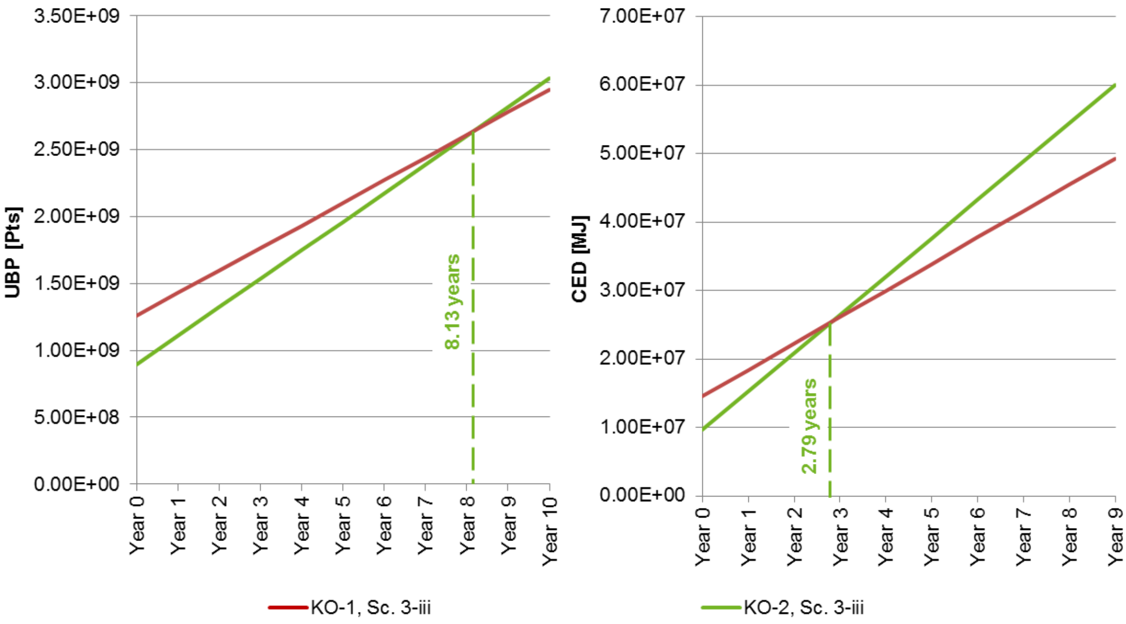


Figure 41 “Payback time” of the KO-2 (selected scenario combination) in time in UBP and CED impact categories. “Year 0” represents embodied environmental impacts of the initial renovation (modules A1-A4) and related waste treatment (modules C1-C4). Annual increase includes environmental impacts related with energy consumption (module B6) and further renovations (module B4). The increase of environmental impacts in module B4 is idealized to be linear due to limitations of the results provided by Eco-Bat 4.0.

Figure 41 further emphasizes the positive effect of the renovation. It compares total environmental impacts of the worst (regarding environmental impacts) scenario combinations in KO-1 and KO-2 during first ten years of the modelled 60-year life cycle. The comparison is shown in UBP and CED impact categories to illustrate that the results share the same trend in all evaluated impact categories, even though particular values differ. The figure shows that KO-2 is initially in disadvantage due to more demanding renovation compared to KO-1. The difference reaches up to 28.87% in UBP and 33.41% CED. However the difference is quickly offset by reduced energy demand. Total environmental impacts of the particular KO-1 and KO-2 scenario combinations equalize 8.13 years after the modelled renovation in UBP and only after 2.79 years in CED impact category. After this “payback time” the KO-2 renovation is more environmentally-efficient than original KO-1. The “payback times” shown in Figure 41 represent extreme values: UBP the highest, CED the lowest. Payback times in NRE and GWP impact categories (as well as other scenario combinations) vary between these values.

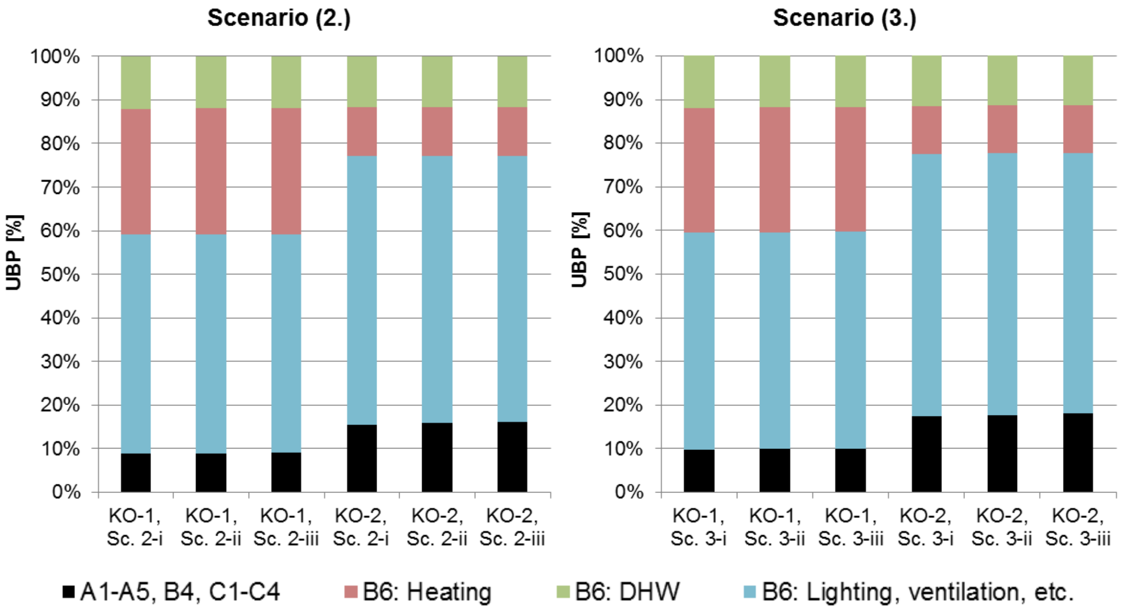


Figure 42 Shares of individual BITS on energy-related OEIs in individual scenario combinations of KO-1 and KO-2 LCA.

Figure 42 shows more detailed view of the results: shares of different technical systems (and their OEIs) on the total environmental impacts. It is clear that electricity consumed in lighting, ventilation and other appliances is the most dominant issue in both KO-1 and KO-2 LCA studies. Depending on particular scenarios it is responsible for 49.63% to 50.35% of total environmental impacts in KO-1 LCA study and 59.71% to 61.52% of total environmental impacts in KO-2 LCA study. Environmental impacts related with heating and DHW are significantly smaller, especially in KO-2 LCA study (see Table 6). Reasons for this are twofold. Firstly, electricity consumption in KO-1 and KO-2 is the same, while the district heating energy consumption (heating and DHW) is reduced by 43.41% by the KO-2 renovation. Thus electricity’s relative share on total results increases at the expense of heating and DHW in KO-2. Secondly, most of the electricity in the Czech Republic comes from fossil fuels. This is reflected in the characterization factors for Czech electricity supply mix. In UBP impact category in Eco-Bat 4.0 the characterization factor of electricity is almost five times higher compared to heat supplied by (gas) district heating. The ratio differs in other impact categories. Still, electricity retains its “dominance”.

Considering the significant role of operational energy consumption, it is clear that the influence of the tested scenarios (i.), (ii.), (iii.), (2.) and (3.) on the total results will be rather small in KO-1 and KO-2 LCA studies. In the context of total results the difference caused by construction waste scenarios (i.), (ii.) and (iii.) is less than 1%. It varies between 0.16% and 0.34% in KO-1 and between 0.29% and 0.67% in KO-2 LCA study. Even when EEIs are separated (see Figure 43) the percentage differences remain relatively small. In KO-1 LCA study the difference between base scenario (i.) and scenarios (ii.) and (iii.) reaches only up to 2.06% and 3.73% respectively. In KO-2 the difference reaches up to 1.93% and 4.17% respectively. In absolute values, the highest difference caused by varying construction waste scenarios (in KO-2, between scenarios (i.) and (iii.) combined with replacement scenario (2.)) equals $7.46 \cdot 10^7$ Pts (scarcity points; unit of UBP). This result is similar in magnitude to environmental impacts of transport in module A4, which reach up to $7.11 \cdot 10^7$ Pts (in KO-2, combination of scenarios (2.) and (iii.)).

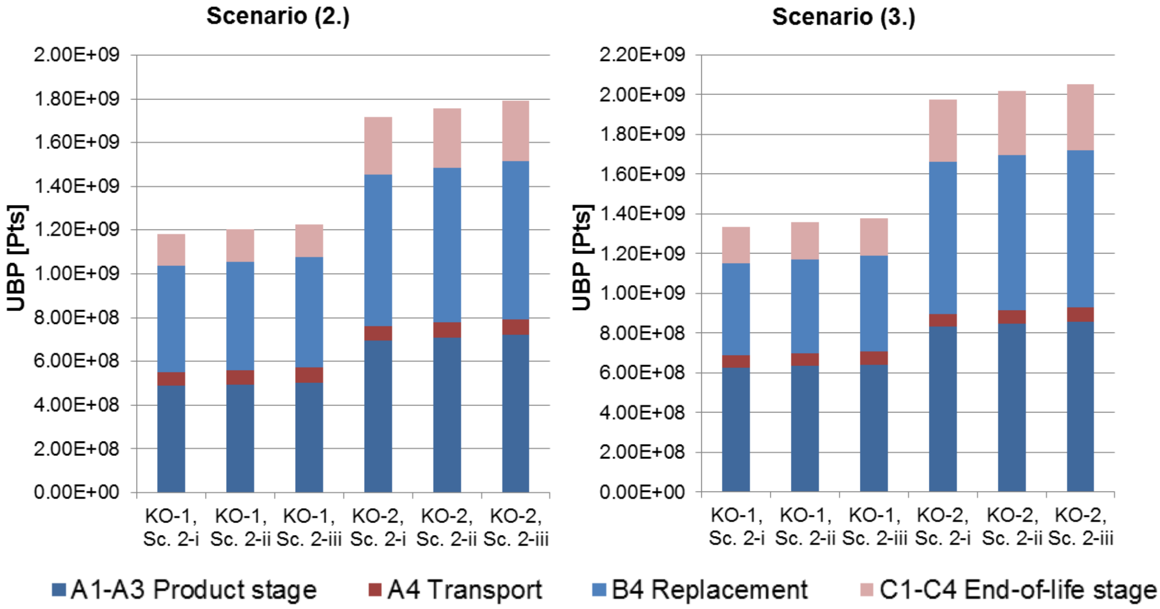


Figure 43 Total EEIs related with individual scenario combinations of KO-1 and KO-2 LCA studies.

It should be noted that the increase of total EEIs between scenarios (i.), (ii.) and (iii.) should be linear. Non-linearity is caused by rounding of the material amounts by package size. The difference between increase of total EEIs (up to 4.17%) and increase of on-site construction losses (up to 10%) indicates how much of the construction materials and elements in considered in KO-1 and KO-2 LCA studies are prepared and processed off-site (see inventory tables in Appendix A).

The differences in environmental impacts caused by replacement scenarios (2.) and (3.) are slightly higher than those caused by construction waste scenarios according to Figure 40 and Figure **43**. Total differences vary between 1.10% and 1.13% in KO-1 LCA study and 2.28% and 2.31% in KO-2 LCA study. Differences in EEIs reach up to 11.45% in KO-1 LCA study and 13.23% in KO-2 LCA study (in combination with construction waste scenario (i.)). Thirteen percent difference may not seem high at the first sight. However in absolute values it equals $2.62 \cdot 10^{8}$ Pts, which in turn equals EEIs related with C1-C4 modules in the same combination of scenarios. This means that selection of replacement scenario has same impact on the results as four LCA modules. In other context, the difference caused in environmental impacts of individual replacement scenarios is comparable with OEIs of a contemporary single-family house (see Section 6.1.2).

Reasons for the differences in EEIs related with the replacement scenarios (2.) and (3.) are visible in Figure 44. Charts in the figure show the shares of individual building elements on the total EEIs in KO-1 and KO-2 LCA studies. Both replacement scenarios are combined with the highest construction waste scenario (iii.) in the charts to emphasize the EEIs. Left chart shows changes in EEIs caused by the replacement scenarios as well as overall difference between KO-1 and KO-2. Right chart illustrates percentage shares of individual building elements on total EEIs. It is clear that addition of new materials to the facades and roofing is responsible for most of the difference. Their combined EEIs increased up to 4.17 times between KO-1 and KO-2 depending on particular scenario. Reason for differences between replacement scenarios (2.) and (3.) is also clear: number of replacement of doors and windows (see inventory tables in Appendix A). There are 332 windows (including balcony doors) and 515 doors in the evaluated block-of-flats. Their replacement involves significant amount of materials, which leads to 32.39% increase of related EEIs. As the doors and windows are produced off-site, it also helps to explain relatively low impact of on-site construction losses described previously.

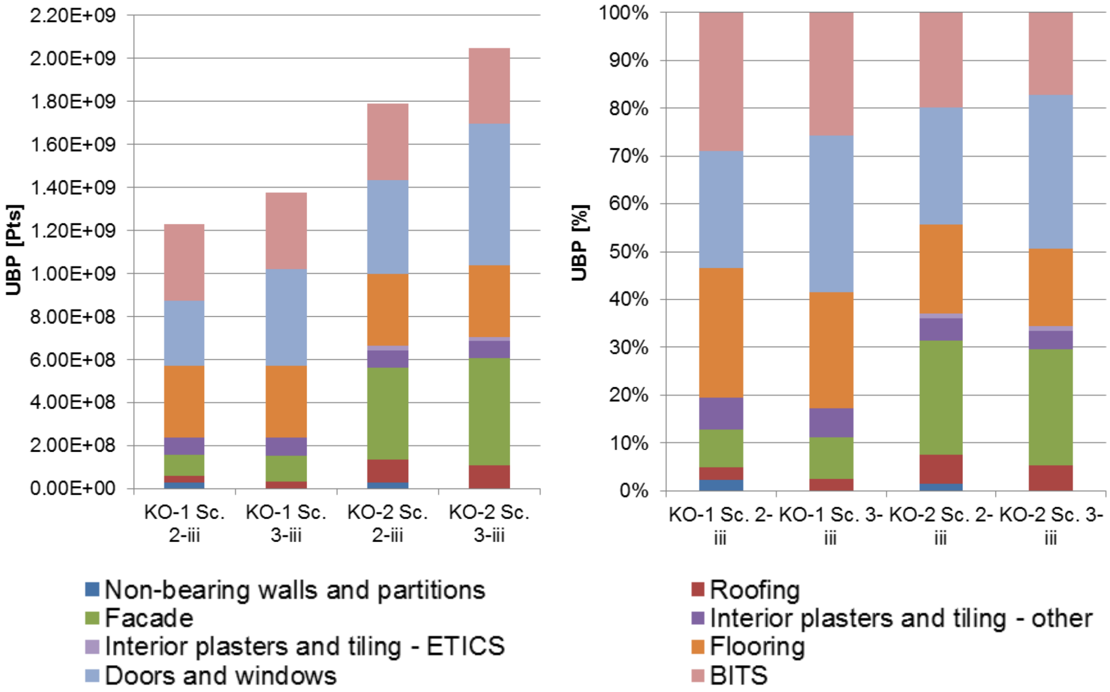


Figure 44 EEIs related with individual scenario combinations of KO-1 and KO-2 LCA studies. The environmental impacts are divided among individual building elements based on grouping in inventory tables. Left: total values, right: percentage shares.

Another interesting fact shown in Figure 44 is the relatively high share of BITS on the total EEIs. Just maintaining of functional BITS in the original building (KO-1) is responsible for more than a quarter of total EEIs. It overshadows environmental impacts related with non-bearing walls, roofing or interior finishes in KO-1. The percentage share of BITS on total results is reduced by addition of new materials during the renovation, but they still retain an important role. The reason for the relatively high environmental impacts of BITS is unclear as Eco-Bat 4.0 does not provide further information. It could be caused by high content of demanding materials (e.g. metals and plastics), which have significantly higher environmental impacts than e.g. masonry.

Figure 45 and Figure **46** provide another view of the EEIs: shares of individual construction materials (or parts). Similarly to Figure 44 the charts in these figures also combine both replacement scenarios with the highest construction waste scenario (iii.). The charts in the figures help explain the results shown in Figure 44. Firstly, expanded polystyrene and mineral wool applied in ETICS and roofing are responsible for 36.12% and 43.39% of the total EEIs increase between KO-1 and KO-2 in replacement scenarios (2.) and (3.) respectively. This explains increased shares of these building elements on the EEIs shown in Figure 44. Secondly, the charts further specify the reason for the difference between replacement scenarios (2.) and (3.) in both LCA studies. Figure 44 indicates that doors and windows in general are the main contributors to the difference. Figure 45 and Figure **46** identify plastic window frames as the most important element in this regard. They are related with up to 50.64% of the environmental impacts caused by all doors and windows in the building. Lastly, the figures also confirm individual BITS as important contributors to the total EEIs. For example sanitary equipment alone has EEIs comparable with environmental impacts of modules C1-C4 in KO-1 LCA study: $1.71\cdot10^{8}$ Pts versus $1.46\cdot10^{8}$ to $1.81\cdot10^{8}$ Pts depending on particular scenario combination.

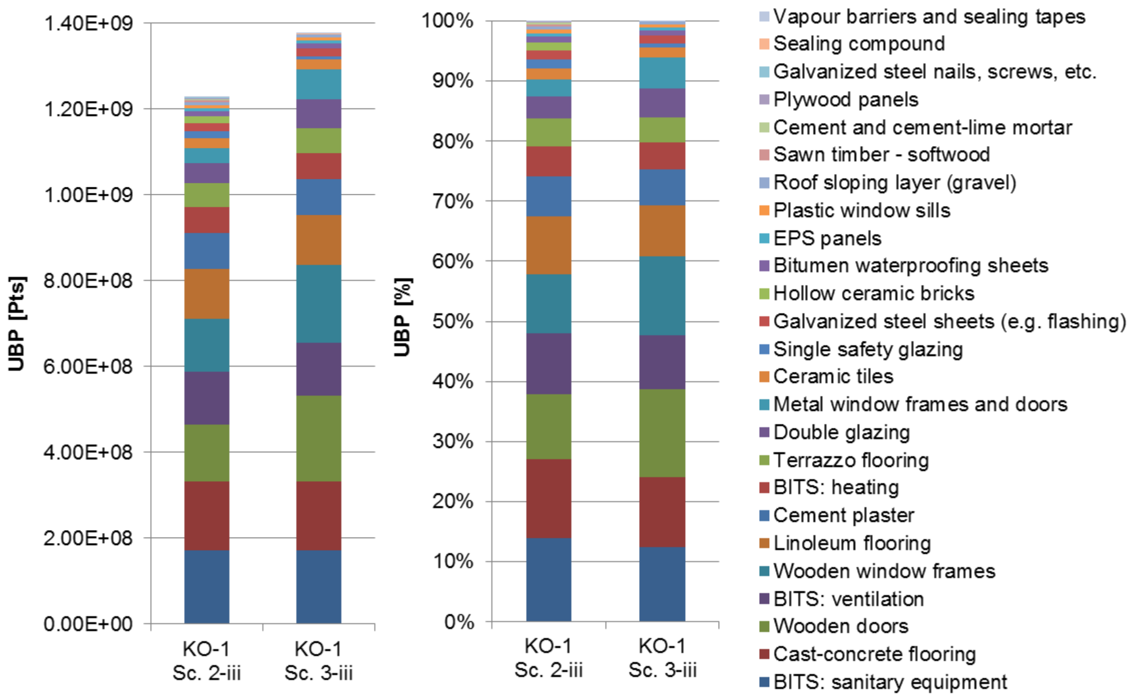


Figure 45 Total EEIs related with combination of construction scenario (iii.) and replacement scenarios (2.) and (3.) in KO-1 LCA study. The impacts are divided between individual construction materials. The materials are listed based on their share on total result: from lowest to highest. Left: total values, right: percentage shares.

Figure 45 and Figure **46** also indicate negligible share of some materials on the EEIs. There are 25 construction materials considered in KO-1 and 31 materials considered in KO-2 LCA studies. Percentage shares in both figures show that only five (in three cases) or six (in one case) of these materials are responsible for more than half of the total EEIs. This means that approx. 16% or 19% of all materials in KO-1 and KO-2 respectively have dominant impact on the total EEIs. In contrast, 10 materials (40% of all materials) in KO-1 and 15 materials (almost 50% of all materials) in KO-2 have less than 1% share on the EEIs each. The 10 materials in KO-1 have only up to 3.61% share on the EEIs when combined. Similarly the 15 materials in KO-2 have only up to 6.21% share when combined. The reason for low shares of these materials on the total results is mostly their low quantity considered in the LCA studies. For example the least EEIs are related with vapour barriers and sealing tapes in both LCA studies. Approx. 25kg of the material have only 0.01% 0.02% share on the results depending on particular scenario. However the influence of weight should not be generalized, as for example 45.44 tonnes of hollow ceramic bricks have only up to 0.99% share on the total EEIs in KO-2 LCA study. In comparison, 1.63 tonnes of galvanized steel have 2.59% share at the same time.

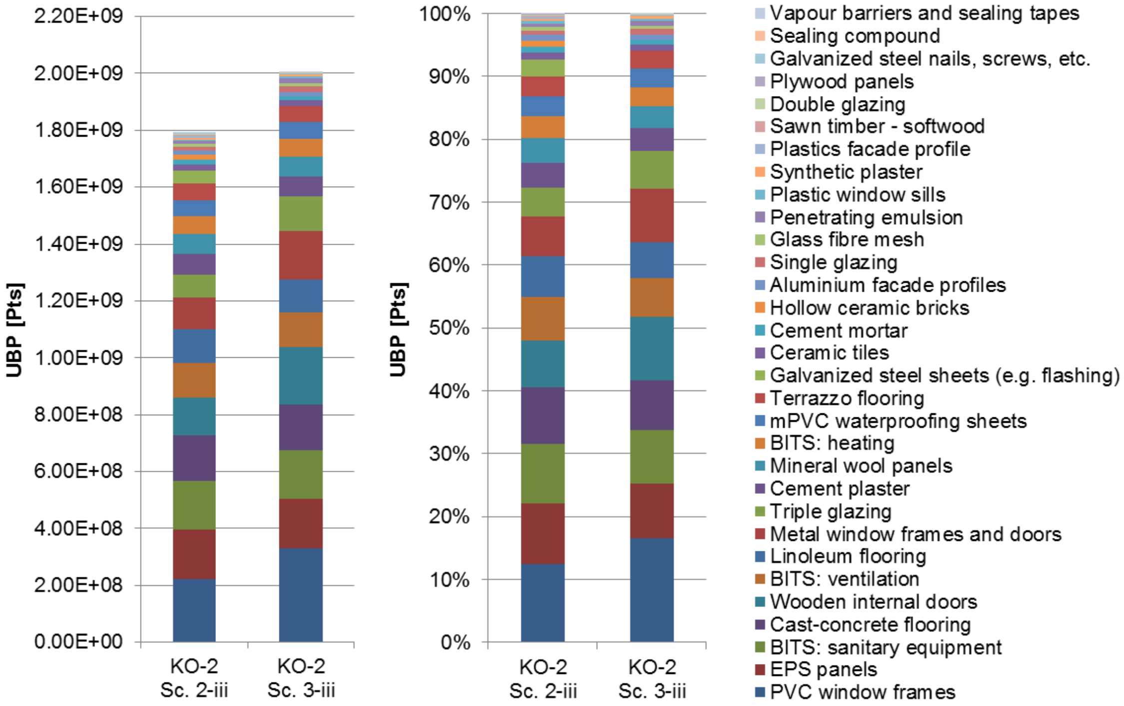


Figure 46 Total EEIs related with combination of construction scenario (iii.) and replacement scenarios (2.) and (3.) in KO-2 LCA study. The impacts are divided between individual construction materials. The materials are listed based on their share on total result: from lowest to highest. Left: total values, right: percentage shares.

Generally, the EEIs in the CED, NRE and GWP impact categories correspond with EEIs in UBP impact category. The most significant differences are visible when viewing the shares of individual materials on the EEIs as illustrated in Figure 47. The figure shows results in KO-2 LCA study combining construction waste scenario (iii.) with replacement scenario (2.). While most of the materials have similar shares on total results in all impact categories, there are some exceptions. The most notable is wooden internal doors. These doors have similar shares on EEIs in UBP (9.76%), NRE (8.29%) and GWP (6.97%). Their share on EEIs in CED is twice as large (19.95%). This reflects the fact that wood has rather low characterization factors in the first three impact categories to represent its supposed renewability. Other materials with significantly higher environmental impacts in one of the four impact categories include ceramic tiles or galvanized steel sheets, which have more than twice (or thrice respectively) higher environmental impacts in UBP compared to the other three impact categories. This is likely related to the fact that both ceramics and steel are made of non-renewable raw materials. The opposite example of the “non-uniformity” could be plastic waterproofing. It has 4.19% share on total EEIs in CED, 4.88% share in NRE and 4.44% share in GWP. In contrast, its share in UBP is only 2.86%. This could be explained by the fact that the production of the material is relatively energy-intensive and releases relatively high amounts of GHG. On the other hand it has relatively lower environmental impacts in some of the other sub-categories that make up the UBP (see Figure 23).

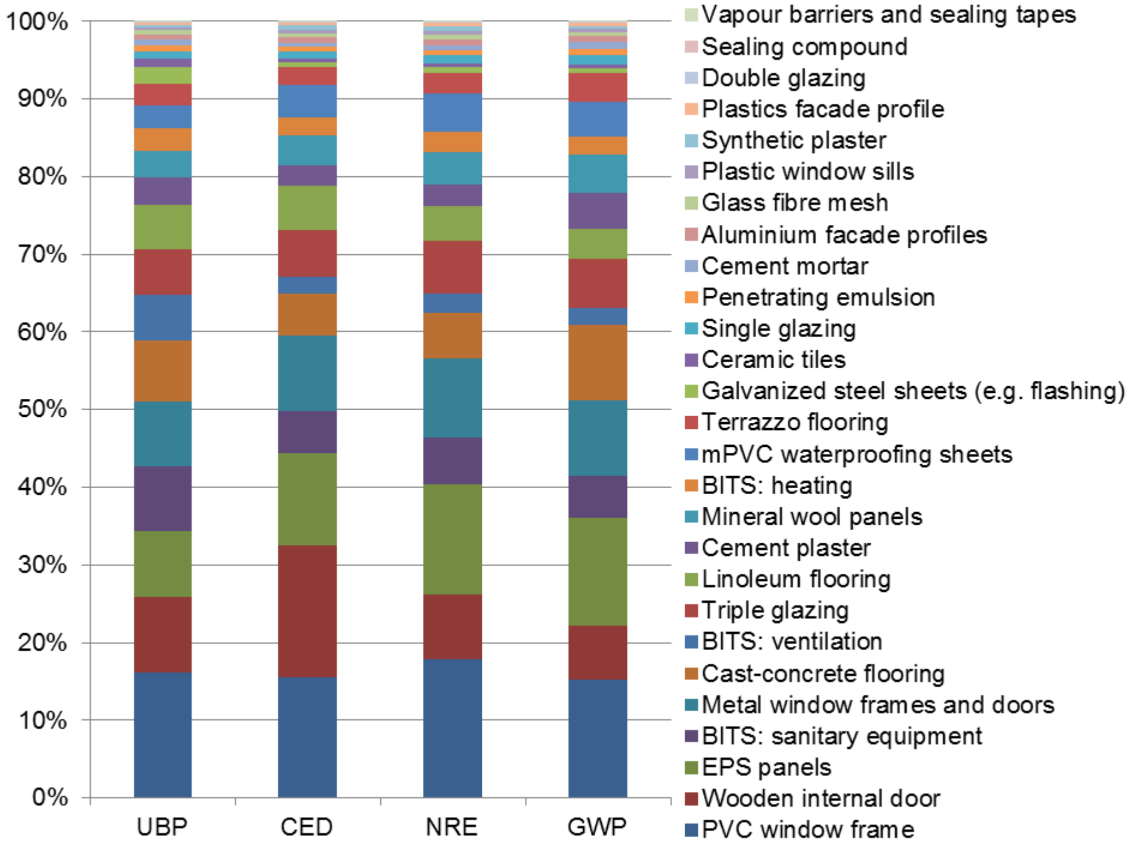


Figure 47 Percentage shares of individual materials on total EEIs in KO-2 LCA study in UBP, CED, NRE and GWP impact categories. The shares are result of combination of waste management scenario (iii.) and replacement scenario (3.).

6.1.2. PB-1, PB-2 and PB-3 LCA studies

Figure 48 shows total environmental impacts of all scenario combinations considered in PB-1, PB-2 and PB3 LCA studies. It should be highlighted that the LCA studies describe buildings of different size. Therefore a direct comparison of total result may be misleading (see Section 6.1.3). The most obvious fact visible in the figure is that the unbuilt PB-2 and the real-life PB-3 have much lower environmental impacts than the original PB-1 building. The highest difference (with the same scenario combinations) is 77.20%. It is between PB-1 and PB-3 combining construction waste scenario (i.) and replacement scenario (3.).

Main reason for the difference between the three LCA studies is in energy-related OEIs. In absolute numbers the corresponding LCA module B6 in PB-1 achieves $2.22 \cdot 10^9$ Pts. This alone is between 3.30 and 4.29 times higher (depending on particular scenario combination) than total environmental impacts of PB-2 and PB-3. Figure 50 further specifies the cause of the difference: heating energy consumption. Heating makes up most of the OEIs in all three LCA studies according to the charts in the figure. Its role is completely dominating especially in PB-1. It makes up to 97.77% ($2.10\cdot10^9$ Pts) of PB-1's total environmental impacts. This situation is result of a combination of two factors: high heating energy demand of the aged PB-1 building and the fact that it utilizes electricity (in individual radiators) as heating energy source. In comparison, PB-2 utilizes natural gas boiler as the main heat source. Natural gas has lower characterization factor than Czech electricity supply mix. Thus heating energy consumption equals "only" $3.93\cdot10^8$ Pts in PB-2 LCA study. This is 81.26% lower value compared to PB-1 even though PB-2 has 15.46% higher heating energy demand (see Table 7). PB-3 also utilizes natural gas boiler for heating and it has further 32.31% lower heating energy demand than PB-2. Therefore it is not surprising that the environmental impacts related with PB-3's heating energy consumption in B6 module are 87.35% lower compared to PB-1.

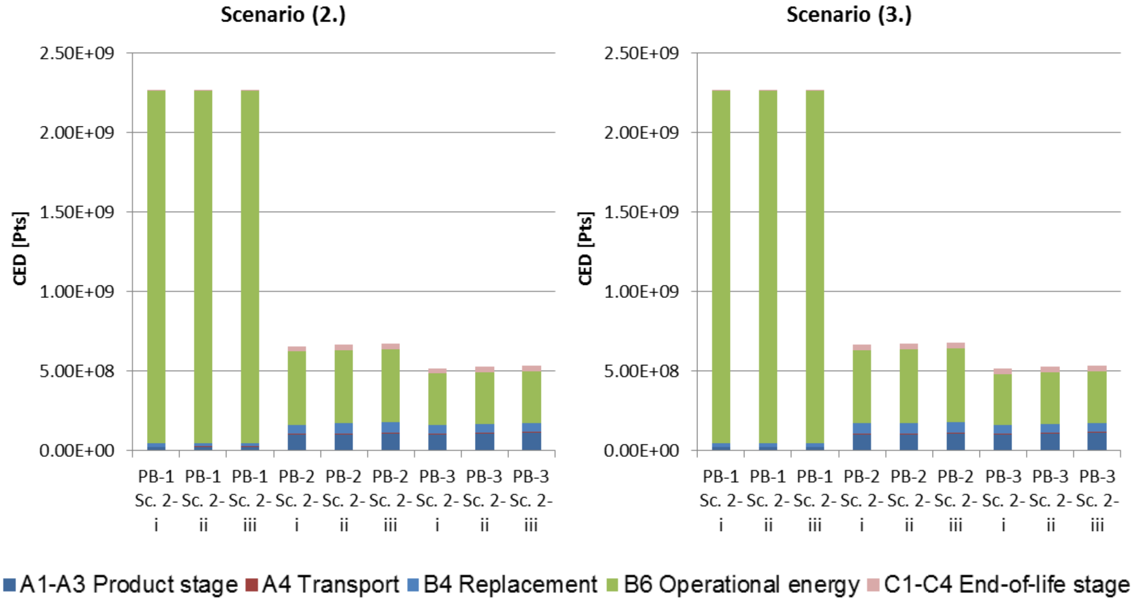


Figure 48 Total environmental impacts related with individual scenario combinations of PB-1, PB-2 and PB-3 LCA studies.

Figure 48 also illustrates influence of the tested scenarios on the total results. In case of PB-1 it is rather minimal due to described dominance of OEIs. The difference between the lowest combination of construction waste scenario (i.) with replacement scenario (3.) and the highest combination of construction waste scenario (iii.) with replacement scenario (2.) is only 0.16% in PB-1. In PB-2 and PB-3 the difference reaches up to 3.38% and 3.25% respectively (considering the same scenario combinations). Still, this makes the difference created by the scenarios more significant than EEIs in module A4 Transport. The contribution of transport to the total environmental impacts reaches only up to 0.14% in PB-1, 0.97% in PB-2 and 1.22% in PB-3.

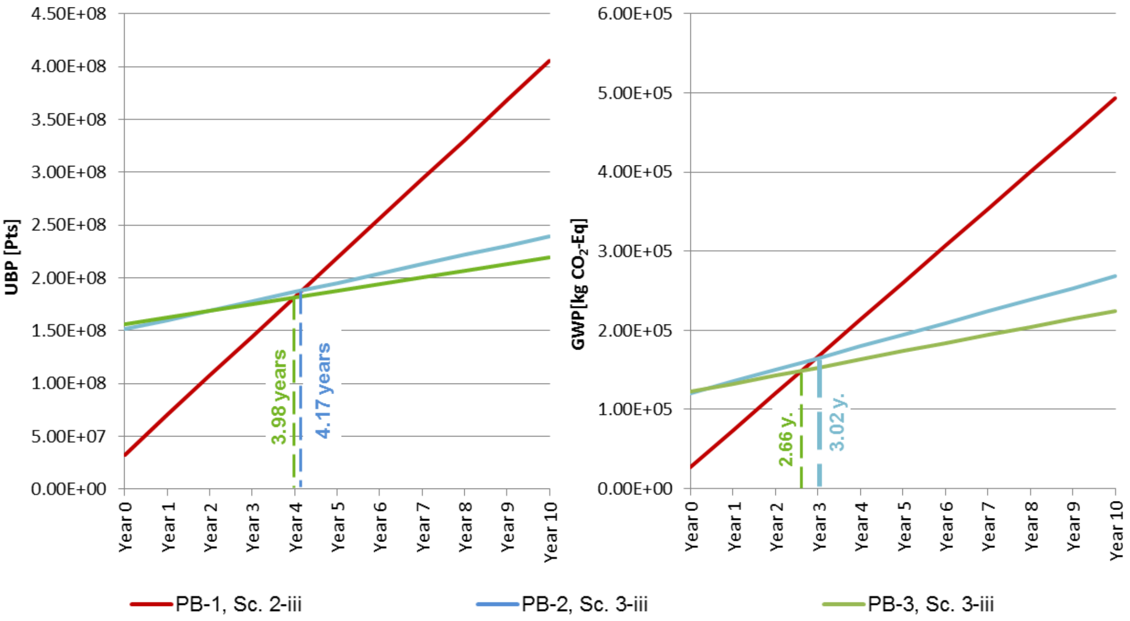


Figure 49 “Payback time” of PB-2 and PB-3 (selected scenario combination) in time in UBP and CED impact categories. “Year 0” represents embodied environmental impacts of the initial renovation (modules A1-A4) and related waste treatment (modules C1-C4). Annual increase includes environmental impacts related with energy consumption (module B6) and further renovations (module B4). The increase of environmental impacts in module B4 is idealized to be linear due to limitations of the results provided by Eco-Bat 4.0.

Figure 49 shows total environmental impacts differently than Figure 48. It highlights the efficiency of planned PB-2 and actually constructed PB-3 by showing development of environmental impacts in selected “worst-case” scenario combinations (selected from those in Figure 48) of the three LCA studies during ten years after the “initial” renovation or construction. UBP and GWP impact categories are used in the figure to illustrate that the outcome is similar in all four evaluated impact categories: high environmental impacts related with operation of PB-1 result in very short “payback time” of the PB-2 and PB-3 LCA studies. It takes only approx. four years in UBP and three years in GWP before the particular PB-2 and PB-3 scenario combinations become more environmentally efficient than the original building PB-1, even though that there are significant construction changes related with them. It should be noted that the UBP and GWP payback times shown in the figure represent extreme values: UBP is the longest and GWP the shortest. Payback times in CED and NRE (and other scenario combinations) are between those shown in the figure.

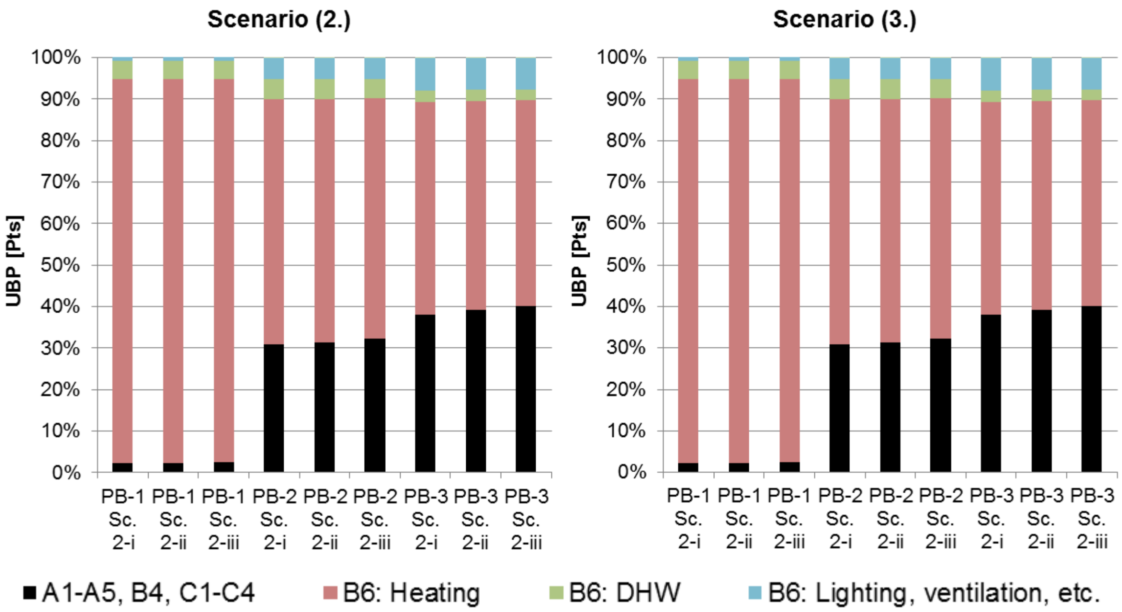


Figure 50 Shares of individual BITS on energy-related OEIs in individual scenario combinations of PB-1, PB-2 and PB-3 LCA studies.

Figure 50 and following figures describe particular details of the results. Figure 50 indicates significant increase of the importance of EEIs in PB-2 and PB-3 compared to the original PB-1 LCA study mentioned before. Figure 51 provides more insight into this issue as it focuses on EEIs of the three LCA studies. It shows that preserving of the original state modelled in PB-1 has up to 75.48% lower EEIs than the major construction works considered in PB-2 and PB-3. The charts in Figure 51 also highlight the influence of individual scenarios on the results. In case of construction waste the difference between base scenario (i.) and scenario (ii.) reaches up to 2.98% in PB-1, 3.98% in PB-2 and 4.94% in PB-3 respectively (depending on particular replacement scenario). Difference between base scenario (i.) and scenario (iii.) is unsurprisingly even higher: up to 5.99% in PB-1, 7.58% in PB-2 and 8.11% in PB-3 respectively (depending on particular replacement scenario). The 8.11% difference equals $1.74 \cdot 10^{7}$ Pts. In comparison, this is up to 2.94 times higher than the result of whole module A4 Transport. It should be noted that (as in KO-1 and KO-2 LCA studies) the increase of EEIs should be linear. Non-linearity is (again) caused by rounding of the material amounts based on package sizes. Influence of the replacement scenarios (2.) and (3.) is lower compared to construction waste scenarios. It reaches up to 1.20% in PB-1, 4.57% in PB-2 and 1.1% in PB-3 respectively (depending on particular construction waste scenario). Influence of the replacement scenarios on the results is further highlighted in Figure 52 to Figure **55**.

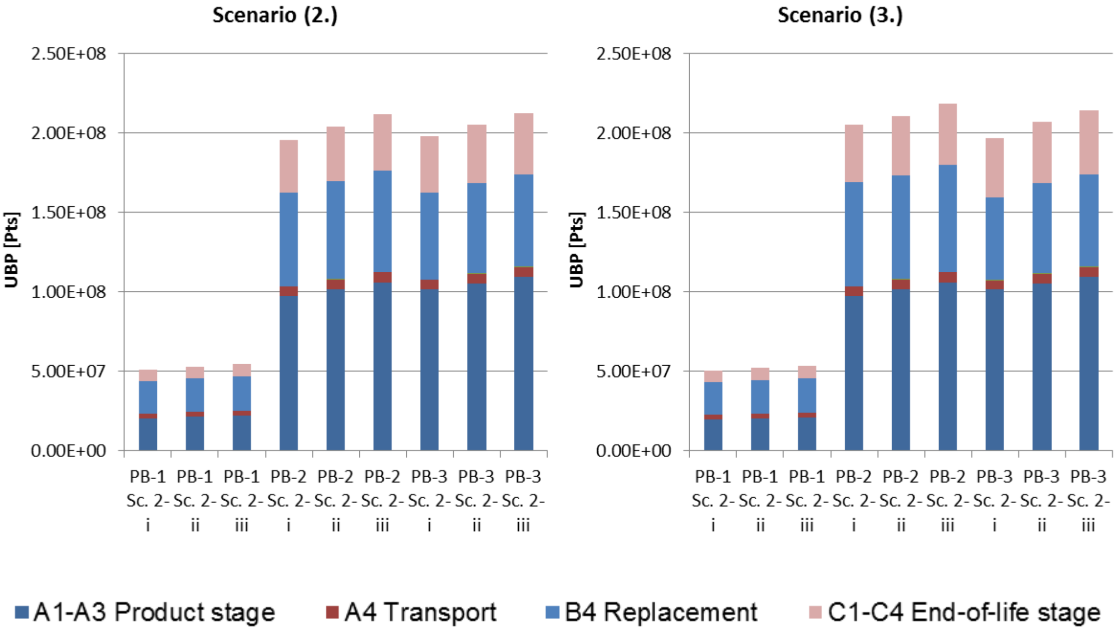


Figure 51 Total EEIs related with individual scenario combinations of PB-1, PB-2 and PB-3 LCA studies.

Figure 52 shows EEIs divided between individual building elements (described in Section 4.2). Charts in the figure combine replacement scenarios (2.) and (3.) with the highest construction waste scenario (iii.) to emphasize the EEIs. The charts show that doors and windows are the biggest contributors to the difference in all three LCA studies as they are replaced more often in scenario (3.) than in scenario (2.). The highest difference caused by door and window replacement is achieved in PB-2 according to the charts. This is not surprising as PB-2 is the largest of the three LCA studies. Doors and windows represent 15.61% andf 21.73% of total EEIs in scenarios (2.) and (3.) respectively in this LCA study. Therefore the 32.45% relative difference between their environmental impacts has major impact on the total results. In absolute numbers their difference equals $1.53 \cdot 10^7$ Pts. This is higher than total EEIs of the load-bearing walls ($1.20 \cdot 10^7$ Pts) in PB-2. Influence of other elements is much lower. For example the second largest contributors in this regard are non-bearing walls and partitions. This is due to the fact that these building elements are not replaced in scenario (3.). The difference equals $3.05 \cdot 10^6$ Pts, which is five times lower compared to the difference caused by doors and windows. It should be noted that this reflects the fact that non-bearing walls and partitions have rather low share on total EEIs in PB-2: up to 3.12% depending on particular scenario combination.

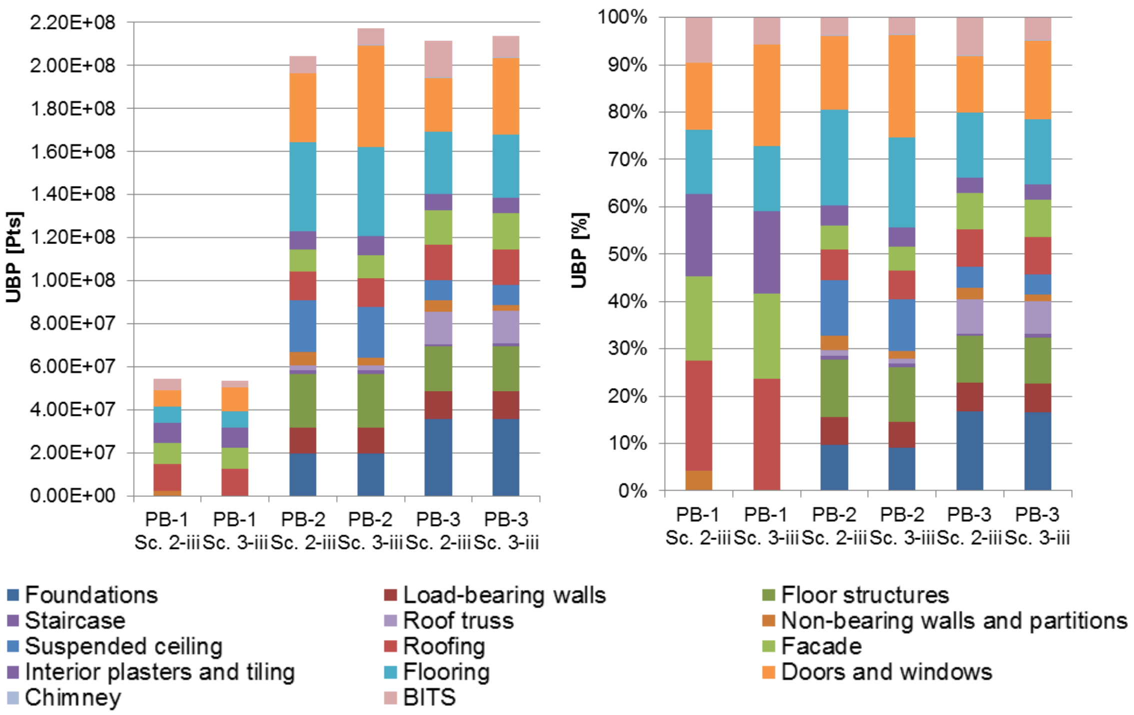


Figure 52 EEIs related with individual scenarios of PB-1, PB-2 and PB-3 LCA studies in UBP impact category. The environmental impacts are divided among individual building elements based on grouping in inventory tables. Left: total values, right: percentages shares.

Charts in Figure 52 also explain the reason for relatively little difference in EEIs between PB-2 and PB-3. The size of the buildings in both LCA studies differs rather significantly (see Section 5.2). Still, the average difference between their EEIs is only 2.09%. Two most obvious elements contributing to minimizing of the difference between these LCA studies are flooring and foundations. Flooring accounts for $4.14 \cdot 10^7$ Pts in the PB-2 scenario combination shown in the charts. At the same time, it accounts only for $2.92 \cdot 10^7$ Pts in the same scenario combination in PB-3. This 33.79% difference is caused by larger floor area of PB-2. The situation turns with foundations. PB-3 foundations account for $3.56 \cdot 10^7$ Pts in the particular scenario combination. PB-2 foundations account for 1.98·10^7 Pts in the same situation due to the fact that only some parts of PB-2 require new foundations according to the designs. This means 44.38% difference between foundations' EEIs in both LCA studies. However a combination of results of these two building elements lowers the absolute difference to 5.71%. This is further mitigated by other considered building elements.

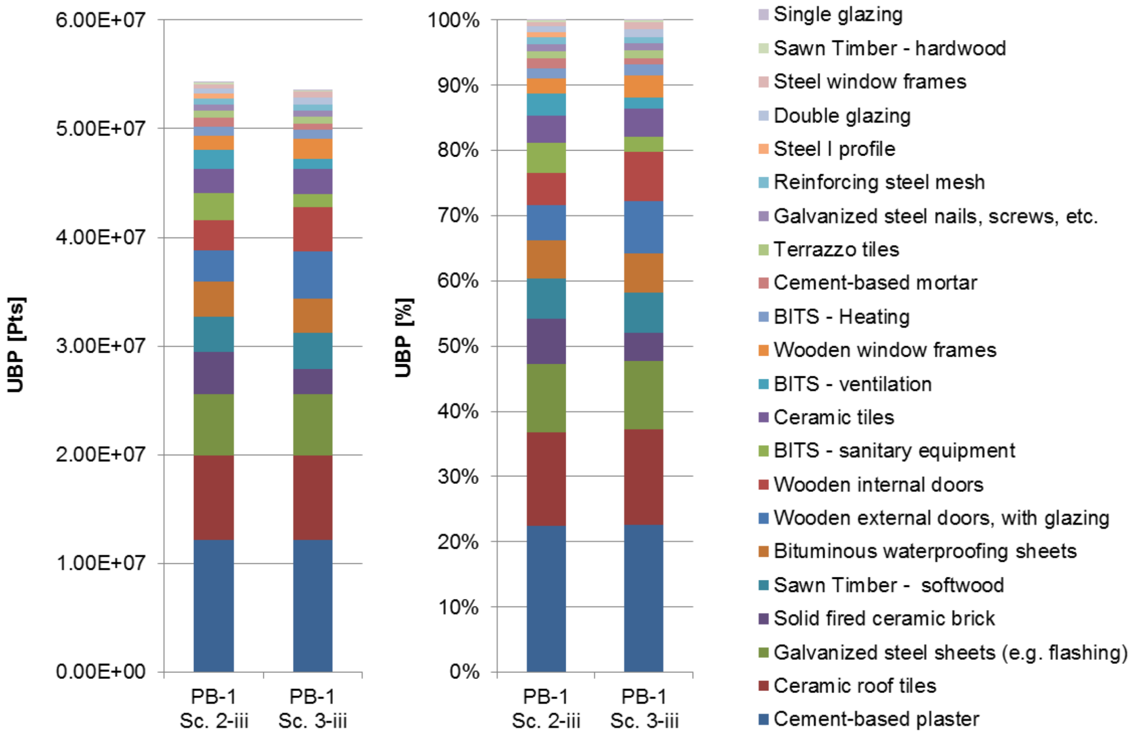


Figure 53 Total EEIs related with combination of construction scenario (iii.) and replacement scenarios (2.) and (3.) in PB-1 LCA study. The impacts are divided between individual construction materials. The materials are listed based on their share on total result: from lowest to highest. Left: total values, right: percentage shares.

Figure 53 to Figure 55 show shares of individual construction materials on total EEIs of the three LCA studies to provide yet another point of view. The figures show only combinations of worst-case construction waste scenario (iii.) with replacement scenarios (2.) and (3.) to emphasize the EEIs. The figures show that there are 22 construction materials and parts considered in PB-1 and 40 materials and parts considered in PB-2 and PB-3 in total. Their shares on the total results differ greatly. Three materials have more than 10% share on the EEIs in PB-1. The most dominant material (cement-based plaster) has up to 22.65% share on total EEIs in PB-1 according to Figure 53 and only four of the 22 materials (approx. 18%) have more than 50% share on total EEIs in PB-1.

PB-2 and PB-3 have more “gradual” distribution of EEIs between materials: no single material has above-10% share on the EEIs according to Figure 54 and Figure **55**. The most dominant material (ceramic tiles) has up to 8.32% or 9.63% share on the EEIs in PB-2 or PB-3 respectively. Only seven out of 40 (also approx. 18%) materials have more than 50% share in PB-2 and PB-3. These dominant materials help with understanding of the absolute difference between EEIs in PB-1 and PB-2 or PB-3 LCA studies. EEIs of the most dominant material (ceramic tiles) in PB-2 equal up to 40.00% of total EEIs of PB-1. The top seven materials in PB-2 count for up to $1.18 \cdot 10^{8}$ Pts together. In PB-3 they count for up to $1.09 \cdot 10^{8}$ Pts points. These values are more than twice higher than total EEIs in PB-1 (up to $5.42 \cdot 10^{7}$ Pts).

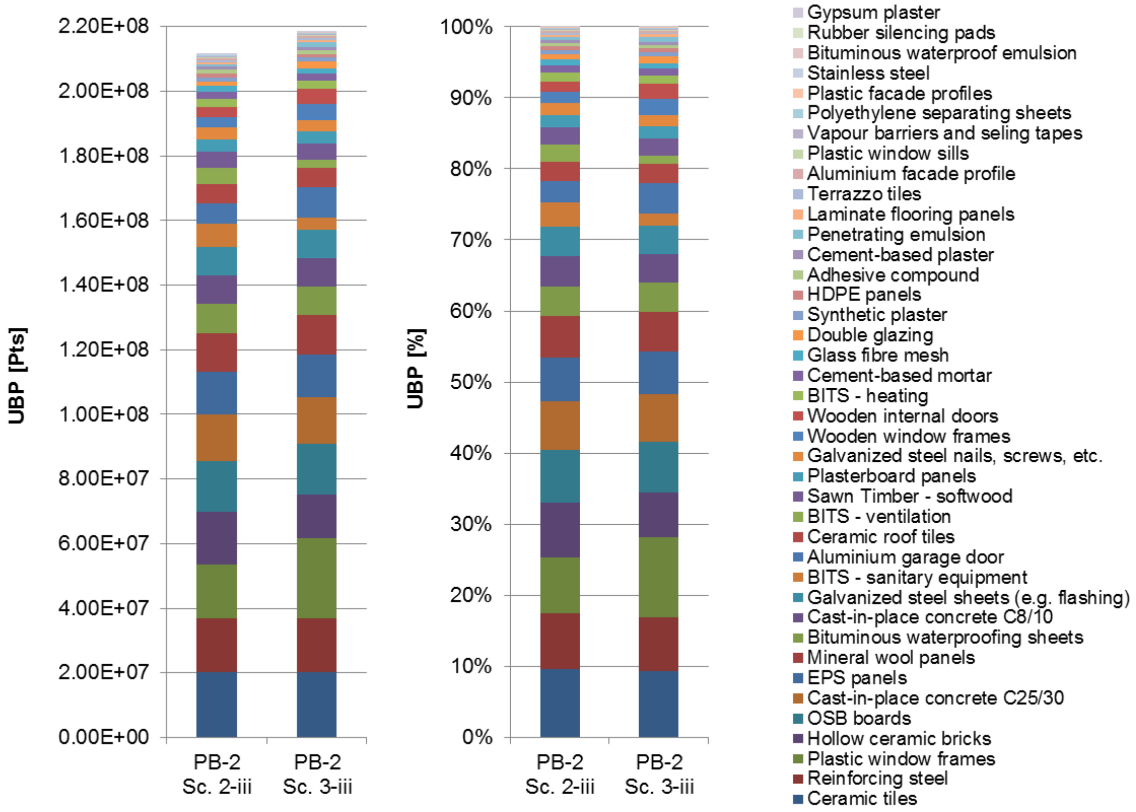


Figure 54 Total EEIs related with combination of construction scenario (iii.) and replacement scenarios (2.) and (3.) in PB-2 LCA study. The impacts are divided between individual construction materials. The materials are listed based on their share on total result: from lowest to highest. Left: total values, right: percentage shares.

In contrast to the dominant materials, there are four materials (approx. 18% of all materials) in PB-1, 18 materials (45% of all) in PB-2 and 21 materials (approx. 47% of all) in PB-3 that have less than 1% share on total EEIs.

Combined, these “low-impact” materials have up to 2.70%, 5.41% and 5.80% share on total EEIs in PB-1, PB-2 and PB-3 LCA studies respectively (considering the particular scenario combination). This means that overall contribution of these materials is comparable with that of the varying replacement scenarios. It should be noted that the contribution of individual materials to the total EEIs may not reflect their quantity due to varying characterization factors. For example there are only 4.1 tonnes of the ceramic tiles, which are the most dominant material in PB-2 with EEIs equalling $2.04 \cdot 10^7$ Pts according to Figure 54. In comparison the 119 tonnes of cast-in-place concrete C25/30 correspond with $1.46 \cdot 10^7$ Pts. Galvanized steel sheets (flashing, gutters, window sills, etc) in PB-1 are another good example. This material has 10.38% share on total EEIs ($5.63 \cdot 10^7$ Pts) in spite of the fact that there are only 197kg of it. On the other hand, it is true that e.g. 14 out of 18 “low-impact” materials are considered in quantities lower than 1 ton in PB-2.

The contribution of individual materials to the total EEIs corresponds with importance of particular building elements in the context of the specific LCA study. For example four most dominant materials in PB-1 are plasters, roof tiles, flashing (including gutters, window sills, etc.) and ceramic bricks according to Figure 53. Three of these materials are related with surface finishes. This reflects the fact that PB-1 focuses on preserving of the original state of the evaluated single-family house. Similarly, seven most dominant materials in PB-2 and PB-3 include ceramic bricks, cast-in-place concrete, reinforcing steel or thermal insulation panels. This corresponds with the volume of new load-bearing structures and with installation of ETICS on most facades in both LCA studies.

The EEIs of individual materials also depend on particular replacement scenarios. For example ceramic bricks are fourth most dominant material in PB-1 combinations considering replacement scenario (2.). However they are ninth, when replacement scenario (3.) is considered. The difference in EEIs reaches up to 40.28%. This is due to the fact that non-bearing walls (only building element incorporating this material) are not replaced in scenario (3.), while they are replaced once in scenario (2.). This difference is one of the main reasons why total EEIs of scenario (2.) are higher compared to scenario (3.) in PB-1. In absolute value the difference equals $1.54 \cdot 10^6$ Pts. In comparison, the four materials with less than 1% share on EEIs together achieve only 1.40·10^6 Pts in the same scenario combination.

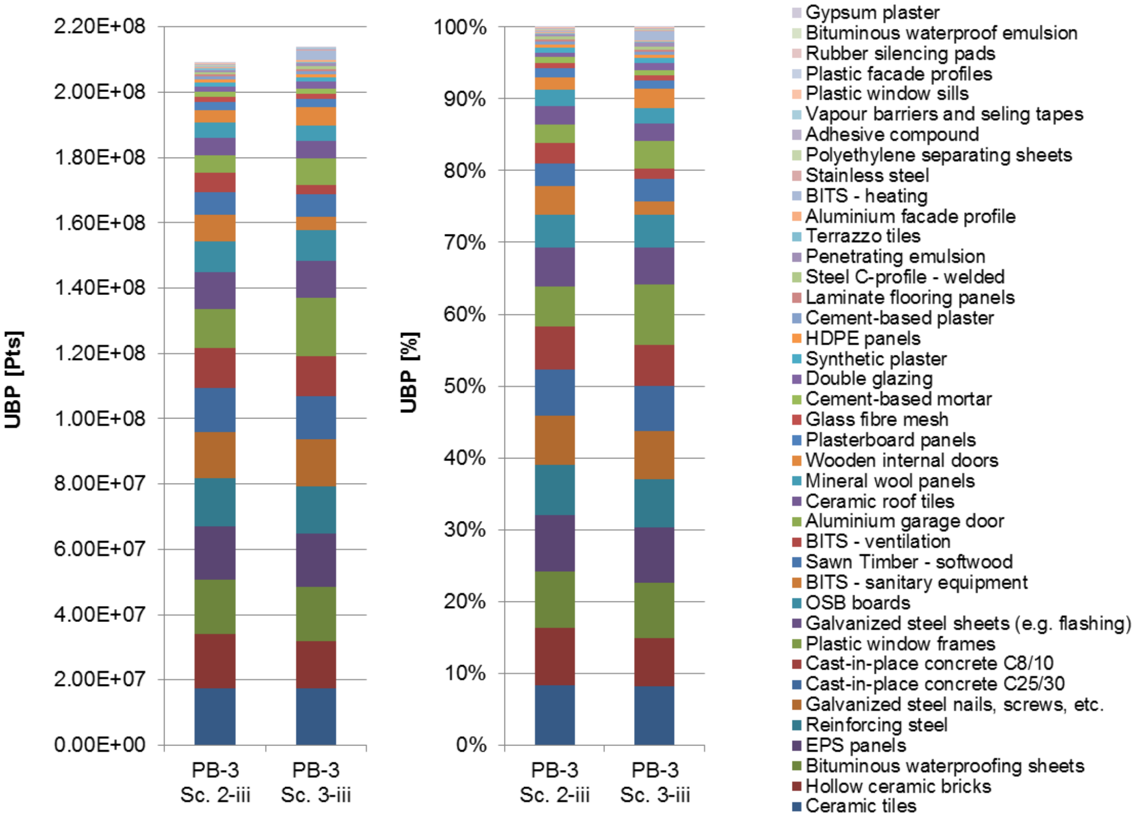


Figure 55 Total EEIs related with combination of construction scenario (iii.) and replacement scenarios (2.) and (3.) in PB-3 LCA study. The impacts are divided between individual construction materials. The materials are listed based on their share on total result: from lowest to highest. Left: total values, right: percentage shares.

6.1.3. Comparison of KO-1, KO-2, PB-1, PB-2 and PB-3 Results

Previous sections present results of five different LCA studies. The question is: Are these results comparable, when the size and capacity of the evaluated buildings differs significantly? Figure 56 shows comparison of total environmental impacts of all variants of the five LCA studies evaluated with Eco-Bat 4.0. The difference in scale is evident. Block-of-flats in KO-1 and KO-2 has much larger environmental impacts compared to the single-family house in PB-1, PB-2 and PB-3. The highest total environmental impacts (1.37·10^{10} Pts) are related with KO-1 combining construction waste scenario (iii.) with replacement scenario (3.). The lowest total environmental impacts (5.16·10^8 Pts) are related with PB-3 combining construction waste scenario (i.) and replacement scenario (3.) according to the charts in the figure. This is 26.53

times less compared to the mentioned KO-1 scenario combination. The difference is so great that EEIs of KO-1 and KO-2 are on average 2.65 times higher than total environmental impacts of PB-2 and PB-3. Further comparisons of total results seem meaningless as they would distort the interpretation of the results. This is the reason for introducing 1m^2 of treated floor area and year of operation as a functional equivalent in Section 4.2.1.2.

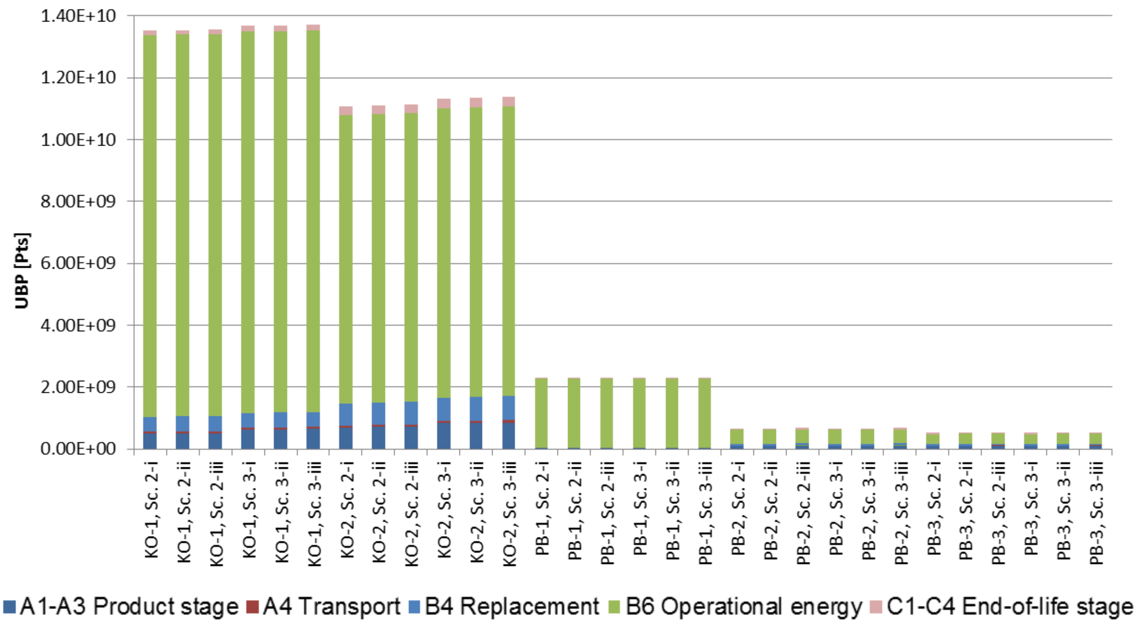


Figure 56 Total environmental impacts related with individual scenario combinations of the LCA studies evaluated with Eco-Bat 4.0.

Figure 57 presents environmental impacts according to the selected functional equivalent. It should be noted that the charts in the figure were modified to emphasize the environmental impacts of KO-1, KO-2, PB-2 and PB-3. The reason is that PB-1 has averagely 12.01 times higher environmental impacts per 1m^2·and year (up to 4.79·10^5 Pts·m^{-2}·a^{-1}) than the other LCA studies due to utilization of electricity for heating (see Figure 50). The difference is so large that PB-1's environmental impacts are 3.75 times higher compared to average of all LCA studies (1.28·10^5 Pts·m^{-2}·a^{-1}). Remaining four LCA studies have environmental impacts 26.07% to 39.05% lower than the average due to lower heat losses as well as utilization of natural gas (either in a boiler or through district heating) as the energy source for heating.

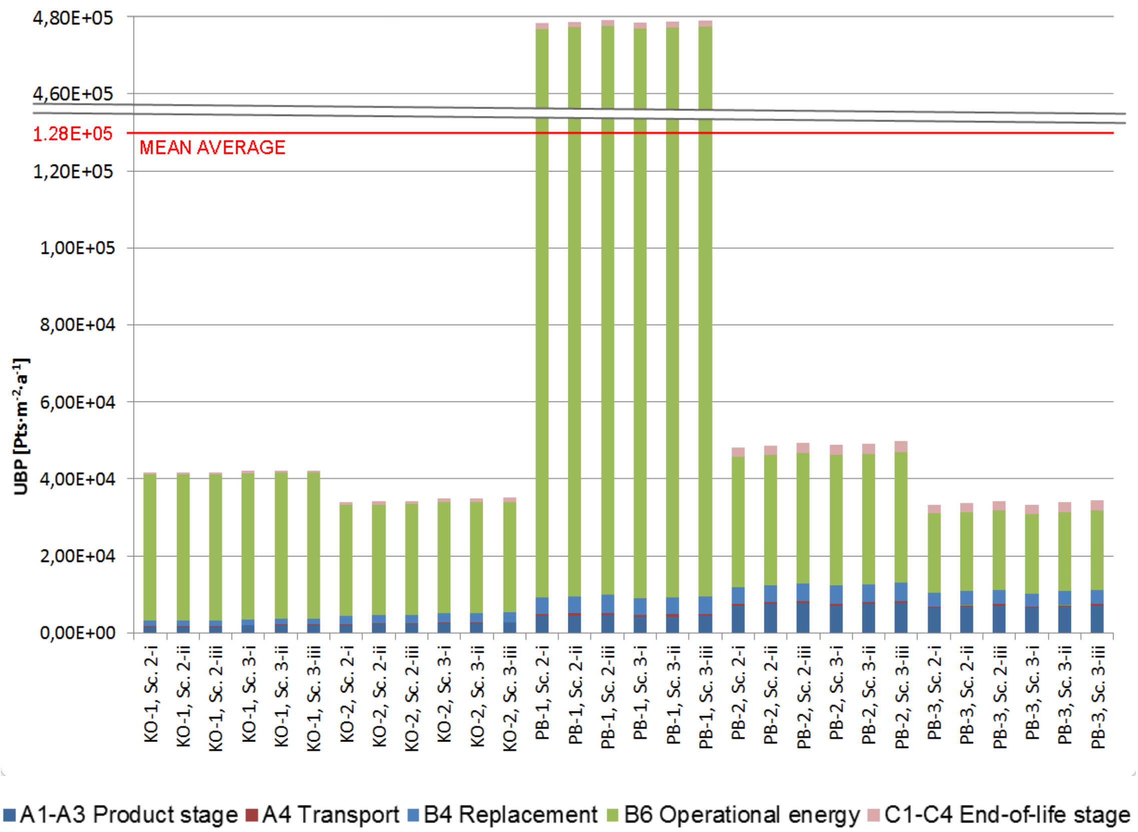


Figure 57 Environmental impacts per 1m^2 of treated floor area and year of operation of the LCA studies evaluated with Eco-Bat 4.0.

Figure 57 illustrates the differences between individual LCA studies more comprehensibly compared to the total results in Figure 56 in author's opinion. The positive effect of the renovations (or demolition and new construction) is still visible and the percentage differences between renovation variants remain the same as in the total results. But it also shows that evaluated scenarios of Koniklecová 4 block-of-flats and Přibice 275 (or 442; except PB-1) reach comparable environmental impacts per m^2 and year. PB-3 is the scenario with the least environmental impacts in this comparison. PB-3 combining construction waste scenario (i.) and replacement scenario (iii.) achieved the lowest environmental impacts according to the figure: 3.33·10^4 Pts·m^{-2}·a^{-1}. PB-3 is closely followed by KO-2, whose lowest combination (construction waste scenario (i.) and replacement scenario (2.)) achieves 3.41·10^4 Pts·m^{-2}·a^{-1}.The figure also indicates the reasons for differences between the particular LCA studies.

Major reason for differences in environmental impacts per 1m^2 and year is the size and shape of the evaluated buildings. Koniklecová 4 block-of-flats is a compact building with 12 heated residential floors whose treated floor area (5412m^2) is larger than the area of the envelope (4777m^2). In contrast, terraced houses in Přibice evaluated in PB-1 to PB-3 LCA studies have relatively small treated floor area (between 79m^2 and 259m^2) and comparatively larger envelope area (between 266m^2 and 628m^2). This means that Koniklecová 4 has comparatively smaller relative area of the envelope exposed to heat losses (up to 0.88m^2 of envelope per 1m^2 of treated floor in KO-1) compared to Přibice 275 or 442 (up to 3.36m^2 of envelope per 1m^2 of treated floor in PB-1). This in turn means relatively lower heating energy demand (per 1m^2 of treated floor area) and related environmental impacts. Similarly the EEIs are relatively smaller in case of KO-1 and KO-2, when calculated per 1m^2 of floor area (and year). This is especially true when comparing KO-1 and PB-1 LCA studies, which both describe preserving of the original state of the buildings. The difference in EEIs is up to 2.70 times to the detriment of PB-1. Furthermore, PB-1 even has almost twice higher EEIs per 1m^2 and year when compared to KO-2. The difference would be even more pronounced when comparing KO-1 or KO-2 to PB-2 and PB-3, which include significant changes of the original building.

Another major reason for the difference is varying total operational (energy-related) environmental impacts. Figure 58 shows OEIs of individual LCA studies divided between the considered technical systems. It confirms that the environmental impacts related with heating energy supply are the highest in PB-1 due to utilization of Czech electric supply mix. The lowest heating-related OEIs per 1m^2 and year are in KO-1 and KO-2 (for the reasons explained in previous paragraph). The difference between the renovated block-of-flats in KO-2 and the original terraced house PB-1 is 99.13%. Even the most efficient terraced house PB-3 has 77.50% higher heating-related environmental impacts per 1m^2 and year than compared to KO-2. However the situation turns when DHW, lighting and electric appliances are considered. PB-1 has the highest environmental impacts per 1m^2 and year related with DHW production as it uses electricity for this purpose too. But KO-1 places second and KO-2 third in this regard. For illustration, KO-2 has 77.00% higher DHW-related OEIs per 1m^2 and year compared to PB-3. The difference is even more pronounced when comparing OEIs per 1m^2 and year related with lighting and other electric appliances. KO-1 and KO-2 have these environmental impacts 5.73 times higher compared to PB-1, 8.30 times higher compared to PB-2 and 8.03 times higher compared to PB-3. This is the reason why KO-1 and KO-2 have environmental impacts comparable with PB-2 and PB-3 in Figure 57. KO-1 and KO-2 would have the least environmental impacts out of five evaluated LCA studies in Figure 57 if their electricity-related environmental impacts were comparable with PB-2's and PB-3's. It should be noted that the reasons for such difference in relative electricity consumption are unknown. The calculations are based on data provided by owners and users of the buildings. User behaviour was not studied in this dissertation.

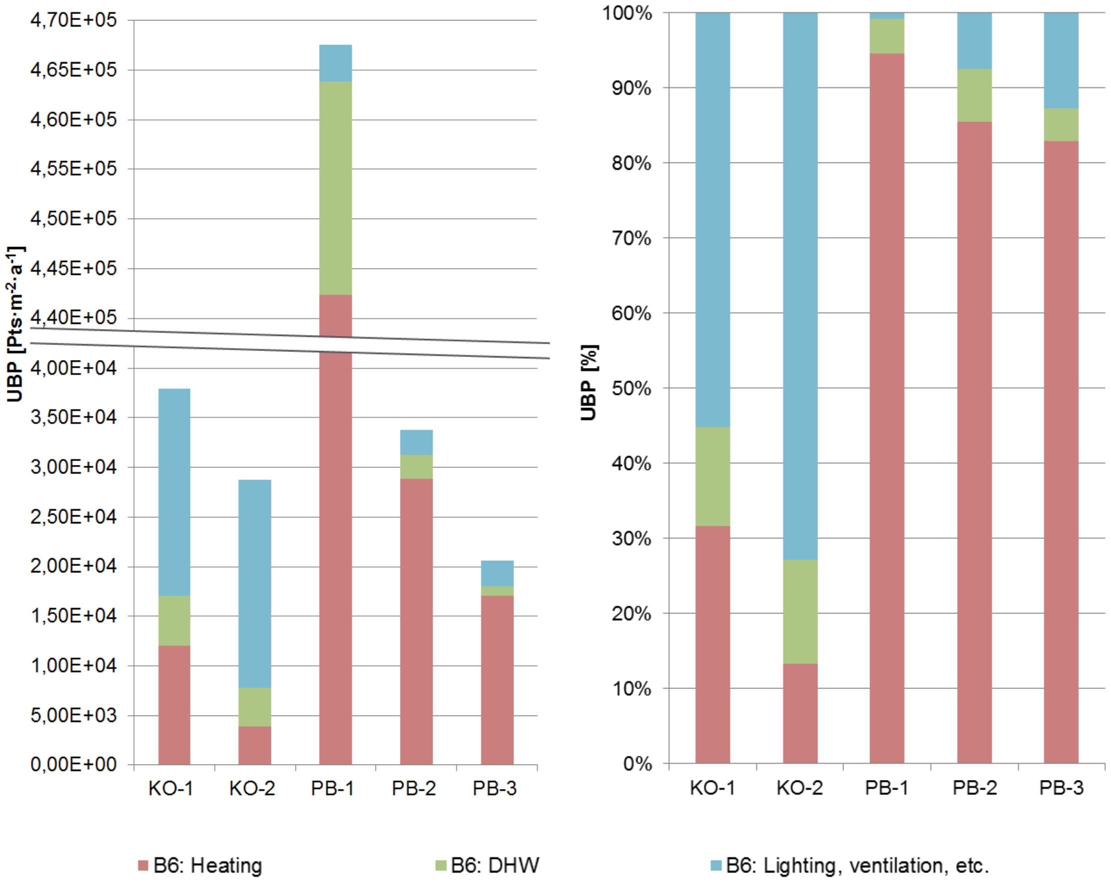


Figure 58 OEIs per 1m^2 of treated floor area and year of operation of the LCA studies evaluated with Eco-Bat 4.0.

Differences between individual LCA studies in Figure 57 are also related to the tested construction waste and replacement scenarios. Their impact on total results is small compared to differences in energy consumption, etc., but visible as confirmed by Figure 59. Details regarding the impact of particular scenario combinations in individual LCA studies are described in Sections 6.1.1 and 6.1.2. The comparison of EEIs in Figure 59 highlights one more thing: different effect of the tested scenarios between the case studies. The figure shows that replacement scenarios have dominant influence in Koniklecová 4 case study, while construction waste scenario have dominant influence in Přibice 275 (and 442) case study. The reason for this difference is related to the amount of construction materials processed on-site in the particular LCA studies. Dominant share of embodied environmental impacts is related to BITS, doors and windows (up to 28.89% and 24.55% respectively) in KO-1 and KO-2 LCA studies. These elements are prepared mostly off-site (they do not contribute to on-site construction losses) and their replacement rate is variable. Therefore these elements make replacement scenarios more important in Koniklecová 4 case study compared to construction waste scenarios. In contrast, materials such as ceramic bricks and roof tiles, reinforced concrete or cement-based plaster have significant role in PB-1, PB-2 and PB-3 LCA studies. All these materials are processed on-site, thus contributing to the construction losses. At the same time the number of doors and windows and the amount of BITS is minimal compared to KO-1 and KO-2. This leads to dominance of construction waste scenarios over replacement scenarios in Přibice 275 (or 442) case study.

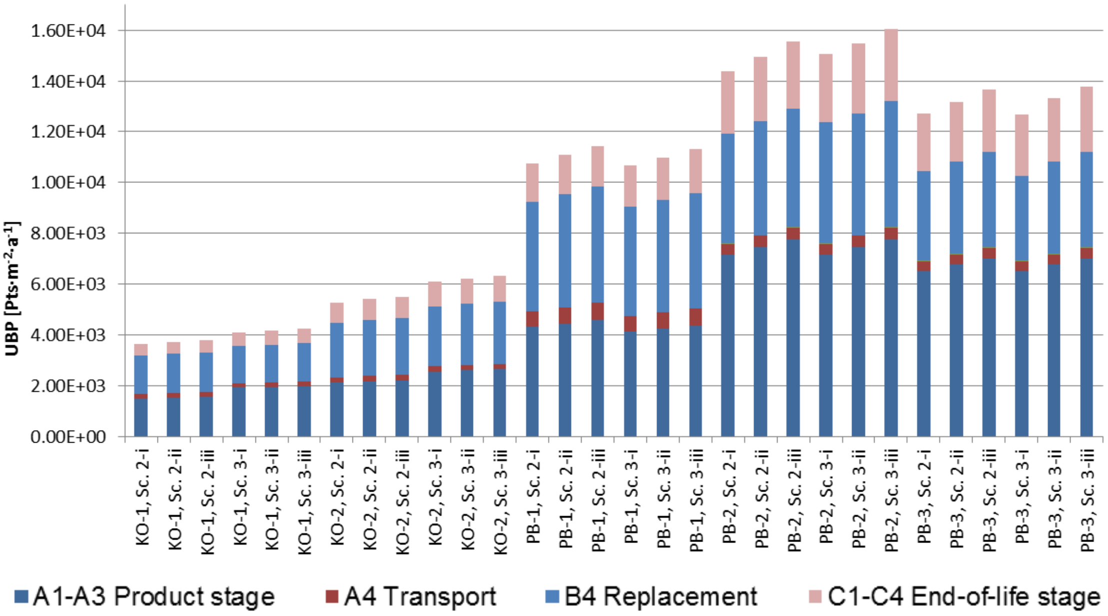


Figure 59 EEIs per 1m^2 of treated floor area and year of operation of the LCA studies evaluated with Eco-Bat 4.0.

6.1.4. Service Life Shortening

All previous results considered 60-year service life of the renovated or newly-constructed buildings. This section illustrates what would happen if 50-year service life common in contemporary building designs would be considered (according to Section 4.2.1.1). Each LCA study is represented by a single combination of scenarios with the highest environmental impacts in this section to enhance clarity of results.

Figure 60 provides full overview of the compared results. Left chart shows noticeable differences between the 50-year and 60-year service life results. The greatest difference is achieved in PB-1 (16.73%), the lowest in PB-3 (13.67%). The total difference is mostly related to the 10-year gap in operational energy consumption, which results in constant 16.67% difference in OEIs in all scenarios. Changes in EEIs caused by lower number of replacements in 50-year scenarios have rather minor impact on the total results. Basically, they are the reason for up to 3.00% difference between reduction of OEIs and reduction of total environmental impacts.

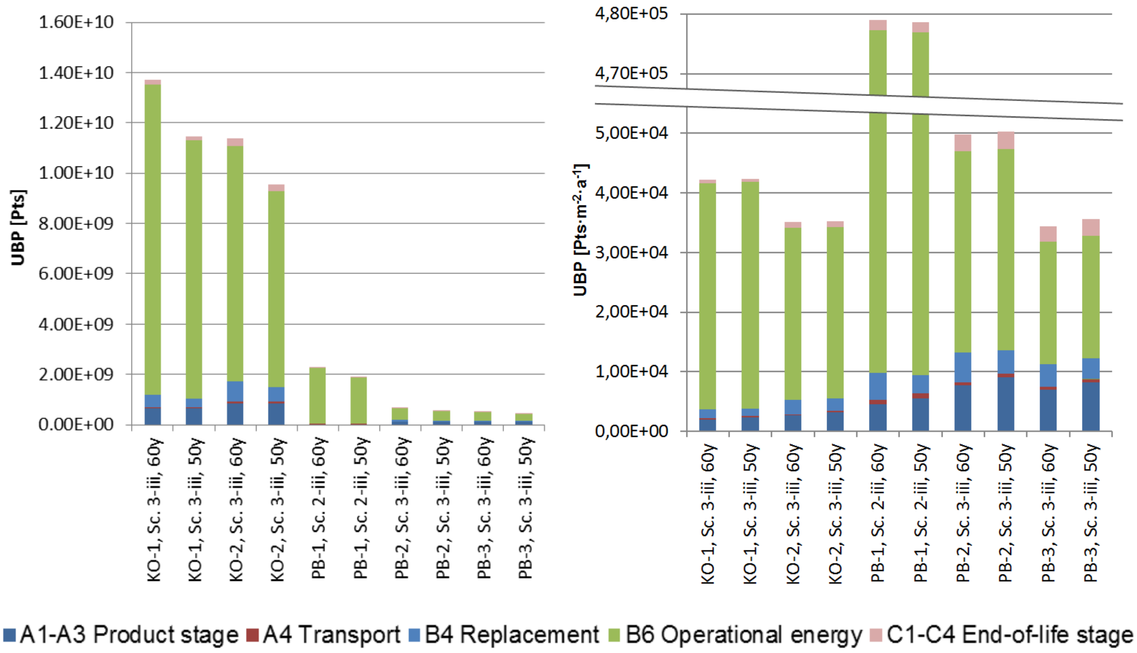


Figure 60 Comparison of environmental impacts of individual LCA studies with 50- and 60-year service life in Eco-Bat 4.0. Left: Total results; Right: results per 1m^2 and year.

Right chart in Figure 60 shows comparison of results per 1m^2 and year. It shows small increase of 50-year service life results. This increase is caused by EEIs as the OEIs remain constant in this comparison. The increase in EEIs is caused by the fact that the initial amount of materials remains the same for both service life lengths and also that the modelled changes in number of replacements are not so high between 50- and 60-year service lives. This issue is further described in Figure 61. Left chart in this figure shows that 10-year shortening of service life reduces total EEIs by 9.21% in PB-3 and 19.01% in PB-1. At the same time the 10-year shortening also increases the relative importance of remaining EEIs when evaluated per 1m^2 and year by 16.67%. Result of the combination of these factors is visible in the right chart. It shows that the only exception where the environmental impacts per 1m^2 and year do not increase when 50-year service life is considered is PB-1. There the total reduction is simply higher than the relative increase. The reason for this noticeable reduction of EEIs in PB-1 is number of replacements of BITS, which is halved by the service life shortening. This influence of BITS is possible only due to relatively low amounts of construction materials considered in PB-1. The reduction of BITS-related EEIs is mitigated by EEIs of other building elements in KO-1, KO-2, PB-1 and PB-2.

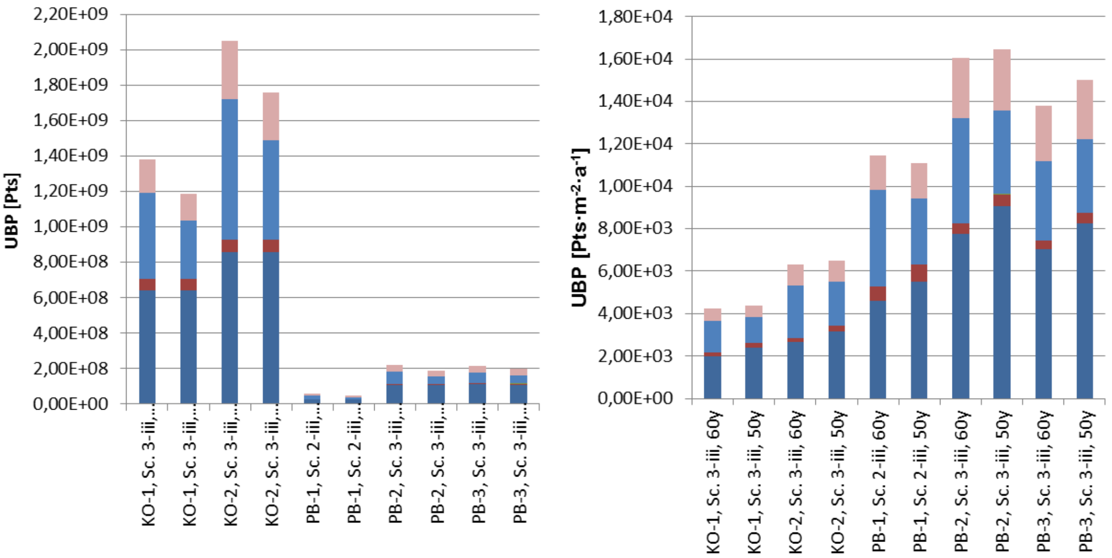


Figure 61 Comparison of EEIs of individual LCA studies with 50- and 60-year service life in Eco-Bat 4.0. Left: Total results,; Right: results per 1m^2 and year.

Service life shortening also influences the length of the “payback time” in both case studies. Increase of total annual environmental impacts shown in the right chart in Figure 60 results in shortening of the payback time (due to inverse proportionality). Figure 62 shows how this affects the “payback times” of scenario combinations with the highest environmental impacts are shown. This guarantees the highest “payback time” reduction compared to results in Figure 41 and Figure **49**.

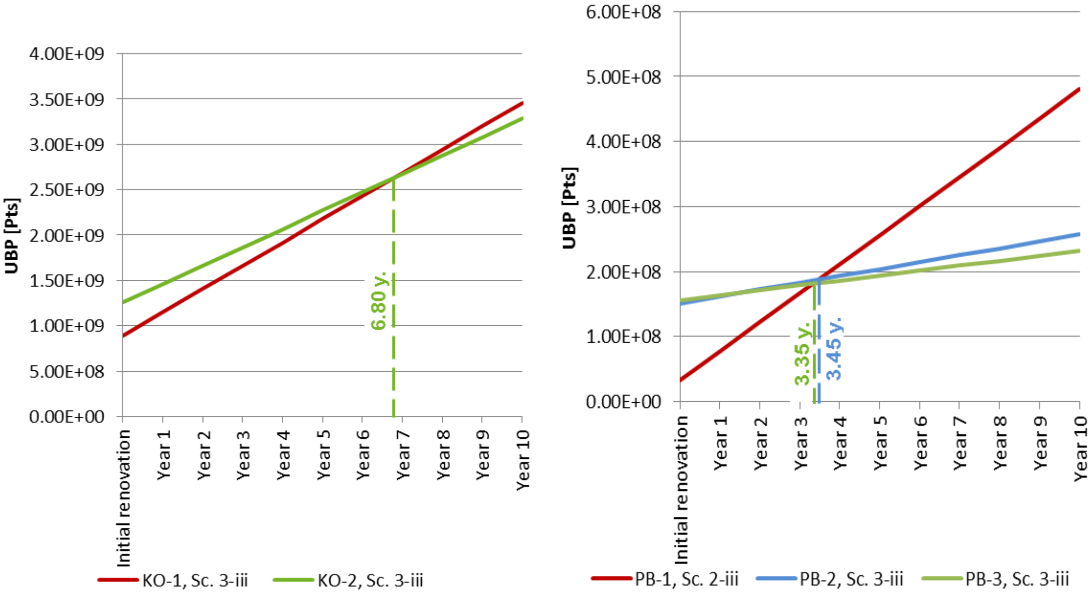


Figure 62 Comparison of environmental impacts of the evaluated case studies in selected scenario combinations in time. “Initial renovation” represents embodied environmental impacts of the initial renovation (modules A1-A4) and related waste treatment (modules C1-C4). Annual increase includes environmental impacts related with energy consumption (module B6) and further renovations (module B4). The increase of environmental impacts in module B4 is idealized to be linear due to limitations of the results provided by Eco-Bat 4.0.

Left chart in Figure 62 shows that the “payback time” decreased from 8.13 years (in Figure 41) to 6.80 years in the particular scenario combinations of Koniklecová 4 case study. In case of Přibice 275 (442) case study the “payback time” decreased from 4.15 years (in Figure 49) to 3.45 years in PB-3 and from 3.98 years to 3.35 years in PB-2 LCA study. Described shortening of the “payback time” varies between 15% and 17% (depending on particular LCA study and scenario combination). This corresponds with 16.67% shortening of the modelled service life.

6.1.5. Influence of Specific Eco-Bat 4.0 Datasets on the Results

Eco-Bat does not provide extensive material catalogue. Still, it is possible to select from multiple datasets in case of materials such as concrete or reinforced concrete, etc. This section shows the difference in total environmental impacts caused by such changes to illustrate possible inaccuracies in the LCA studies caused by application of seemingly comparable datasets. PB-2 LCA study combining construction waste scenario (iii.) and replacement scenario (3.) is selected for this comparison as it has the highest environmental impacts per 1m^2 and year. The datasets selected for replacement are *Concrete C25/30* and *Reinforcing steel (37% recycled)* representing reinforced concrete together and *Expanded polystyrene* representing EPS panels in the LCA study. They will be replaced with corresponding amounts of *Reinforced concrete C25/30, 120kg·m^{-3}* (of reinforcements), and *Expanded polystyrene (100% recycled)* respectively.

Table 9. Comparison of EEIs of selected material datasets in modules A1 to A3.

Original material	Weight [kg]	A1-A3 UBP [Pts]	Compared material	Weight [kg]	A1-A3 UBP [Pts]
Concrete C25/30	951.67	1,94E+05	Reinforced concrete C25/30, 120kg·m^{-3} of reinforcments	1000	1,89E+05
Reinforcing steel	48.32				
EPS	1000	3,22E+06	EPS (100% recycled)	1000	4,34E+05

The difference in EEIs (caused by different characterization factors) of the materials described by these datasets is shown in Table 9. It shows EEIs related with production (LCA modules A1 to A3) of 1 ton of the selected materials in Eco-Bat 4.0. Utilization of two separate datasets (concrete and reinforcing steel) instead of one dataset representing reinforced concrete results in slightly higher production-related EEIs (by 2.58%) according to the table. On the other hand the difference between production-related EEIs of the regular EPS and 100% recycled EPS is 86.52% according to the table. It should be noted that this difference is reduced by addition of EEIs related with transport, replacements and waste management.

Figure 63 illustrates the influence of the switching of selected datasets on the total EEIs of the specified PB-2 scenario combination. Total EEIs of EPS panels are reduced by 46.37%. Reduction of EEIs caused by introduction of reinforced concrete dataset is harder to explain as both plain concrete and reinforcing steel are still present in the modified PB-2 in structures such as flooring. However a combination of reinforced concrete, plain concrete and reinforcing steel in the modified PB-2 has 8.24% lower total EEIs compared to combination of plain concrete and reinforcing steel in original PB-2. Overall the charts in Figure 63 show that replacement of the selected datasets results in 4.36%

difference in EEIs (per 1m^2 and year). This is comparable with the difference caused by varying replacement scenarios in this LCA study (see Section 6.1.2).

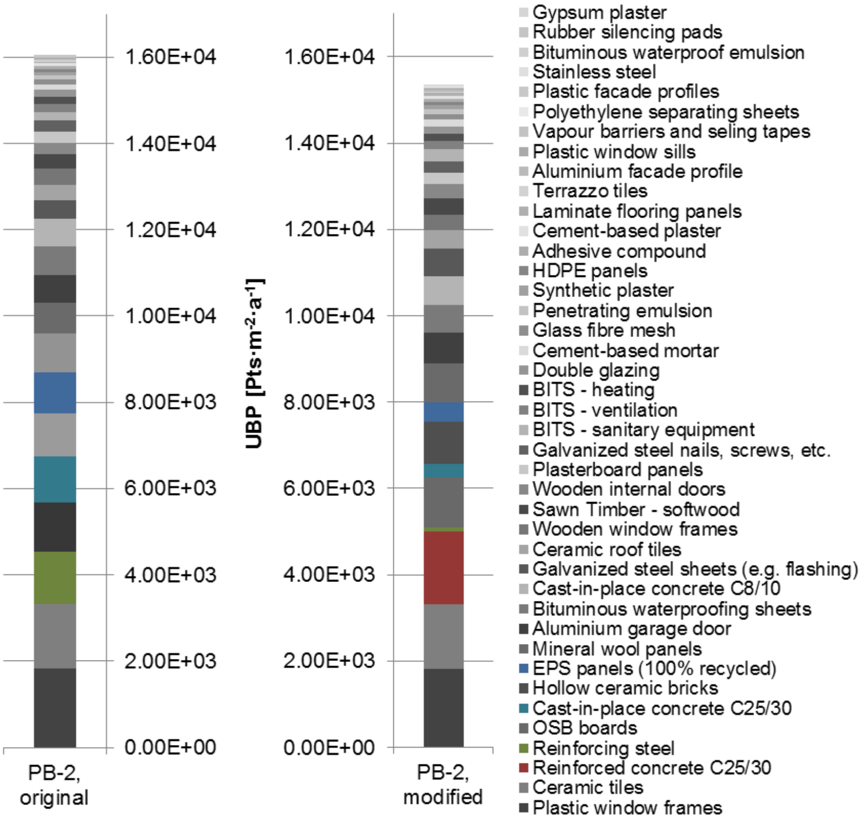


Figure 63 Comparison of EEIs (per material) of the original PB-2 and PB-2 with selected dataset replacements. Presented results combine construction waste scenario (iii.) and replacement scenario (3.). Colours highlight the construction materials represented by the replaced (or replacing) datasets in Eco-Bat 4.0.

6.1.5.1. Change of Energy Source in PB-1

Selection of different datasets is not limited to construction materials in Eco-Bat 4.0. There are also many datasets describing various energy sources (with different OEIs). It enables easy comparison as optimization, especially in buildings with dominant role of OEIs (like those in the dissertation). On the other hand it creates opportunity for errors (i. a. selecting improper energy source dataset) that could significantly distort the results.

This section presents an example of a simple comparison of energy sources in Table 10 and Figure 64. The figure compares OEIs (module B6) of the original PB-1 (PB-1 A in the figure) with six other variants. Variants B, C and D maintain electricity as the only energy source in the building (the same as original). They show what would happen if a different electricity supply mix was (accidentally) selected during the modelling of building life cycle in Eco-Bat 4.0. The results of such change vary greatly depending on efficiency (characterization factor) of electricity production in particular country. For example replacing of Czech electricity supply mix with Austrian would result in 53.96% reduction of OEIs in PB-1 due to high ratio of renewable electricity sources in Austria. Non-the-less, comparison of the PB-1 A, B, C and D OEIs in Figure 64 indicates that (accidental) change of electricity supply mix would not change the overall outcome of PB-1 LCA study. It would still have the highest environmental impacts per 1m^2 and 1 year of operation compared to the remaining four evaluated LCA studies.

Table 10. Combination of energy sources compared in Figure 64.

	Heating	**DHW**	**Lighting, electric appliances, etc**
PB-1, A	Electricity supply mix CZ	Electricity supply mix CZ	Electricity supply mix CZ
PB-1, B	Electricity supply mix AT	Electricity supply mix AT	Electricity supply mix AT
PB-1, C	Electricity supply mix PL	Electricity supply mix PL	Electricity supply mix PL
PB-1, D	El. supply mix UCTE	El. supply mix UCTE	El. supply mix UCTE
PB-1, E	Nat. gas boiler, cond.	Nat. gas boiler, cond.	Electricity supply mix CZ
PB-1, F	Wood, logs, hardwood	Wood, logs, hardwood	Electricity supply mix CZ
PB-1, G	Wood, pellets	Wood, pellets	Electricity supply mix CZ

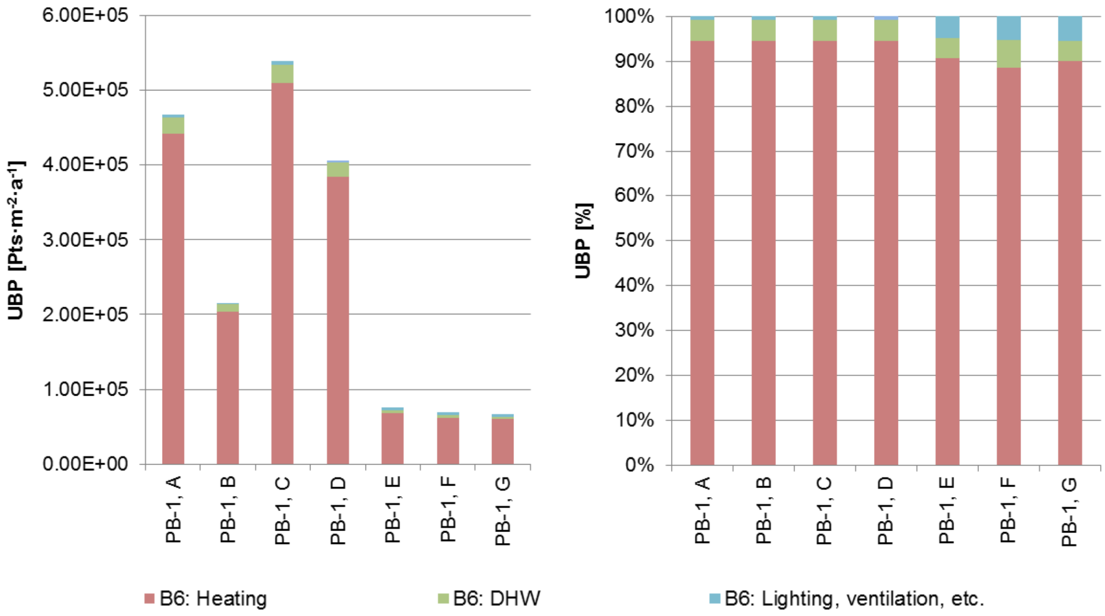


Figure 64 Comparison of the influence of various energy sources on the energy-related OEIs in PB-1.

PB-1 E, F and G are hypothetical variants showing possible reduction of OEIs in PB-1 LCA study due to change of heating and DHW energy source to natural gas (PB-1 E), wood logs (PB-1 F) or wood pellets (PB-1 G). Resulting change of OEIs reaches up to 85.73% (in case of PB-1 G). However even such significant improvement would not change the fact that PB-1 is the least environmentally efficient of the five evaluated LCA studies (due to high energy consumption per 1m^2 or floor area).

6.2. GaBi 4 Results

This section describes environmental impacts of individual scenarios considered in PB-1 and PB-3 LCA studies as calculated with the GaBi 4. The results were calculated for 324 scenario combinations in A1 to A5 modules and 27 scenario combinations in B1, B2 and C1 to C4 modules in each LCA study as defined in Section 5.3. First the total results of the scenario combinations that most resemble reality (in author's opinion) are shown in Section 6.2.1. The structure of the section follows structure of Eco-Bat 4.0 results in Section 6.1.2 to allow easier comparison. Sections 6.2.1 to 6.2.2.4 present overview of the influence of tested scenarios on the total results. Finally, Section 6.2.3 evaluates influence of particular ecoinvent 2.0 datasets on the results.

6.2.1. Results of PB-1 and PB-3 Scenario Combinations Most Resembling Reality

This section describes environmental impacts of PB-1 and PB-3 scenario combinations that most resemble reality in author's opinion: individual replacement scenarios, construction waste scenario (ii.), waste management scenario (II.) and transport scenario (d.). Results of these scenario combinations are shown in Figure 65. Environmental impacts of the worst scenario combinations in the figure equal $1.88 \cdot 10^9$ Pts in PB-1 (left chart, right column) and $8.74 \cdot 10^8$ Pts in PB-3 (right chart, middle column). The 53.63% difference is caused mostly by operational energy (see Table 7) and related OEIs in module B6. Energy-related OEIs in PB-1 equal to $1.48 \cdot 10^9$ Pts. This is 78.79% of total environmental impacts in this worst scenario combination. It is also 1.70 times more than total environmental impacts of the worst PB-3 scenario combination or 5.27 times more than energy-related OEIs in PB-3 ($2.82 \cdot 10^8$ Pts).

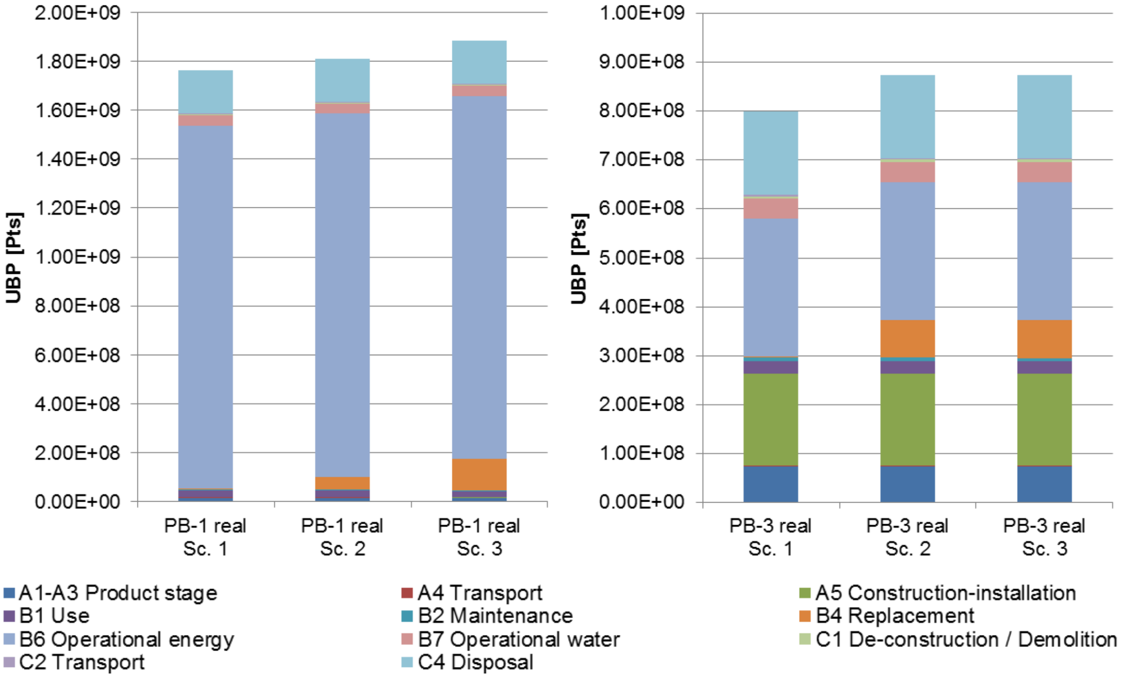


Figure 65 Total environmental impacts related with PB-1 and PB-3 scenario combinations most resembling reality.

Left chart in Figure 65 shows that LCA modules other than B6 have rather low share on the total environmental impacts in PB-1. The second highest share (up to 9.35%) on total environmental impacts belongs to waste management (landfilling) in module C4, which equals $1.76 \cdot 10^8$ Pts. This result makes the C4 module the most important regarding EEIs (modules A1-A5, B4 and C1-C4) as EEIs altogether reach $3.33 \cdot 10^8$ Pts in the worst scenario combination (17.70% share on total). The chart also indicates influence of the tested scenarios on the total results of the particular scenario combination. E.g. the difference between the three replacement scenarios reaches 6.40% in the chart.

Right chart in Figure 65 shows higher importance of EEIs in PB-3. They equal up to $5.26 \cdot 10^8$ Pts (1.58 times more than in PB-1), which means up to 60.17% share on total environmental impacts. Major part of the EEIs is related with waste management (landfilling) again. Demolition of the original building in module A5 reaches $1.84 \cdot 10^8$ Pts and final demolition in modules C1-C4 $1.77 \cdot 10^8$ Pts, which (when combined) equals two thirds of total EEIs of the particular PB-3 scenario combination. This confirms importance of the tested scenarios (particularly waste management scenarios) in PB-3. Also the difference caused by the replacement scenarios is noticeable. It reaches up to

8.57% between the PB-3 scenario combinations in the chart. The reasons for the difference are further specified in Figure 67 and accompanying texts.

Environmental advantages of PB-3 over PB-1 are further highlighted in Figure **66**. It shows (similarly to Figure 49) payback time of the worst PB-3 scenario combination from Figure 65 when compared to the corresponding PB-1 combination. The figure shows environmental impacts UBP and GWP impact categories, which have the longest and shortest payback times of all evaluated impact categories (and scenario combinations). Initial values in “Year 0” represent total EEIs in modules A1-A5 and C1-C4. These are higher in PB-3 than in PB-1. However PB-3 also has much smaller annual increase of environmental impacts in modules B1, B2, B4, B6 and B7. This results in environmental payback time of 12.11 years in UBP and very low environmental payback time of only 1.73 years in GWP impact category. This confirms that in the particular case a radical solution described in PB-3 is (environmentally) more desirable than preservation of inefficient original building.

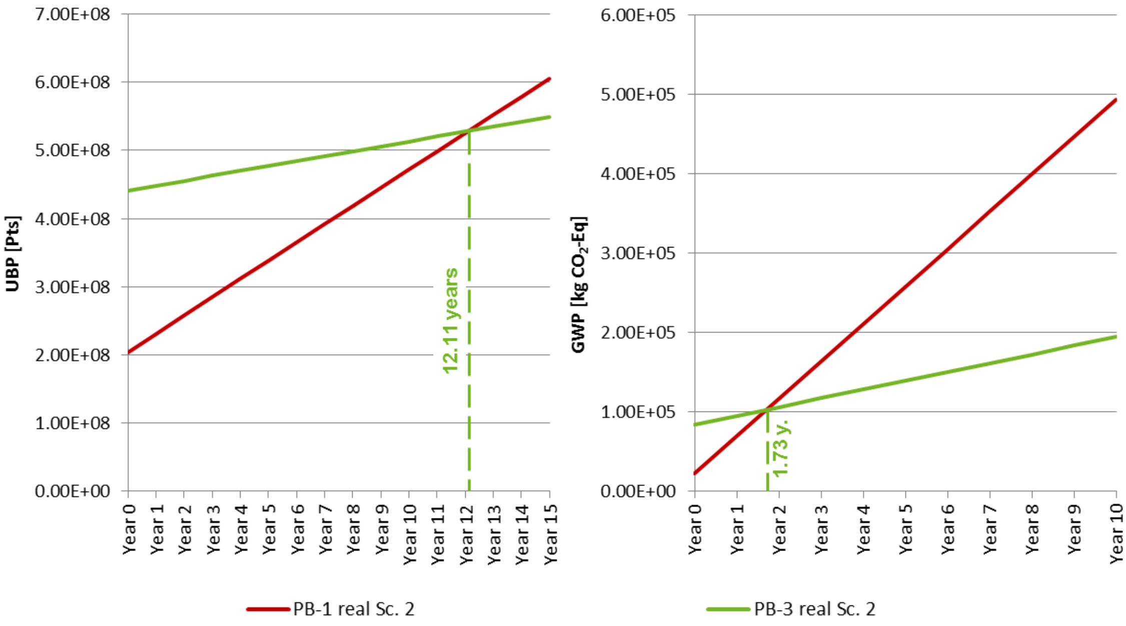


Figure 66 Comparison of environmental impacts of selected PB-1 and PB-3 scenario combinations in time in UBP and GWP impact categories. “Year 0” represents embodied environmental impacts of the initial renovation or demolition and new construction (modules A1-A5) and related waste treatment (modules C1-C4). Annual increase includes environmental impacts related with modules B1, B2, B4, B6 and B7. The increase of environmental impacts in module B4 is idealized to be linear to allow comparison with Eco-Bat 4.0 results.

Figure 67 to Figure **69** show details of the total results of the particular PB-1 and PB-3 scenario combinations. First of all, Figure 67 highlights up to 52.78% difference in EEIs between comparable scenario combinations in both LCA studies. It also highlights the difference in EEIs caused by individual replacement scenarios within these studies: up to 36.16% or 14.26% in the particular PB-1 or PB-3 scenario combinations respectively. The figure shows that these differences are related mostly with replacement of construction materials in module B4. The differences are most notable in PB-3 (right chart) due to larger amounts of materials in this LCA study. EEIs in module B4 equal $2.76\cdot10^{6}$ Pts in the PB-3 scenario combination including replacement scenario (1.). The EEIs in module B4 rise to 7.77^{7} Pts or $7.84\cdot10^{7}$ Pts when replacement scenarios (2.) or (3.) are considered instead. The reason is that only BITS are replaced in scenario (1.); while the other two scenarios contain at least one replacement of almost all non-bearing building elements (see Appendix A).

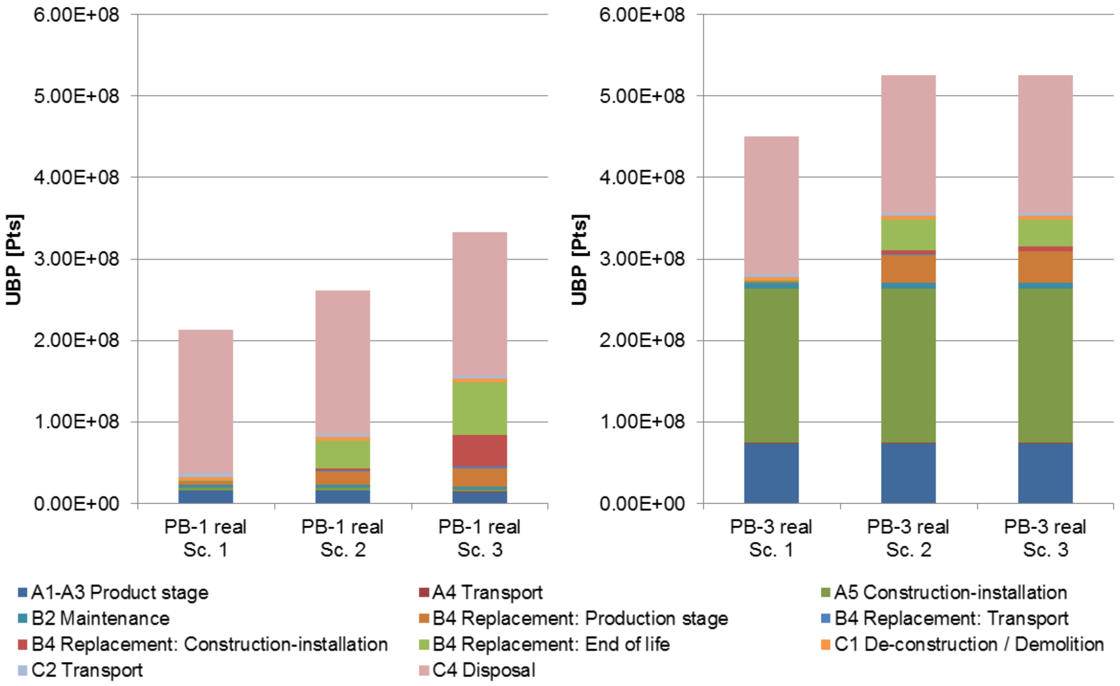


Figure 67 Total EEIs of the PB-1 and PB-3 scenario combinations shown in Figure 65.

Another issue visible in Figure 67 is major influence of waste management on the total EEIs which was already mentioned before. Landfilling of construction and demolition waste dominates the EEIs in the described scenario combinations of both LCA studies. Module C4 alone makes up to 52.85% of EEIs in PB-1. Dominance of waste management is even more pronounced in

PB-3 as it includes two demolitions: demolition of the original Přibice 275 in module A5 and final demolition of the Přibice 442 in modules C1-C4. In fact, Figure 67 indicates that the demolition of the original building and subsequent landfilling of the demolition waste makes module A5 the most significant contributor to the total EEIs in PB-3 with $1.90\cdot10^8$ Pts (out of up to $5.26\cdot10^8$ Pts). This value is so high that it almost equals total EEIs of the lowest PB-1 scenario combination in the figure ($2.13\cdot10^8$ Pts).

Figure 68 and Figure **69** further elaborate the issue of production of construction materials and its influence on total EEIs. Charts in both figures focus on environmental impacts of production of the construction materials in modules A1-A3. It should be noted that all PB-3 scenario combinations have the same EEIs in these modules as they represent the beginning of the PB-3 building life cycle. Also the only difference in modules A1-A3 between PB-1 scenario combinations described in this section is in the fact that replacement scenario (3.) does not include non-bearing walls.

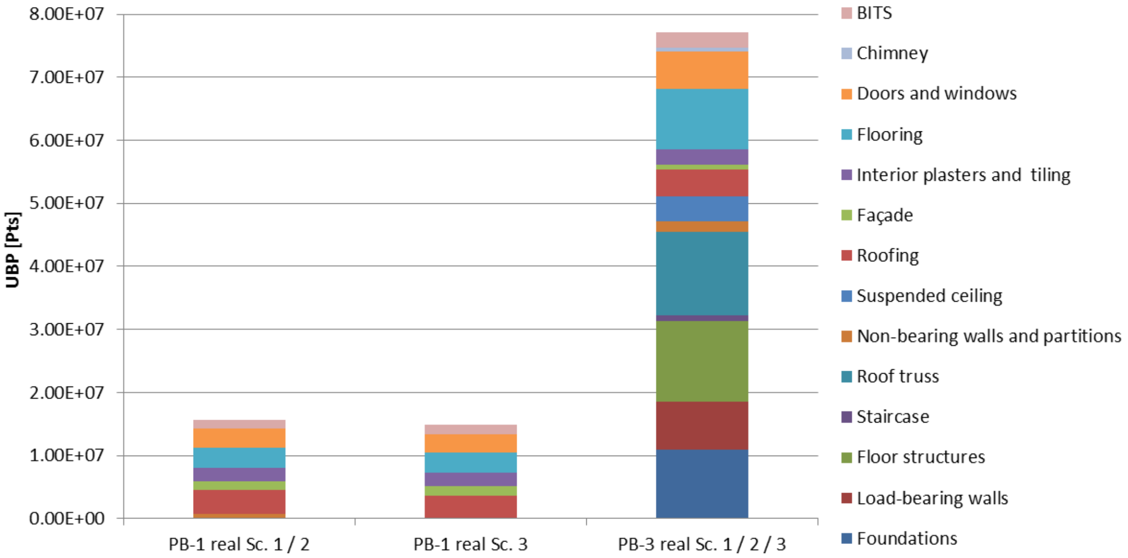


Figure 68 Environmental impacts related with production of construction materials (modules A1-A3) considered in PB-1 and PB-3 (scenario combinations shown in Figure 65) divided between individual building elements. The chart is ordered according to Appendix A.

Figure 68 shows total EEIs of selected PB-1 and PB-3 scenario combinations in modules A1-A3 divided between individual building elements (according to Appendix A). The results in this comparison clearly favour preservation and maintenance of the original state in PB-1. It achieves only up to $1.56\cdot10^7$ Pts in this comparison, while PB-3 achieves $7.72\cdot10^7$ Pts (79.74% more). Just production of materials necessary in new load-bearing elements in PB-3 is up to 65.65% more environmentally demanding than production of all construction materials necessary for “initial renovation” in PB-1. On the other hand elements such as interior plasters, roofing or BITS have comparable or smaller environmental impacts in PB-3. This is due to smaller size of the PB-3 building and utilization less demanding materials (e.g. plastics instead of steel for pipes).

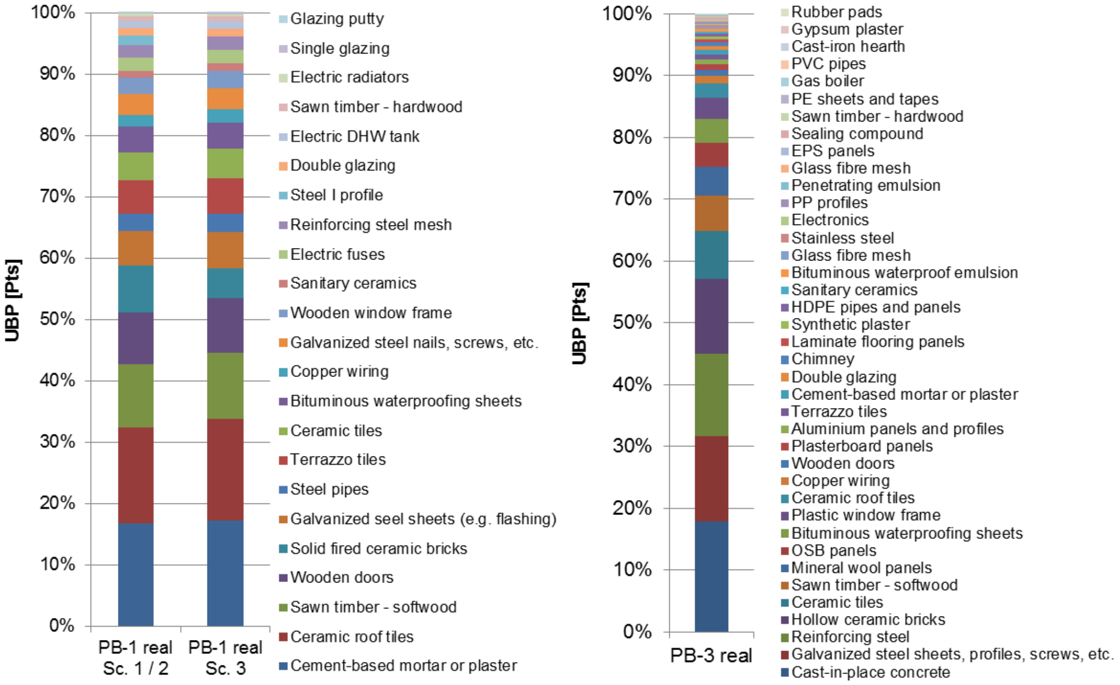


Figure 69 Percentage shares of individual construction materials on total EEIs in modules A1-A3 in PB-1 and PB-3 (scenario combinations shown in Figure 65). The materials in the chart are ordered according to their shares on the total EEIs: highest to lowest from bottom to top.

Figure 69 brings more insight into the distribution of EEIs between individual materials. It shows shares of individual construction materials, on the EEIs of selected PB-1 (22 or 23 materials) and PB-3 (39 materials) scenario combinations in modules A1-A3. Most notable fact is that only four construction materials are responsible for more than 50% of total environmental impacts in PB-1 and PB-3 LCA studies. The most demanding materials in PB-1 are cement-based mortars and plasters, which have 17.29% share on total EEIs in modules A1-A3 when replacement scenario (3.) is included in the combination. This share reflects importance of interior and exterior wall finishes in the (23.72% combined share on EEIs in A1-A3) particular scenario combination visible in Figure 68. Most demanding material in PB-3 is cast-in-place concrete, which has 17.80% share on total EEIs in modules A1-A3. EEIs related with production of this material equal $1.29 \cdot 10^7$ Pts in the particular scenario combination. That is more than total EEIs in modules C1-C4 in the same scenario combination ($1.24 \cdot 10^7$ Pts). Importance of concrete is related with its application (in combination with reinforcing steel, which placed third) in foundations and floor structures. Other demanding materials in PB-3 include galvanized steel and (surprisingly) and softwood. These particular materials have the second (13.92%) and the sixth (5.82%) highest share on EEIs in modules A1-A3 in the particular scenario combination. This is related to the fact that most of these materials are found in PB-3's roof truss, which is the single most demanding building element according to Figure 68.

In contrast to the demanding materials there are also four materials in PB-1 and 27 materials in PB-3 scenario combinations that have lower than 1% share on total EEIs in Figure 69. Interestingly enough, even the combined shares of these "low-impact" materials on EEIs in A1-A3 modules reach only up to 1.40% in PB-1. In PB-3 these materials have 10.04% combined share on the EEIs in A1-A3 modules. This is comparable with the ceramic bricks, which is the fourth most demanding material (12.22%) in A1-A3 modules of the particular scenario combination. Low individual shares of specific materials on the EEIs are mostly related with their small quantities considered in the inventory tables: e.g. 5.85 kg of glazing putty (in windows) or 3.34 kg of rubber pads (in staircase), which are the least demanding materials in PB-1 and PB-3 respectively according to Figure 69. However this should not be generalized. For example production of five tonnes of reinforcing steel is more demanding than production of 70 tonnes of ceramic bricks ($9.60 \cdot 10^6$ Pts vs. $5.55 \cdot 10^7$ Pts) in PB-3.

6.2.2. Influence of the Tested Scenarios on the Total Results

Figure 70 to Figure **76** illustrate wide range of total environmental impacts in both LCA studies performed in GaBi 4 caused by different scenario combinations. Figure 70 shows scenario combinations with the highest and lowest environmental impacts in UBP impact category in both LCA studies. Overall, the scenario combination with the worst (highest) environmental impacts in UBP impact category is (unsurprisingly) PB-1 including replacement scenario (3.), construction waste scenario (iii.), waste management scenario

(II.) and transport scenario (a.). It receives 1.97·10^9 Pts. The same (also the worst) scenario combination in PB-3 reaches “only” 1.01·10^9 Pts. In comparison the best (most environmentally-friendly) scenario combination is PB-3 including replacement scenario (1.), construction waste scenario (i.), waste management scenario (III.) and transport scenario (d.). It achieves 4.28·10^8 Pts, which is 4.60 times less compared to the worst combination. Overall the difference between environmental impacts of the highest and lowest scenario combinations in Figure 70 reaches 20.48% in PB-1 and 57.47% in PB-3. The reasons for the difference are also visible in the figure: replacement of materials and components in module B4 and construction (demolition) waste processing in modules A5 (especially in PB-3), C3 and C4.

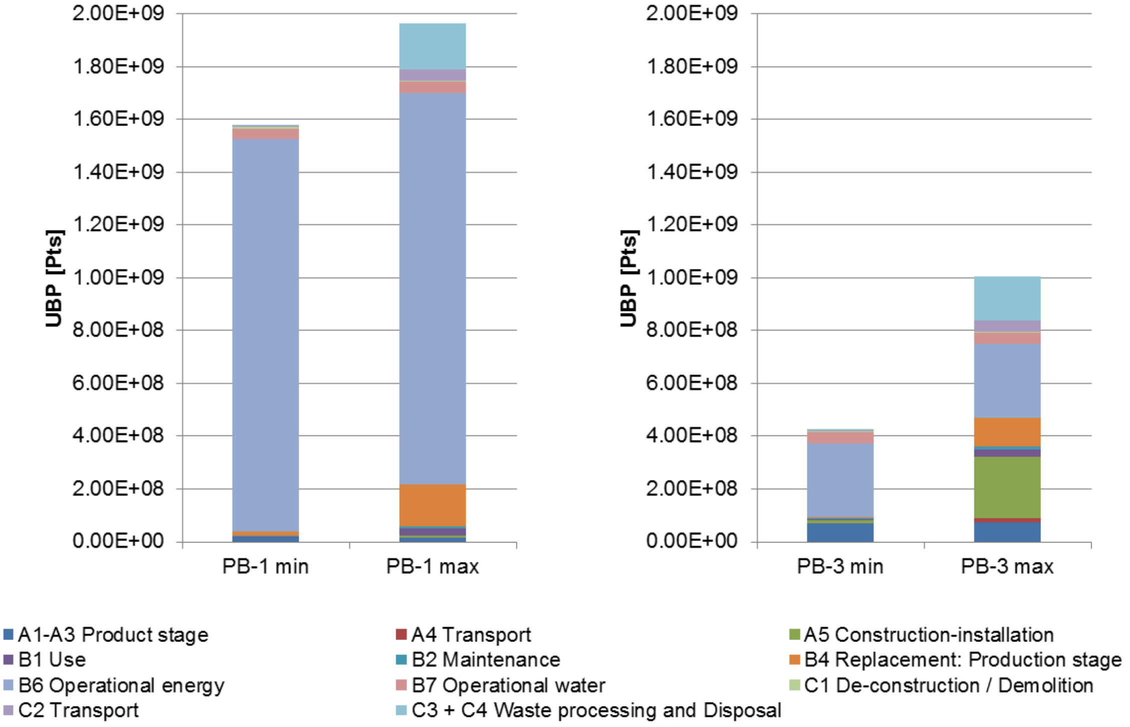


Figure 70 Total environmental impacts of the best (lowest) and the worst (highest) scenario combinations in PB-1 and PB-3 LCA studies.

The differences in module B4 visible in Figure 70 are result of combination of all tested scenarios. Reason for the difference was already mentioned: only BITS are replaced in the lowest scenario combination, while the highest scenario combination considers replacements of most non-bearing building elements. Add varying amount of construction waste, transport distances or waste processing and the difference between the lowest and the highest environmental impacts in module B4 reaches 88.37% (1.40·10^8 Pts) in PB-1 and 97.82% (1.07·10^8 Pts) in PB-3 LCA studies respectively. The difference is more pronounced in PB-3 as BITS have lower share on the EEIs there.

The differences in modules A5, C3 or C4 are caused primarily by the waste management scenarios (as mentioned in Section 6.2.1). These differences are caused by the approach to the waste processing. Results indicate that recycling (scenario (III.)) is the most efficient waste management option and landfilling (scenario (II.)) the worst in the UBP impact category.

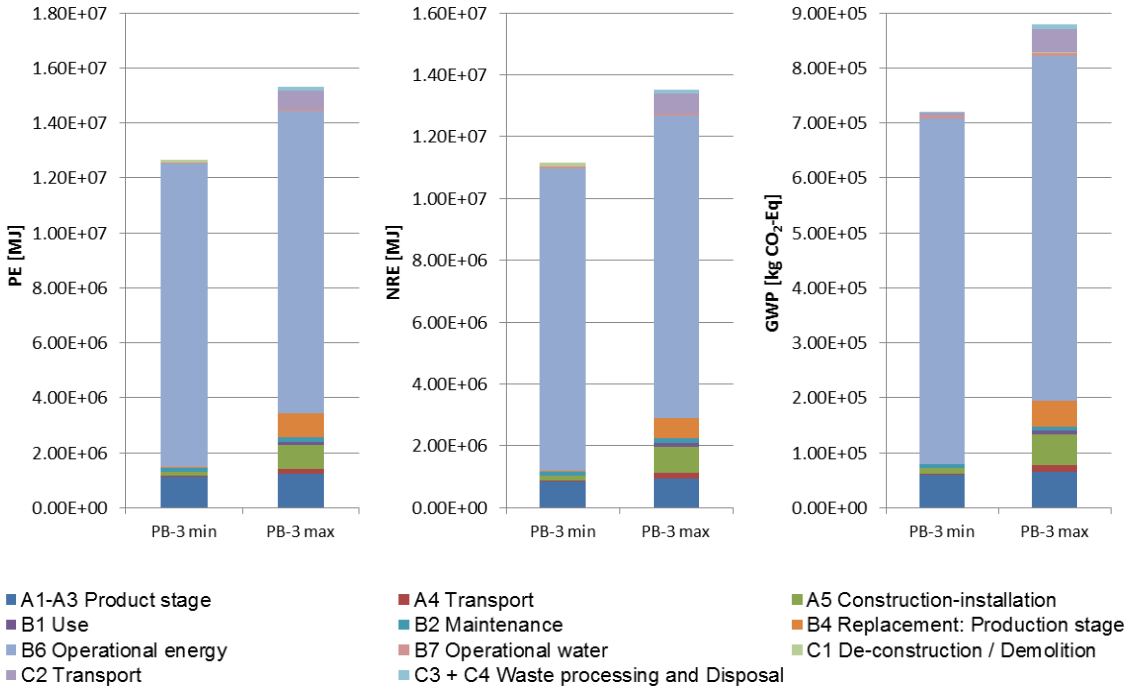


Figure 71 Total environmental impacts of the best (lowest) and the worst (highest) scenario combinations in PB-3 LCA study in PE, NRE and GWP impact categories.

Figure 71 illustrates differences between the best (lowest environmental impacts) and worst (highest environmental impacts) scenario combinations in PE, NRE and GWP impact categories. The figure includes only PB-3 results as the differences are more pronounced in this LCA study. It should be noted that the best and worst scenario combinations in these three impact categories share three out of four scenarios with the UBP impact category results: replacement, construction waste and transport. Only difference is in waste management. Lowest total environmental impacts have the scenario combinations including waste management scenario (I.) in PE and NRE and (III.) in GWP impact category. Highest total environmental impacts have the scenario combinations including waste management scenario (III.) in all three impact categories. This is almost opposite to the results in UBP impact category. Another noteworthy fact is similar difference between the best and worst scenarios: 17.16% in PE, 17.54% in NRE and 18.09% in GWP impact category respectively. However this similarity is purely coincidental.

The differences caused by the tested scenarios are further described in following sections (focusing on UBP impact category). Charts in Figure 72 to Figure 76 show the influence of particular scenarios on the total results. Green columns in the individual charts show the range of total environmental impacts of all tested scenario combinations divided between the particular scenarios. Wider range (higher green column) indicates lower influence of the particular scenario on the total environmental impacts.

6.2.2.1. Influence of Replacement Scenarios on the Results

Figure 72 shows variations of the results caused by the three tested replacement scenarios. PB-1 scenario combinations including replacement scenario (3.) have on average 4.68% ($8.31 \cdot 10^7$ Pts) or 2.60% ($4.62 \cdot 10^7$ Pts) higher environmental impacts than combinations including replacement scenarios (1.) or (2.) respectively. This correlates with impact of LCA module B4 Replacement on the total EEIs visible in Figure 67. Interestingly enough, these differences account for 4.33 (or 2.41 respectively) times more environmental impacts than modules A1-A3 in PB-1. This suggests that accuracy of the replacement scenario is more important than accuracy of the inventory table describing modules A1-A3 in PB-1.

PB-3 scenario combinations including replacement scenario (2.) have on average 6.67% ($4.98 \cdot 10^7$ Pts) or 0.42% ($3.12 \cdot 10^6$ Pts) higher environmental impacts than combinations including replacement scenarios (1.) or (3.) respectively. This makes the difference between scenarios (1.) and (2.) in PB-3 more important than whole life cycle module B6 ($4.15 \cdot 10^7$ Pts). Much smaller difference between replacement scenarios (2.) and (3.) almost equals EEIs related with production of new plastic window frames ($2.45 \cdot 10^6$ Pts) in PB-3. It should be noted that the small scale of this difference is caused by particular building elements in PB-3: Higher number of replacements of flooring, doors and windows in scenario (3.) is compensated by higher number of replacements of non-bearing walls and BITS in scenario (2.). Overall the differences caused by particular replacement scenarios are relatively lower in PB-3 compared to PB-1. Environmental impacts related with these differences do not exceed environmental impacts of the modules A1-A3 in PB-3. This is likely caused by the fact that PB-3 includes much more construction materials than PB-1.

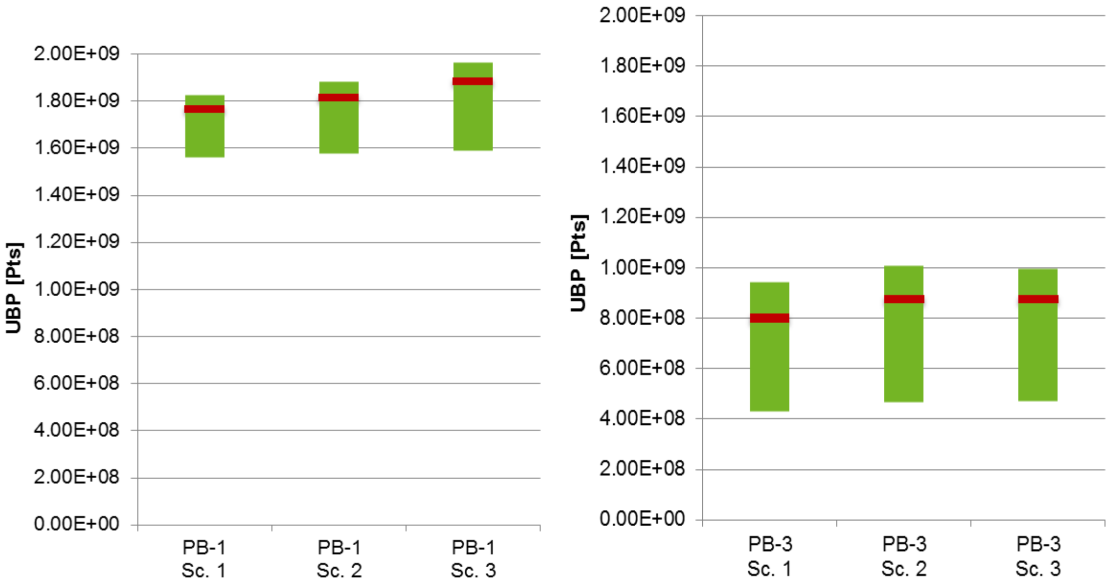


Figure 72 Range of total environmental impacts (green) of individual scenario combinations in PB-1 and PB-3 LCA studies. Separate columns represent individual replacement scenarios. Red marks indicate scenario combinations that most closely match reality described in Section 6.2.1.

6.2.2.2. Influence of Construction Waste Scenarios on the Results

The amount of construction waste produced during the initial renovation (modules A1-A5) of PB-1 reaches up to 6.00 tonnes, depending on particular scenario combination. Subsequent renovations (module B4) produce up to 11.85 tonnes of construction waste in PB-1. This means that the weight of construction waste equals 8.86% of total weight of construction materials necessary during modelled life cycle of PB-1. Environmental impacts related with processing and disposal of the construction waste equal up to $1.52 \cdot 10^7$ Pts. This is 0.77% of total environmental impacts of the particular scenario combination. The situation is similar in PB-3. There is up to 17.66 tonnes of construction waste in the worst PB-3 scenario combination. This equals 4.09% of the total weight of all construction materials considered in the particular scenario combination. This amount of construction waste is responsible for $1.57 \cdot 10^7$ Pts of environmental impacts, which equals 1.55% of total environmental impacts of the particular PB-3 scenario combination.

Above mentioned facts suggest rather low influence of construction waste scenarios on the variations of total results. This presumption is confirmed by Figure 73, which shows minimal differences between environmental impacts of the scenario combinations with various construction waste scenarios. The highest environmental impacts are (unsurprisingly) related with those scenario combinations that include construction waste scenario (iii.) both in PB-1 and PB-3 LCA studies. Average difference between these scenario combinations and scenario combinations including construction waste scenarios (i.) or (ii.) is only 0.45% ($8.01 \cdot 10^6$ Pts) or 0.23% ($4.00 \cdot 10^6$ Pts) respectively in PB-1. The relative difference is only slightly higher in PB-3. Scenario combinations including construction waste scenario (iii.) have 1.73% ($1.25 \cdot 10^7$ Pts) or 0.87% ($6.30 \cdot 10^6$ Pts) higher environmental impacts compared to scenario combinations including construction waste scenarios (i.) or (ii.) respectively in this LCA study. For illustrations, these differences are lower than environmental impacts related with municipal waste processing in module B1, which reach up to $3.01 \cdot 10^7$ Pts.

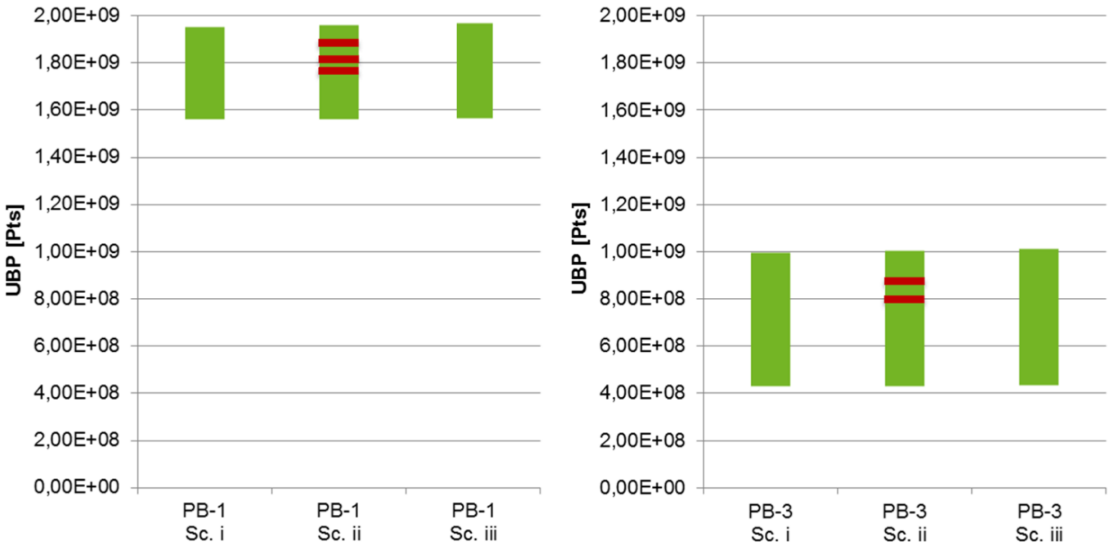


Figure 73 Range of total environmental impacts (green) of individual scenario combinations in PB-1 and PB-3 LCA studies. Separate columns represent individual construction waste scenarios. Red marks indicate scenario combinations that most closely match reality. The marks are overlapping in right chart.

6.2.2.3. Influence of Waste Management Scenarios on the Results

Previously described results (e.g. Figure 70) suggest high influence of waste management scenarios on the total environmental impacts, especially in UBP impact category. This is confirmed in Figure 74. The charts in the figure show relatively narrow ranges of total environmental impacts in individual columns, which indicate limited influence of other tested scenarios. The figure also shows significant differences between individual waste management scenarios. Especially scenario (III.) is standing apart from the remaining scenarios. Scenario combinations including scenario (III.) have on average 13.36% ($2.49 \cdot 10^8$ Pts) lower total environmental impacts than the worst scenario combinations including scenario (II.) in PB-1. This average difference reaches 44.04% ($3.99 \cdot 10^8$ Pts) in PB-3. On the other hand, average difference between scenario combinations including scenarios (I.) and (II.) is less than 1% in both LCA studies.

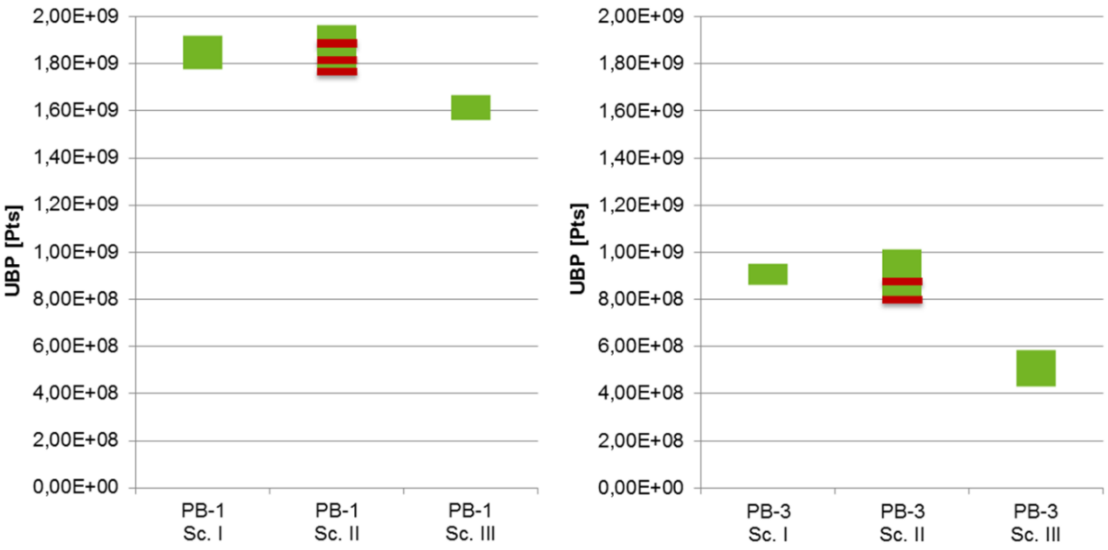


Figure 74 Range of total environmental impacts (green) of individual scenario combinations in PB-1 and PB-3 LCA studies. Separate columns represent individual waste management scenarios. Red marks indicate scenario combinations that most closely match reality. The marks are overlapping in right chart.

The reason for the differences lies in applied database datasets and related characterization factors. This is illustrated in Figure 75, which compares environmental impacts of dismantling, transport and disposal of 1kg of ceramic bricks according to tested waste management scenarios in all four impact categories. Transport scenario (d.) is considered in the comparison to highlight the influence of dismantling and waste processing.

Figure 75 shows similar trends in all four impact categories: Highest environmental impacts are related with scenario (II.), which models landfilling of the waste (see Figure 38) in Czech conditions. It has between 1.52% (in UBP) and 40.07% (in GWP) higher environmental impacts in individual impact categories than generic landfilling datasets utilized in scenario (I.). The difference is caused mostly by more accurate modelling of waste transport and application of Czech electricity supply mix in scenario (II.).

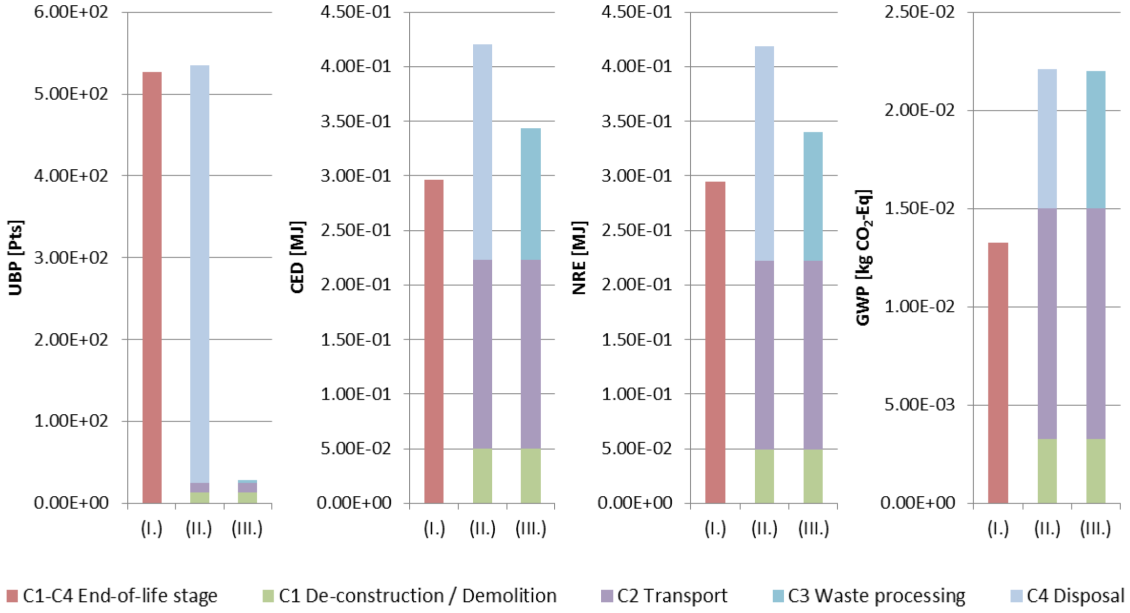


Figure 75 Environmental impacts of the end-of-life of 1kg of ceramic brick remains in all four evaluated impact categories.

Recycling modelled in scenario (III.) has lower environmental impacts than landfilling modelled in scenario (II.) in Figure 75. It should be noted that both scenarios have the same environmental impacts in modules C1 and C2. The difference is only in the final module: C3 in scenario (III.) or C4 in scenario (II.). This difference varies between 1.78% in GWP and 99.24% in UBP impact category. This explains the difference in total results visible in Figure 74. The reason for such high difference in UBP is in applied characterization factors. UBP impact category originates in Switzerland. Therefore it discourages landfilling to save limited land available in the country.

Charts in Figure 75 also show that recycling modelled in scenario (III.) has higher environmental impacts than landfilling based on generic ecoinvent 2.0 datasets in three out of four impact categories (up to 39.73% in GWP). The difference suggests that recycling is potentially more demanding than landfilling. However this conclusion might be inaccurate. The reason for lower environmental impacts of generic process is that it does not include dismantling, it utilizes fixed 15km transport distance, transport or it utilizes Swiss electricity supply mix, not Czech. Its accuracy is therefore questionable. This situation suitably illustrates dangers of using generic database datasets in LCA studies.

6.2.2.4. Influence of Transport Distance Scenarios on the Results

Figure 76 shows influence of varying transport distances on the total environmental impacts. Unsurprisingly, the highest environmental impacts are related with scenario combinations including transport scenario (a.) with 100km transport distance of all materials and services. The lowest total environmental impacts are related with scenario combinations including transport scenario (d.) with transport distances most resembling reality. Average difference between these scenario combinations is 3.38% ($6.03 \cdot 10^7$ Pts) in PB-1 LCA study. This is more than production of all construction materials and elements considered in modules A1-A3 and B4, which equals “only” up to $3.99 \cdot 10^7$ Pts. In PB-3 the difference reaches 14.36% ($1.10 \cdot 10^8$ Pts). This is almost as much as environmental impacts related with production of all construction materials and elements considered in modules A1-A3 and B4 (up to $1.16 \cdot 10^8$ Pts). This makes transport the second most influencing scenario in PB-3 (after waste management).

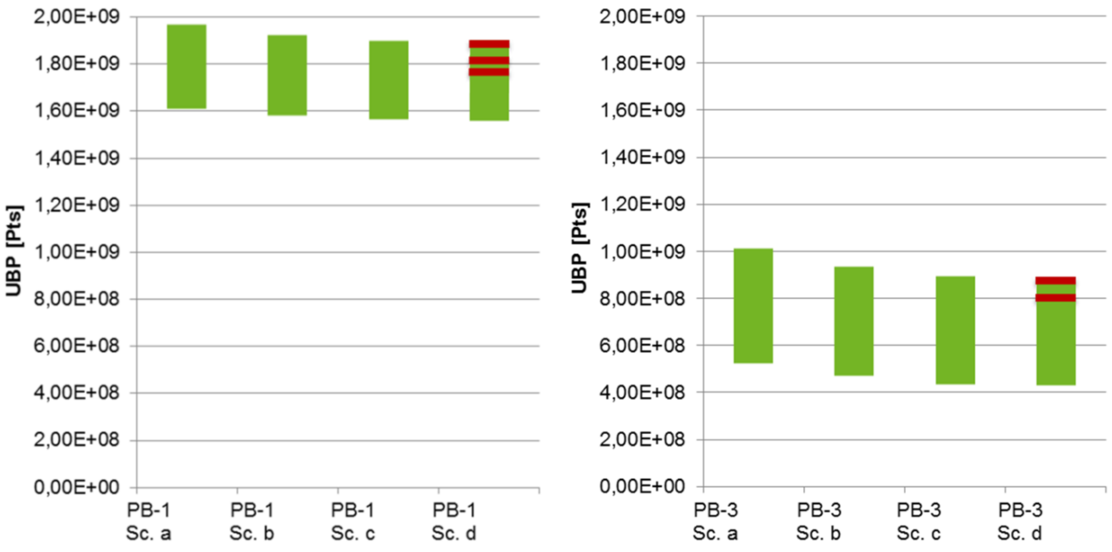


Figure 76 Range of total environmental impacts (green) of individual scenario combinations in PB-1 and PB-3 LCA studies. Separate columns represent individual transport scenarios. Red marks indicate scenario combinations that most closely match reality. The marks are overlapping in right chart.

6.2.3. Influence of Specific ecoinvent 2.0 Datasets on the Results

Previous sections show that total environmental impacts could be significantly influenced by selection of specific material, energy or transport options. However the same is true for selection of particular datasets (and their combinations) representing these options. Waste management scenarios (see Section 6.2.2.3) are prime example of this issue. Modelling of individual construction materials and elements could provide other examples, such as galvanized steel elements (wires, joints, etc.). E.g. production of galvanized steel wire is modelled as a combination of three ecoinvent 2.0 datasets in GaBi 4: *RER: steel, low-alloyed, at plant* and *RER: wire drawing, steel* represent production of the steel wire and *RER: zinc coating, pieces* represents the final coating. 71.66% of environmental impacts caused by production of the modelled material are related with the first dataset (production of steel). This means that omitting of the two datasets representing processing and coating of steel could reduce environmental impacts of the material production by almost one third. Galvanized steel is one of the most demanding materials according to the results in Figure 69. Such simplification would therefore noticeably lower

EEIs of the evaluated buildings. For example the decrease of EEIs in UBP impact category would reach up to 14.35% in the PB-3 scenario combinations most closely resembling reality.

Another noticeable difference might be caused by selection of particular datasets representing waste transport (especially in C2 LCA module). All modelled scenario combinations utilize dataset *CH: transport, municipal waste collection, lorry 21t* for this purpose. It has much higher environmental impacts compared to the dataset *RER: transport, lorry 3.5-16t, fleet average* utilized for transport of new materials (e.g. in A4 LCA module). The difference is 71.59% in UBP, 71.08% in PE, 71.40% in NRE and 74.64% in GWP impact category. Hypothetical unification of transport options and utilization of the later dataset would reduce total environmental impacts of the worst scenario combination in UBP impact category by 2.14% ($4.21 \cdot 10^7$ Pts) in PB-1. This means that replacement of transport dataset would have almost twice higher impact than modules A1-A5 (up to $2.21 \cdot 10^7$ Pts) in PB-1. In PB-3 the difference reaches 6.64% ($6.62 \cdot 10^7$ Pts). This is less than 13% lower compared to environmental impacts of modules A1-A3 ($7.57 \cdot 10^7$ Pts) in this LCA study. All these results confirm that selection of the most suitable datasets has crucial role for the accuracy of a LCA study. It is potentially more important than all tested scenarios.

6.3. Comparison of Eco-Bat 4.0 and GaBi 4 Results

This section compares PB-1 and PB-3 calculation results provided by Eco-Bat 4.0 and GaBi 4. Aim of this comparison is evaluation of the influence of software tool specifics and limitations on the results similarly to (Silva, 2017). Scenario combinations most resembling reality are selected to represent GaBi 4 calculations in this comparison (see Section 6.2.1). Combinations of all evaluated replacement scenarios with construction waste scenario (ii.) are selected to represent Eco-Bat 4.0 calculations as they should be most similar to the selected GaBi 4 scenario combinations.

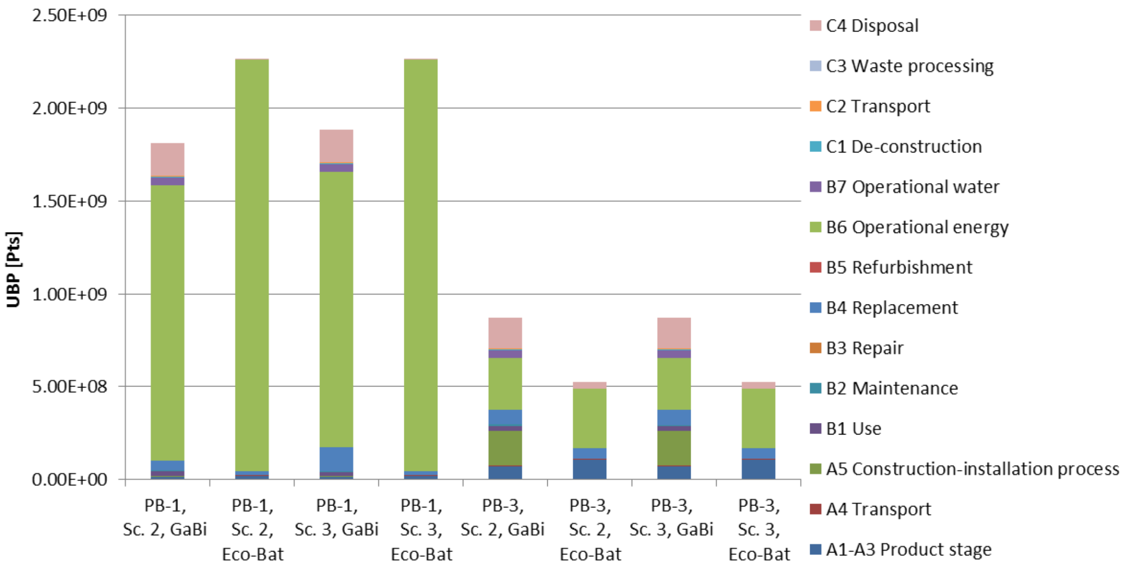


Figure 77 Comparison of total environmental impacts of PB-1 and PB-3 LCA studies in Eco-Bat 4.0 and GaBi 4. Scenario combinations most resembling reality represent GaBi 4 results (see Section 6.2.1). Combinations of all replacement scenarios with construction waste scenario (ii.) represent Eco-Bat 4.0 results.

The differences vary across impact categories. Least pronounced differences are in GWP impact category (up to 2.63% in PB-3). Most pronounced differences are in UBP impact category. Figure 77 therefore shows comparison of total environmental impacts (divided into LCA modules) of all the specified scenario combinations in UBP impact category. The differences between the results provided by both software tools reach up to 20.12% (4.56·10 Pts) in PB-1 and 39.93% (3.49·10^8 Pts) in PB-3. The differences are related with multiple issues; most notably software limitations and differences in characterization factors (see Sections 2.2.3 and 4.2.2). Importance of these issues depends on particular LCA studies. Figure 77 indicates that characterization factors are responsible for majority of differences in the particular PB-1 scenario combinations. On the other hand, differences in PB-3 scenario combinations are (mostly) caused by the fact that GaBI 4 calculations incorporate more LCA modules (or their parts) than Eco-Bat 4.0 calculations.

Variations in characterization factors (between characterization methods) and resulting differences in environmental impacts are inevitable (see Section 2.2.3). Most notable example of these differences in Figure 77 is energy consumption (especially in PB-1) although similar differences could be encountered in all materials and processes considered in the LCA studies. The differences in environmental impacts related with energy consumption are further elaborated in Table 11. This table shows environmental impacts of 1MJ of electricity and natural gas supply calculated in both software tools. It shows that characterization factors in Eco-Bat 4.0 are higher than those in GaBi 4 in the UBP impact category. The difference is 35.08% in case of electricity and 29.36% in case of natural gas. This is likely a result of changes in the utilized versions of UBP methodology. The situation is slightly different in other impact categories. Characterization methods utilized in GaBi 4 give higher environmental impacts in PE, NRE and GWP. The difference reaches up to 16.37% in case of electricity (in PE) or 11.29% in case of natural gas (in NRE). The lowest differences are in GWP impact category: only 0.26% in case of electricity or 8.19% in case of natural gas. The reason for these differences is utilization of different characterization methods for calculations of environmental impacts in these impact categories in both software tools. Very low difference in electricity's environmental impacts in GWP impact category just illustrates that the differences may not always be easily recognizable (as mentioned in Section 2.2.3.2 and Table 3)

Table 11. Comparison of environmental impacts related with 1 MJ of supplied energy in Eco-Bat 4.0 and GaBI 4.

Eco-Bat 4.0			**GaBi 4**		
Impact category	**Electricity, low volt.**	**Natural gas**	**Impact category**	**Electricity, low volt.**	**Natural gas**
UBP [Pts]	2,04E+02	3,15E+01	**UBP** [Pts]	1,33E+02	2,22E+01
CED [MJ]	3,73E+00	1,12E+00	**PE** [MJ]	4,46E+00	1,26E+00
NRE [MJ]	3,64E+00	1,11E+00	**NRE** [MJ]	4,37E+00	1,26E+00
GWP [kg CO_2-Eq.]	2,57E-01	6,60E-02	**GWP** [kg CO_2-Eq.]	2,56E-01	7,19E-02

Lack of some LCA modules (or their parts) is another issue, which decreases comparability of the results. It should logically cause that environmental impacts calculated in Eco-Bat 4.0 are lower compared to those calculated in GaBi 4. Interestingly, this is true only in PB-3 scenario combinations, where the impact of varying characterization factors is not as pronounced as in PB-1. Figure 77 shows that most notable difference (99.77%) is in module A5 in PB-3. Main reason for this difference is the fact that GaBi 4 calculations include demolition of the original building in this module, which is impossible to do in Eco-Bat 4.0. The impact of this software limitation is rather important. Difference between total environmental impacts of PB-3 calculated in both software tools would decrease from (up to) 39.93% down to 23.33% if they would share the same environmental impacts in A5. Another example of this issue is operational water consumption in module B6, which is also considered only in GaBi 4 calculations. Omitting of this module would reduce environmental impacts in the GaBI 4 scenario combinations in Figure 77 by up to 5.20% ($4.15{\cdot}10^7$ Pts).This change in environmental impacts in UBP impact category would in turn increase the difference between the results in both LCA tools by 1.83% in PB-1 or decrease it by 3.00% in PB-3.

Importance of individual sources of the differences introduced in this section varies. However Figure 77 clearly shows that their combination influences the total results of the evaluated LCA studies greatly. In fact only the differences caused by waste management scenarios in GaBi 4.0 calculations (see Section 6.2.2.3) have comparable impact on the results. This shows that selection of LCA software and characterization method is potentially more important for the accuracy of the LCA results than quality of the input data in the inventory tables.

6.4. Comparison of the Results with Literature

In general, literature confirms that renovations are beneficial (see Section 2.3.2) to the environment. However comparison of the efficiency of various building renovations is challenging. Previous section as well as Sections 2.3 and 2.4 illustrate that comparison of results of different LCA studies is potentially misleading and inaccurate due to differences in size of the buildings, scope of the assessment, characterization methods, etc. Another problem is that existing studies often do not provide detailed numerical results, which makes comparisons even more complicated. This situation is illustrated by following example.

LCA of an apartment building in Spain is selected for the comparison with KO-1 and KO-2 LCA studies. This LCA study was prepared by Ana Sánchez-Ostiz and Silvia Domingo-Irigoyen as a part of the Annex 56 project. Summary of the study is available in one of the Annex 56 deliverables, (Venus, 2017). The reason for this comparison is the fact that this LCA study utilizes Eco-Bat 4.0 software. Therefore it should share the limitations of the LCA studies described in Section 6.1. Also the extent of the renovation between the Spanish apartment building and Koniklecová 4 block-of-flats is similar: addition of thermal insulation to the envelope, changes in windows and BITS. Environmental impacts of the Spanish apartment building were presented in CED (described as PE), NRE (described as NRPE) and GWP impact categories in (Venus, 2017). Their overview is in Figure 78. It should be noted that the environmental impacts are structured according to Annex 56 template. Any modifications of the results are impossible due to lack of original data. Therefore Figure 79 shows environmental impacts of the worst Eco-Bat 4.0 scenario combinations in KO-1 and KO-2 LCA studies structured according to the same template to allow comparison. It should be noted that both figures show environmental impacts per 1m^2 of treated floor area and year of operation of the building to increase objectivity of the comparison (as the size of the compared buildings differs).

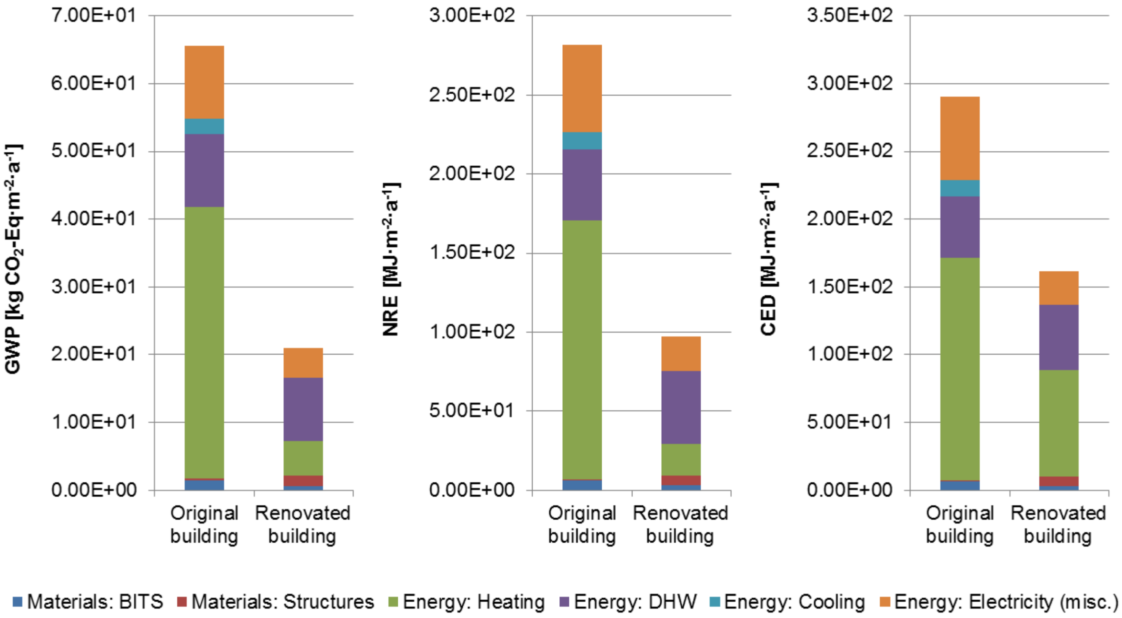


Figure 78 Total environmental impacts of a Spanish apartment building before and after renovation structured according to Annex 56 project template. (Venus, 2017)

A general comparison is rather easy. Figure 78 and Figure **79** show that OEIs play major role in all compared LCA studies. For example they have 97.36% share on total environmental impacts of the original Spanish building in GWP impact category. Similarly, they have 95.22% share on total environmental impacts in GWP impact category in KO-1. After renovation the importance of OEIs slightly decreased. Their share on total environmental impacts in GWP impact category is 89.63% in case of renovated Spanish building or 88.64% in KO-2. The differences between these shares in Spanish building and KO-1 or KO-2 are caused by the EEIs. KO-1 and KO-2 have higher EEIs due to larger scale of the buildings and the extent of the renovations (e.g. thicker thermal insulation).

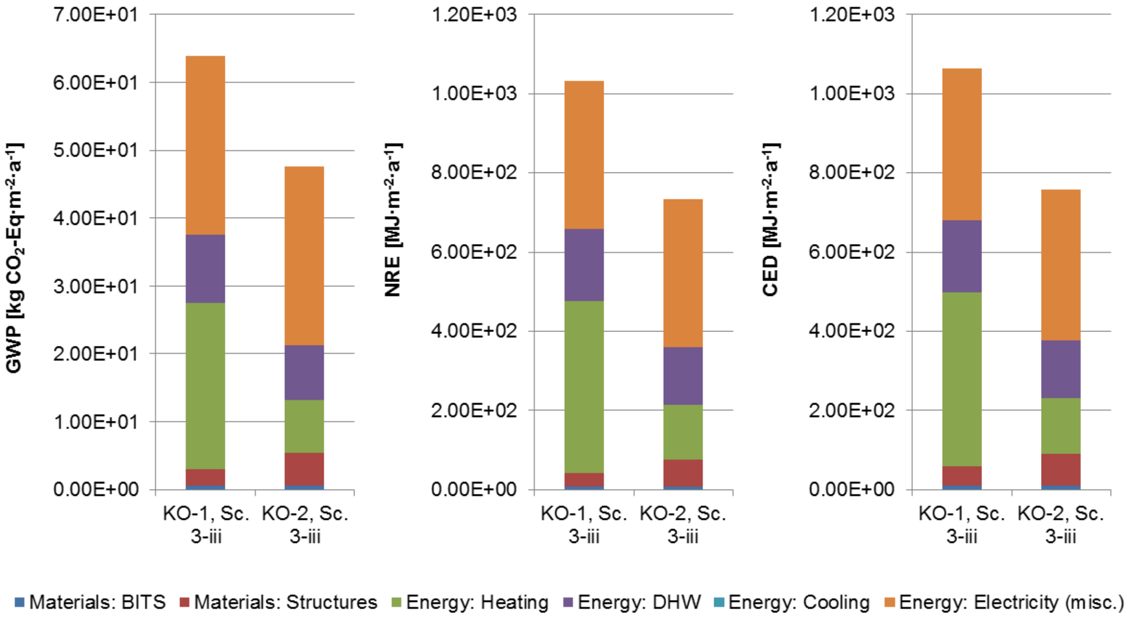


Figure 79 Total environmental impacts of KO-1 and KO-2 LCA studies in the same impact categories as the Spanish apartment building in Figure **78**.

Any further comparisons are potentially misleading or outright meaningless. Both buildings differ in scale and energy consumption (and related energy supply mixes), etc. Figure 78 and Figure **79** show that Czech KO-1 and KO-2 buildings have several times higher environmental impacts compared with the Spanish apartment building. The only exception of this rule is GWP impact category. The difference between total environmental impacts of the original Spanish building and KO-1 is only 2.51% (in favour of KO-1) there. However this similarity is only coincidental, which is proven by different distribution of environmental impacts among individual parts of the buildings’ life cycle.

There are other comparisons which could be performed. Detailed comparisons could focus on particular building elements or systems (if sufficient data were available). The LCA studies could be also made part of a larger group of studies for a statistical analysis similar to the work of Famuyibo et al. (Famuyibo, 2013) described in Section 2.3.2. However such comparisons are out of scope of this dissertation.

6.5. Section Summary

Section 6 presents and discusses results of all five LCA studies evaluated within this dissertation. These case studies evaluate environmental efficiency of the renovations of a block-of-flats Koniklecová 4 in Brno and single-family house no. 275 (later 442) in Přibice. Generally, the results correspond with literature in confirming that renovations of existing residential buildings significantly reduce their environmental impacts. Average environmental savings of 17.39% are calculated with Eco-Bat 4.0 in UBP impact category in Koniklecová 4 case study (see Section 6.1.1). In Přibice 275 (442) case study the average savings between PB-1 and PB-2 are 70.57% according to Eco-Bat 4.0 calculations (see Section 6.1.2). Interestingly enough, the savings between PB-1 and PB-3 are even higher: on average 76.83% in Eco-Bat 4.0 calculations (see Section 6.1.2) and 59.48% in GaBi 4 calculations (see Section 6.2.2). These results indicate that even significant increase of EEIs related with renovations or new construction in KO-2, PB-2 and PB-3 LCA studies does not overweigh reduced OEIs of the renovated (or newly constructed) buildings.

This section also shows significant variations of the results caused by individual tools, characterization methods and scenario combinations. The results indicate that there are two main reasons for the variations. First is lack of standardization in available LCI databases (and uneven quality of datasets they contain), LCA tools and characterization methods. It is expectable that the results would differ due to varying characterization methods (or their versions). However there are also limits such as lack of certain parts of the building life cycle or lack of support information describing some parts of the background calculations (e.g. modelling of BITS in in Eco-Bat 4.0). This unnecessarily adds to the difference between results of calculations provided by both utilized tools, which easily reaches almost 40% in comparable scenario combinations (see Figure 77). Second reason for limited accuracy and comparability of the LCA studies is in the accuracy of input data and boundary conditions. This issue was tested using four variables defined in Section 5.3: frequency of replacements, amounts of construction waste, waste management and transport distances. Impact of the variations on Eco-Bat 4.0 calculations is visible in Section 6.1. Impact on GaBI 4 calculations is described in detail in Section 6.2.2. When looking at the tested variables and the resulting scenarios individually, we can say that:

- **Number of replacements** has limited effect on the total environmental impacts of the evaluated LCA studies. Most significant difference is caused by the fact that one of the scenarios considers only minor replacements of BITS, while the other two scenarios includes replacements of more building parts. The highest difference between scenario combinations caused by number of replacements (in both tools) is 6.67% in PB-3.
- **Construction waste amount** variations influence total environmental impacts in the evaluated LCA studies the least. Their impact on the results is in order of several percent even in PB-3, with its high share of EEIs.
- **Waste management** variations most influence the results according to GaBi 4 calculations. They could change total environmental impacts of a building by tens of percent (44.04% in UBP impact category in PB-3), which is comparable with the differences caused by the software tools and characterization methods mentioned previously. The highest environmental impacts (in this dissertation) are related with scenario combinations that include localized model of landfilling defined in scenario (II.). This suggests that landfilling could be considered as worst case scenario in LCAs in Czech conditions.
- **Transport distance** variations have higher influence on the total environmental impacts than the replacement or construction waste scenarios according to calculations in GaBi 4. This may be surprising considering low environmental impacts of transport calculated in Eco-Bat 4.0. It is partially result of the utilization of particular ecoinvent 2.0 datasets in the calculations (see Section 6.2.2.4). The highest environmental impacts are unsurprisingly related with transport scenario (a.), which considers 100km transport distance for everything. Actual

transport distances are mostly much lower in Czech (particularly South Moravian) conditions.

Overall difference between the best and worst scenario combination is 20.48% in PB-1 and 56.06% in PB-3 in UBP impact category. The differences are lower in other impact categories. Still, they could influence conclusions of the LCA studies. The problem posed by these differences could be illustrated by the fact that even the relatively low variations of construction waste amounts have higher impact on the total results than some of the construction materials. This is true especially for “auxiliary” materials which are considered in relatively low quantities, such as sealing tapes. These materials could have been omitted during the calculations without any noticeable impact on the results.

7. Conclusions

The aims of this dissertation are set to deepen the knowledge in the field of building renovation LCA (in Czech conditions). They focus on the evaluation of the efficiency of building renovations as well as the accuracy of the LCA process: importance of utilized software, databases, boundary conditions, etc. Following present conclusions based on the dissertation and point out identified future research prospects.

7.1. Environmental Efficiency of Building Renovations

Generally, the results of the case studies evaluated in this dissertation correspond with literature in confirming that renovations of existing buildings could help mitigate total environmental impacts in the construction sector. Even significant increase of EEIs related with renovations or new construction (lower ratio between operational and embodied environmental impacts) in KO-2, PB-2 and PB-3 LCA studies does not overweigh reduced OEIs of the renovated buildings. On the contrary, comparison of PB-1 and PB-3 LCA studies (see Sections 6.1.3 and 6.2.1) has proven that even demolition of the original building and new construction in its place could be more environmentally sound than its maintenance or renovations in some cases.

It should be noted that the environmental savings identified in the LCA studies mostly correlate with energy savings (especially heating) achieved through the renovations. The results (especially evaluation of the influence of scenarios in Section 6.2.2) of this dissertation therefore may be of limited use for (modern) buildings with high energy efficiency. Assessors of such buildings may want to focus on environmental performance of particular materials and energy sources instead of heat losses, etc. This is partially illustrated in Section 6.1.5.1, which shows potential environmental savings achievable by avoiding of grid electricity as the main energy source. Reason for this recommendation is environmental inefficiency (in comparison with others) of the considered Czech electricity supply mix.

7.2. Accuracy of Building Renovation LCA

The LCA studies in this dissertation show significant scattering of the results depending on the tested variables and scenarios. The results suggest that it is caused by lack of data and standardization. The lack of environmental data on individual processes and materials is not surprising as buildings are complex systems containing dozens of individual elements. Existing LCI databases currently provide sufficient information only for fraction of these materials. Others have to be modelled and accuracy of this modelling is questionable. Four variables evaluated in scenario combinations in this dissertation (especially in Section 6.2.2) illustrate this problem well. Even individually, these variables could change the LCA results by tens of percent. The difference in results caused by the combined variables reaches up to 56.06% in this dissertation. It should be noted that these variables influenced only EEIs. This means that the difference would be even higher in buildings with low OEIs, such as nZEBs. Given the recent development of building regulations (see Section 1) it encourages further case studies on such buildings.

Another issue is analysed in Section 6.3: utilization of different tools, databases and characterization methods. Some differences should be expected for reasons mentioned in Sections 2.2.2.1 and 2.2.3.2. Still, almost 40% difference in comparable scenario combinations in Eco-Bat 4.0 and GaBi 4 is rather surprising. Especially, when the individual differences seemed rather minor (e.g. different version of the characterization methods).

Overall, the wide scattering of the results caused by above mentioned issues is unacceptable. It compromises accuracy of the LCAs as the variables have more impact on the results than any of the considered construction materials. In some cases the difference between particular scenario combinations is even higher than the buildings' OEIs! Moreover, the scattering of results limits comparability in LCA to comparative studies with predefined boundary conditions or statistical analyses of large quantities of individual studies. Further development of standards, databases, characterization methods, etc. is therefore necessary if LCA should reach its full potential.

7.3. Recommendations for Practise and Future Research Prospects

Generally, the results of this dissertation promote building renovations as a simple way towards cleaner, more efficient construction sector. Next phase of the work should include more case studies to evaluate efficiency of building renovations in buildings of different archetypes, energy efficiency, materials, etc. This phase should be followed by publishing and dissemination of work among general public and professionals alike. The knowledge of potential environmental, energy and monetary savings should motivate owners and inhabitants to renovate their buildings and help with repairing of the damage done to the environment.

This dissertation shows that LCA could be a suitable tool for optimization of building renovation designs. However it also identifies and tests several issues compromising its accuracy and thus discouraging this particular application. This means that further work is necessary before widespread application of LCA in this field. Part of it could be done within the case studies mentioned in previous paragraph. Larger number of case studies should for example further elaborate the issues related with variables evaluated in this dissertation, especially:

- **Negligible share of construction waste on total environmental impacts.** The results of the LCA studies in this dissertation suggest that the amount of construction waste has to exceed 10% of all construction materials to become a relevant issue.
- **Accuracy of applied waste management models.**
- **Accuracy of applied transport models.** The dissertation shows that actual transport distances in the particular case studies are much shorter than those applied in the reviewed LCA studies. Further work is needed to verify if the increased LCA accuracy could outweigh complicated data gathering. Especially as application of longer average distances (100km, 50km, etc.) provides intentionally higher results “being on the safe side”.

There are also several parts of the future work that could be done separately:

- **LCA standards.** Contemporary European standards such as EN 15978 could be considered world’s state-of-art in the field of building LCA. They provide usable guidelines for evaluation of the whole building life cycle. However an expansion of the standard or other supplementary guidelines (compulsory nationally or EU-wide) should be adopted when evaluating building renovations. The reason is that some of the modules describing the use of the building contain too much information. For example module B6 describes overall energy-related OEIs, while proper renovation design needs separate data on individual technical systems. This creates opportunity for different interpretations resulting in problems with comparability of LCA results. Similarly, suitable (compulsory) guidelines should be defined for division of buildings into individual elements and systems. More detailed division of building elements could be advantageous for identification of critical issues, which in turn could improve the efficiency of renovation designs.

- **LCA software.** The dissertation indicates that neither GaBi 4 nor Eco-Bat 4.0 is ideal supporting tool for building renovation design in Czech Republic. Open structure of GaBi 4.0 is suited for detailed research, but it is too cumbersome for design practise. Eco-Bat 4.0 was developed for this role, but there are issues such as the fact that it does not cover whole building life cycle or lack of adaptation for Czech conditions (characterization method, evaluation of BITS, etc.). Still, it could find limited use e.g. in comparable studies due to its simple interface and fast workflow. This means that another tool should be identified or developed for the Czech designers (and LCA practitioners in this field) during future works.
- **LCI databases.** The dissertation confirmed lack of LCI data describing Czech construction sector. This lack of data (and subsequent need for individual modelling and estimates) is one of the sources of variations evaluated in the dissertation. Therefore one of the aims of any future LCA works should be establishing of a proper Czech LCI database (e.g. on the basis of existing Envimat database) and its expanding with data provided by material producers, contractors and other professionals. The data should contain not only direct environmental impacts, but also supplementary information such as durability of the described materials. This would ensure that different LCA studies would work with comparable boundary conditions. The database could be even enhanced with a map application that would allow fast calculations of transport distances and

related environmental impacts. Another related field of future work should be compiling of detailed data on existing building stock. Statistics based on such data could for example help to fill the gaps in future LCIs or even simplify the LCIs similarly as utilization of KBOB data in Eco-Bat software.

- **Characterization methods.** The dissertation shows advantages of single-criteria characterization method for the interpretation of results: Conversion of various environmental impacts into one impact category leads to some level of distortion. However it makes the results and their comparison comprehensible even for professionals with limited LCA experience and general public, (desirably) increasing recognition of the environmental issues. On the other hand the results in the dissertation (see Figure 75) show some “inconsistencies” indicating that the utilized versions of UBP characterization do not sufficiently respect Czech conditions (e.g. regarding waste management). Future work could therefore result in localization of this (or another suitable) characterization method. In the meantime it is desirable to utilize another existing characterization method, such as primary energy in the LCA studies describing Czech conditions.

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9. List of Abbreviations and Acronyms

ADP-elements	Abiotic Resource Depletion Potential for Elements
ADP-fossil fuels	Abiotic Resource Depletion Potential for Fossil Fuels
AIST	National Institute of Advanced Industrial Science and Technology
ANL	Argonne National Laboratory
AP	Acidification Potential of Land and Water
BEAT	Biomass Environmental Assessment Tool
CEN	Comité Européen de Normalisation
CML	Institute of Environmental Sciences of Leiden University
CPM	Swedish Life Cycle Centre
CRMD	Canadian Raw Materials Database
CTU	Czech Technical University in Prague
EBC	Energy in Buildings and Communities Programme
EC	European Commission
EDIP	Environmental Design of Industrial Products
EED	Energy Efficiency Directive
EEIs	Embodied Environmental Impacts
EIA	Environmental Impact Assessment
EP	Eutrophication Potential
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene

EPS	Environmental Priority Strategies in product design (only in Table 2)
ETICS	External Thermal Insulation Composite System
EU	European Union
GEMIS	Global Emission Model for Integrated Systems
GHG	Greenhouse Gas
GWP	Global Warming Potential
IBO	Ökologische Bauen Gesund Wohnen
IDEA	Inventory Database for Environmental Analysis
IEA	International Energy Agency
IINAS	International Institute for Sustainability Analysis and Strategy
ILCD	International reference Life Cycle Data system
IPCC	Intergovernmental Panel on Climate Change
JEMAI	Japan Environmental Management Association for Industry
JRC	Joint Research Centre
LCA	Life-Cycle Assessment
LCDN	Life-Cycle Data Network
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
LESBAT	Laboratory of Solar Energetics and Building Physics
LIME	Life-cycle Impact assessment Method based on Endpoint modelling

LUCAS	LCIA method Used for a CAnadian-Specific context
MEEuP	Methodology study for Ecodesign of Energy-using Products
Mtoe	Million Tonnes of Oil Equivalent
NOAA-ESRL	National Oceanic & Atmospheric Administration - Earth System Research Laboratory
NREL	National Renewable Energy Laboratory
nZEB	nearly Zero-Energy Building
ODP	Stratospheric Ozone Layer Depletion Potential
OECD	Organisation for Economic Co-operation and Development
OEIs	Operational Environmental Impacts
POCP	Formation potential of tropospheric ozone photochemical oxidants
REPA	Resource and Environmental Profile Analysis
RES	Renewable Energy Source
SETAC	Society of Environmental Toxicology and Chemistry
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UAE	United Arab Emirates
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UoM	University of Manchester

UoW	University of Waterloo
USA	United States of America
USEtox	UNEP-SETAC toxicity model
USLCI	US Life Cycle Inventory
WCED	World Commission on Environment and Development
WMO	World Meteorological Organization

10. List of Figures

11. List of Tables

Table 11. Comparison of environmental impacts related with 1 MJ of supplied energy in Eco-Bat 4.0 and GaBI 4.

Appendix A. Inventory Tables

Digital copy of the inventory tables is in a supplementary CD, which is part of this dissertation. The inventory tables include:

- List of inputs and outputs (materials, energy, waste, etc.) considered in individual LCA studies, their quantities and number of replacement according to scenarios defined in Sections 5.3.2 and 5.3.3,
- list of Eco-Bat 4.0 and ecoinvent 2.0 datasets assigned to the considered inputs and outputs during LCIA according to scenarios defined in Sections 5.3.1 and 5.3.4.

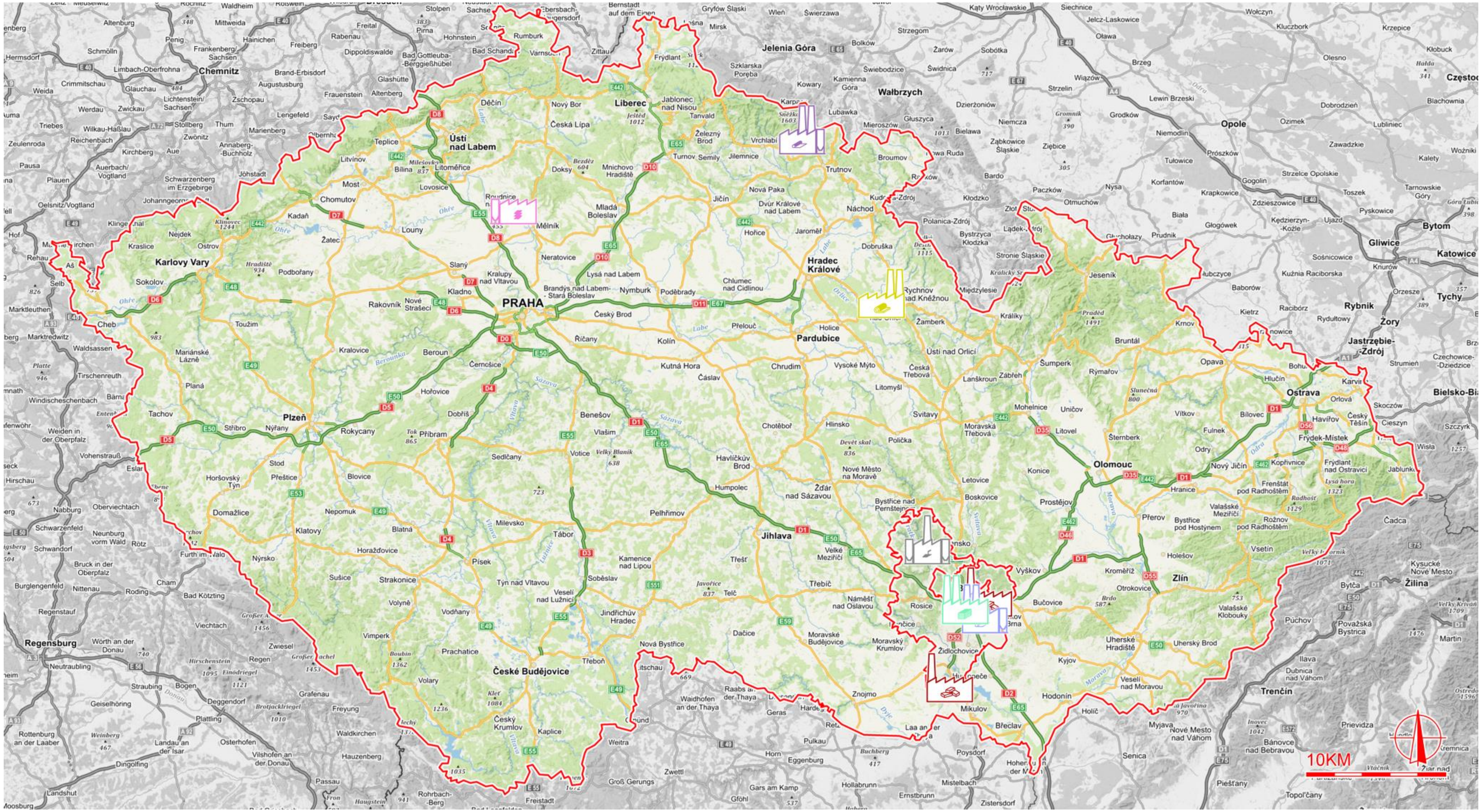
The grouping of the data in inventory tables is described in Section 4.2. Generally, the inventory tables group data into life cycle modules based on EN 15978 (CEN, 2011). Construction materials (e.g. in modules A1-A3) are further grouped based on the particular building elements to increase clarity of the tables:

- Foundations,
- load-bearing walls,
- floor structures,
- staircase,
- roof truss,
- non-bearing walls and partitions,
- suspended ceiling,
- roofing,
- façade,
- interior plasters and tiling,
- flooring,
- doors and windows,
- chimney,
- BITS.

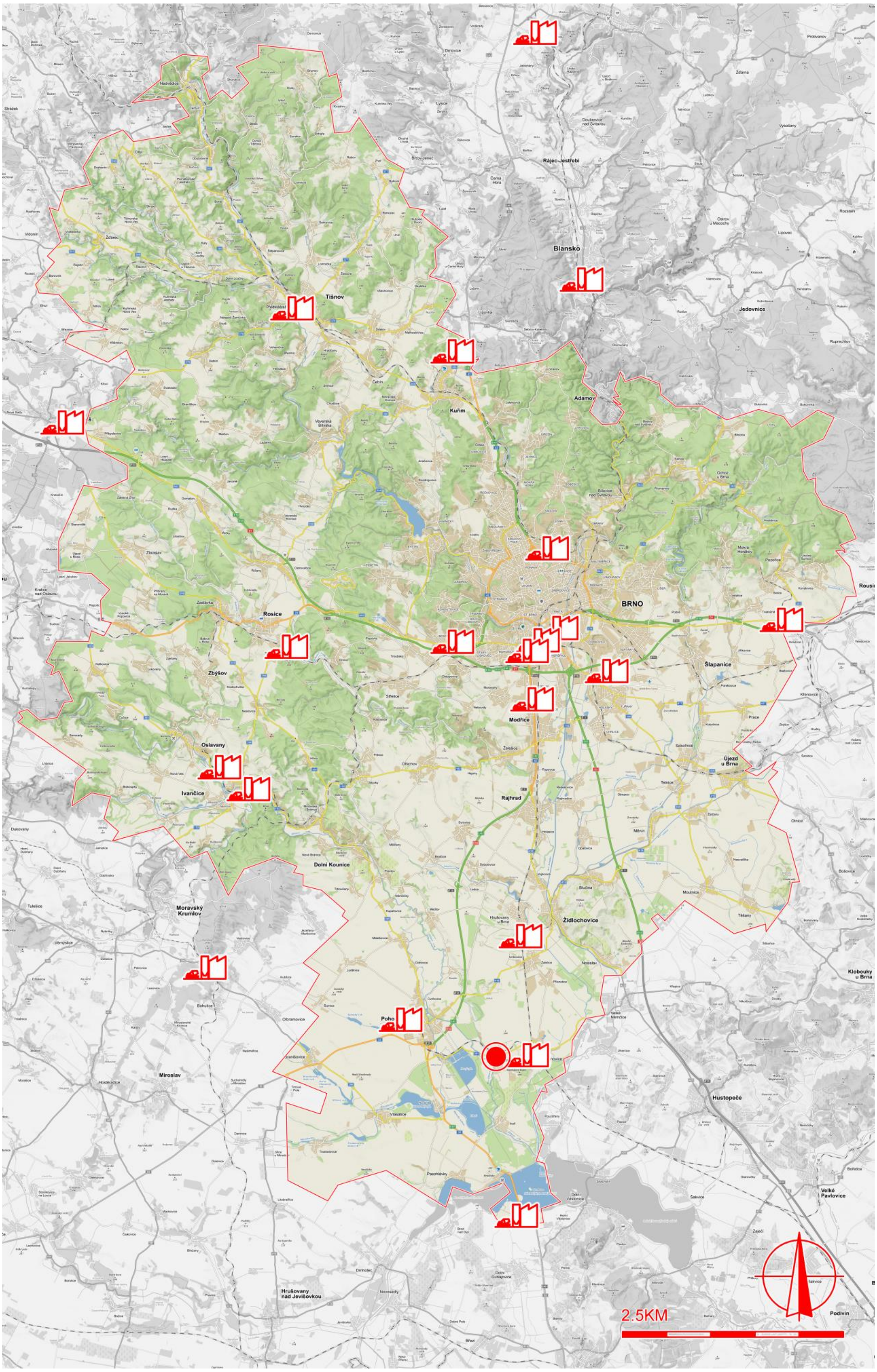
This grouping into 14 above listed building elements is based on literature review, EN 15978 (CEN, 2011) and Annex 56 (Ott, 2017) guidelines and author’s previous experience.

Appendix B. Transport Maps

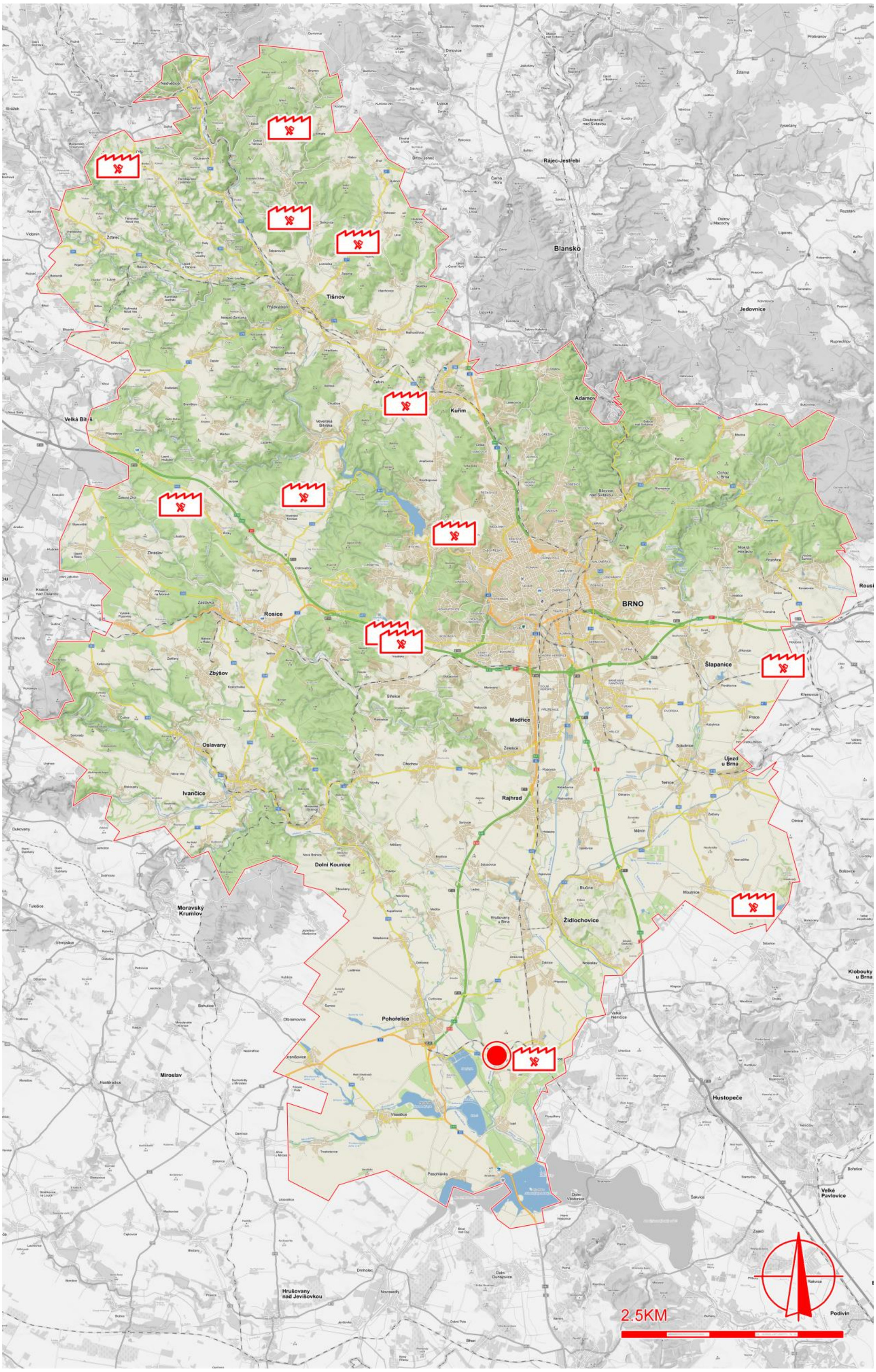
Maps in this appendix document availability of landfills and production facilities supplying concrete, ceramic roof tiles, hollow ceramic bricks, mineral wool, mortars and plasters, plasterboards, plastic and bituminous waterproofing and sawn timber (and other wood products) that are considered for calculations of transport distances in (c.) and (d.) scenarios in PB-1 and PB-3 LCA studies (see Section 5.3.5 and Appendix C) in GaBi 4. The maps were last updated in June 2017.



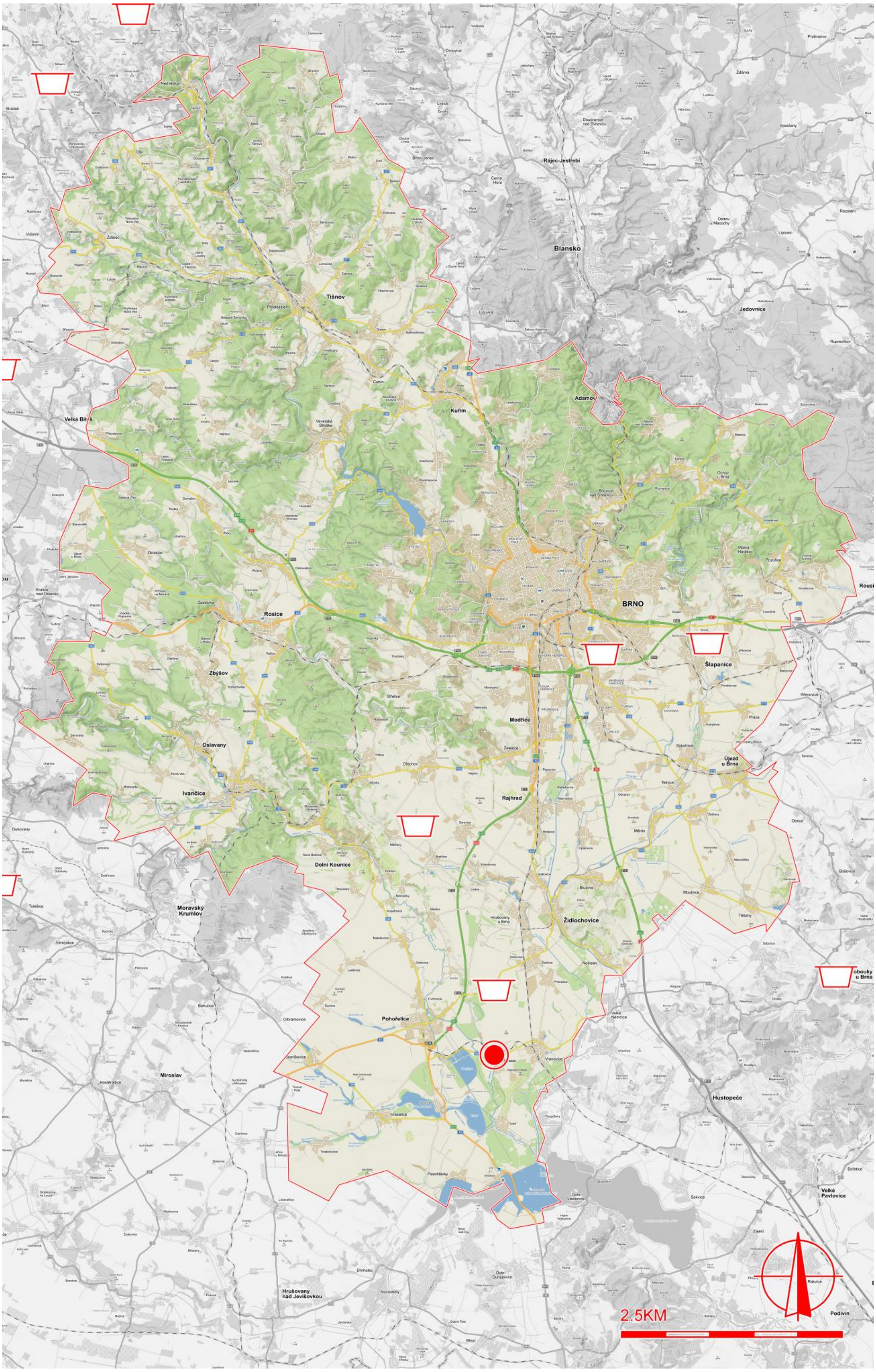
Production facilities of ceramic roof tiles and hollow ceramic bricks (red symbol), mineral wool (yellow symbol), mortars and plasters (grey symbol), plasterboard (pink symbol), plastic (blue symbol) and bituminous (purple symbol) waterproofing and polystyrene (green symbol) nearest to the municipalities in Brno-město and Brno-venkov districts.



Map documenting availability of concrete production plants (red symbols) in the vicinity of Brno-město and Brno-venkov districts. Red dot indicates position of building site in Přibice.



Map documenting availability of sawmills plants (red factory symbols) in Brno-město and Brno-venkov districts. Red dot indicates position of building site in Přibice.



Map documenting availability of landfills (red factory symbols) in the vicinity of Brno-město and Brno-venkov districts. Red dot indicates position of building site in Přibice.

Appendix C. Transport Distances

Three tables in this appendix represent material, waste and personnel transport distances applied in scenarios (c), (d) and (e) in LCA studies in this dissertation. The data are based on maps available in Appendix B and Eco-Bat 4.0 database.

Real transport distances calculated according to scenario (c.) applied in PB-1, and PB-3 LCA studies (see Section 5.3) in GaBi 4.

Facility	**Transport distance [km]**
Bituminous waterproofing	216
Ceramic blocks producer	22
Ceramic roof tiles producer	34
Concrete	3
Landfill	9
Mineral wool producer	155
Mortar and plaster producer	49
Plasterboard producer	258
Plastic waterproofing	25
Polystyrene (and PUR/PIR) producer	23
Sawmill	3
Other (median value)	25

Real transport distances calculated according to scenario (d.) applied in PB-1, and PB-3 LCA studies (see Section 5.3) in GaBi 4.

Facility	**Transport distance [km]**
Landfill	16
Ceramic blocks producer	31
Ceramic roof tiles producer	33
Sawmill	10
Mineral wool producer	128
Polystyrene (and PUR/PIR) producer	25
Mortar and plaster producer	23
Plasterboard producer	233
Plastic waterproofing	27
Bituminous waterproofing	188
Concrete	7
Other (median value)	27

Transport distances pre-defined in individual datasets in the Eco-Bat 4.0 that were applied in scenario (e.) of all LCA studies (see Section 5.3).

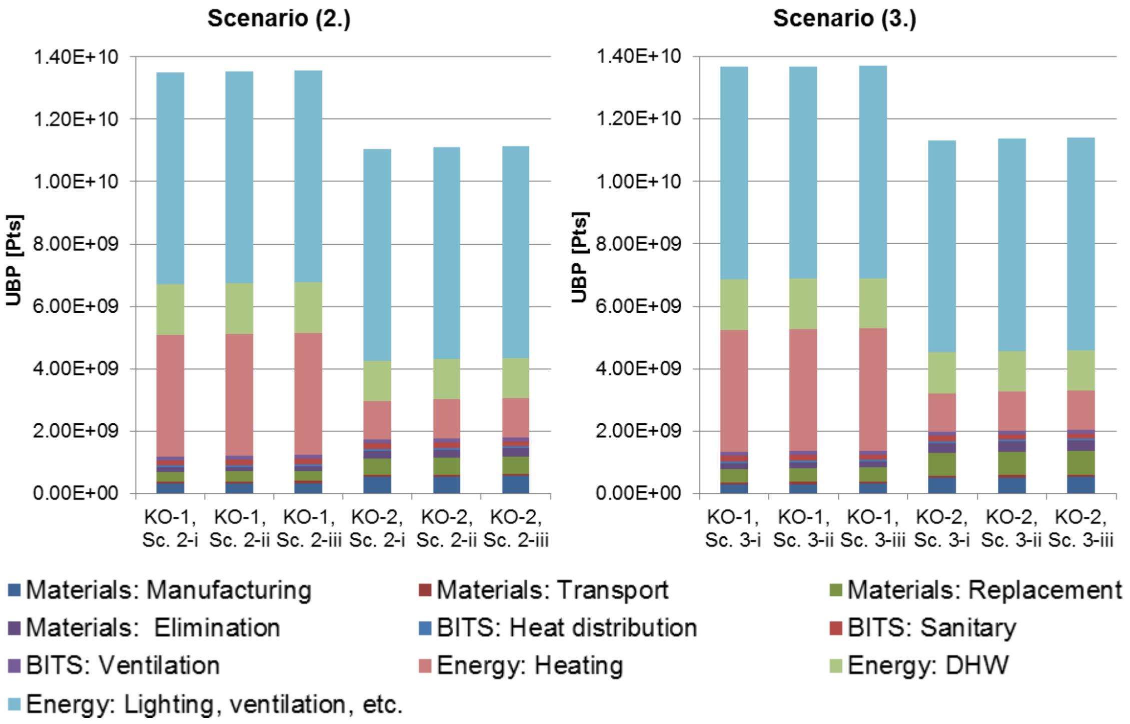
Eco-Bat dataset	Transport distance [km]
Acrylic dispersion	80
Aluminium profil, uncoated	500
Aluminium window frame + 2-IV glazing (air)	40
Bitumen emulsion, 1 layer	80
Bitumen sealing V60	100
Cement mortar	40
Ceramic roof tile	60
Ceramic slab	80
Concrete C 25/30	30
Concrete C 8/10	30
Expanded polystyrene (EPS)	60
Glass fibre reinforced polyester	80
Gypsum plaster	40
Gypsum plasterboard	100
HDPE pipe	60
Chromium steel 18/8	500
Laminate	60
OSB board	80
polyethylene sheet	100
PP pipe	60
PVC window frame + 2-IV glazing (air)	40
Rockwool	100
Rubber	---
Sawn Timber, softwood, air dried, planed	40
Silicone sealing compound	50
Solid ceramic brick	40
Steel armature (37% recycled)	500
Steel profile, galvanized	500
Steel sheet, coated with zinc	500
Synthetic plaster	40
Terrazzo, vitrified	80
Vapour barrier PE	100
Wooden internal door	40
Wooden window frame + 2IV glazing (air)	40

Appendix D. Eco-Bat 4.0 Results

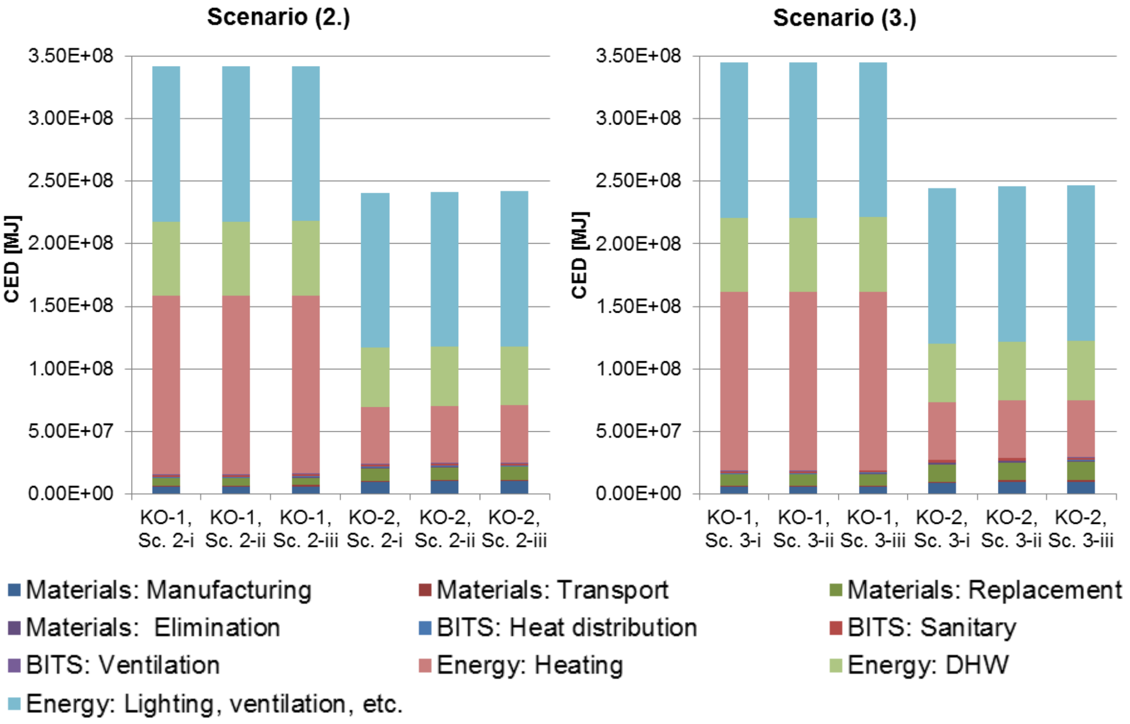
This appendix presents charts with all results of Eco-Bat 4.0 calculations. Full numerical results are archived by the author and are available on request. The charts in the appendix show:

- Total environmental impacts of all scenario combinations in all four impact categories structured according to Eco-Bat 4.0 and EN 15978. Both 60-year and 50-year service life is considered.
- EEIs of all scenario combinations structured according to EN 15978 – excerpt of the total results. Only 60-year service life is considered.
- EEIs (during whole building life cycle) of all scenario combination divided per individual structures.
- EEIs (during whole building life cycle) of all scenario combination divided per individual materials.

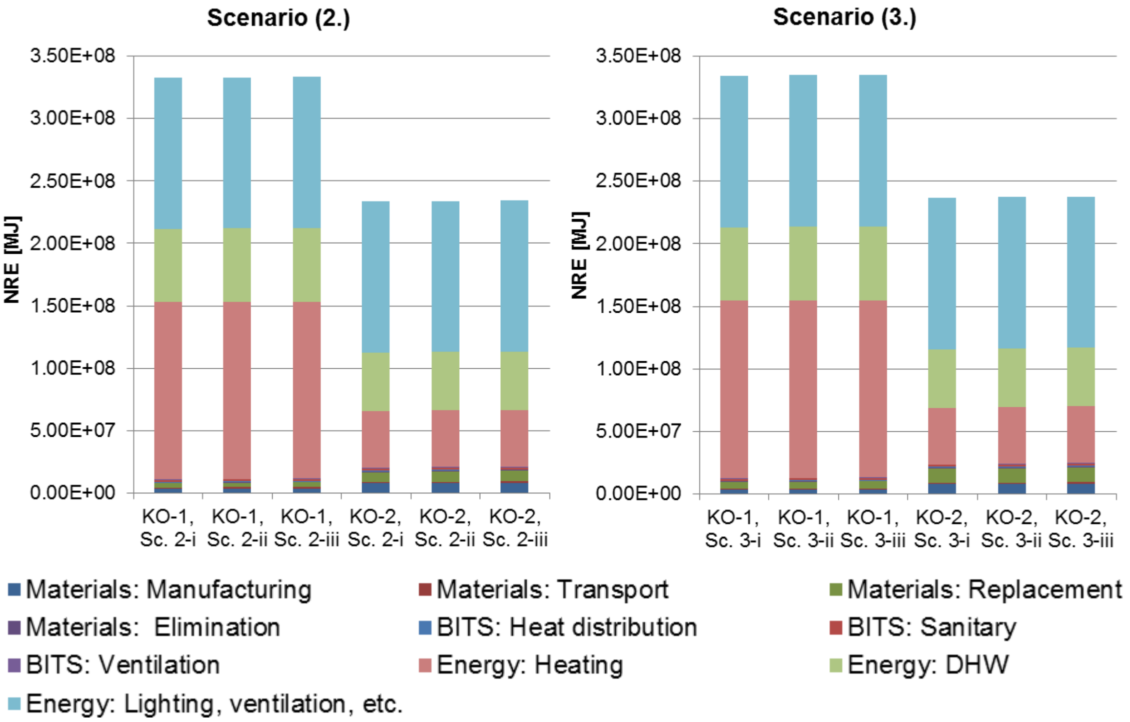
Total environmental impacts of KO-1, KO-2 (60-year service life)



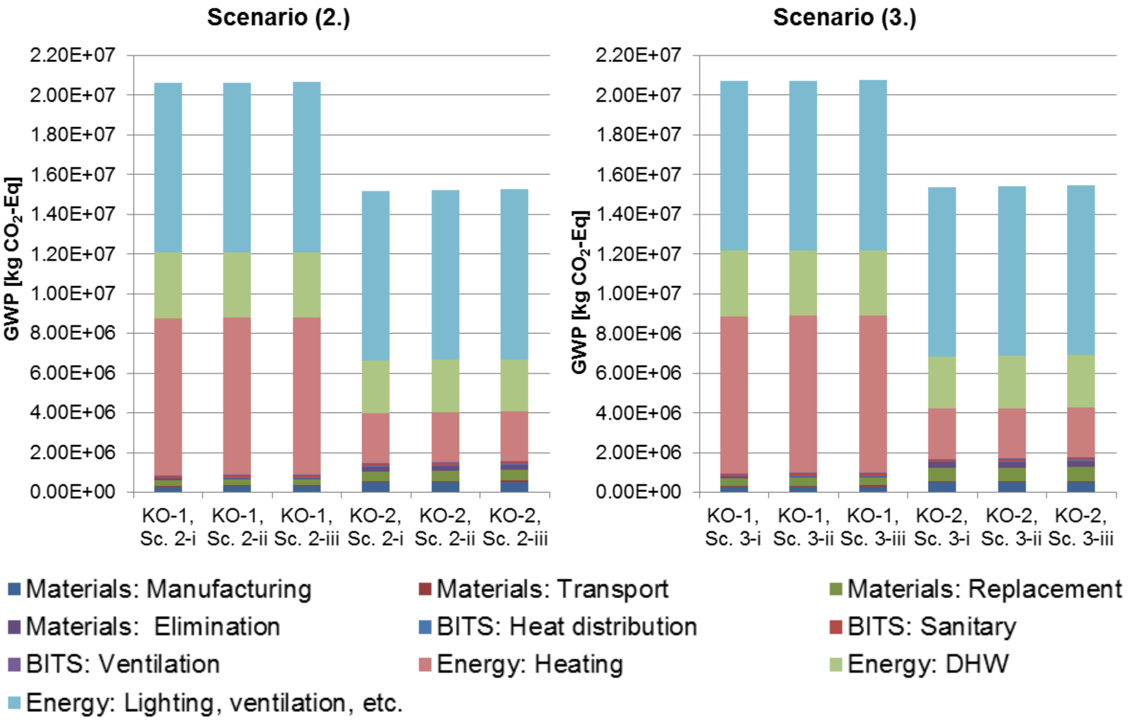
Total environmental impacts of individual KO-1 and KO-2 scenario combinations in UBP impact category structured according to Eco-Bat 4.0 tool. 60-year building service life is considered.



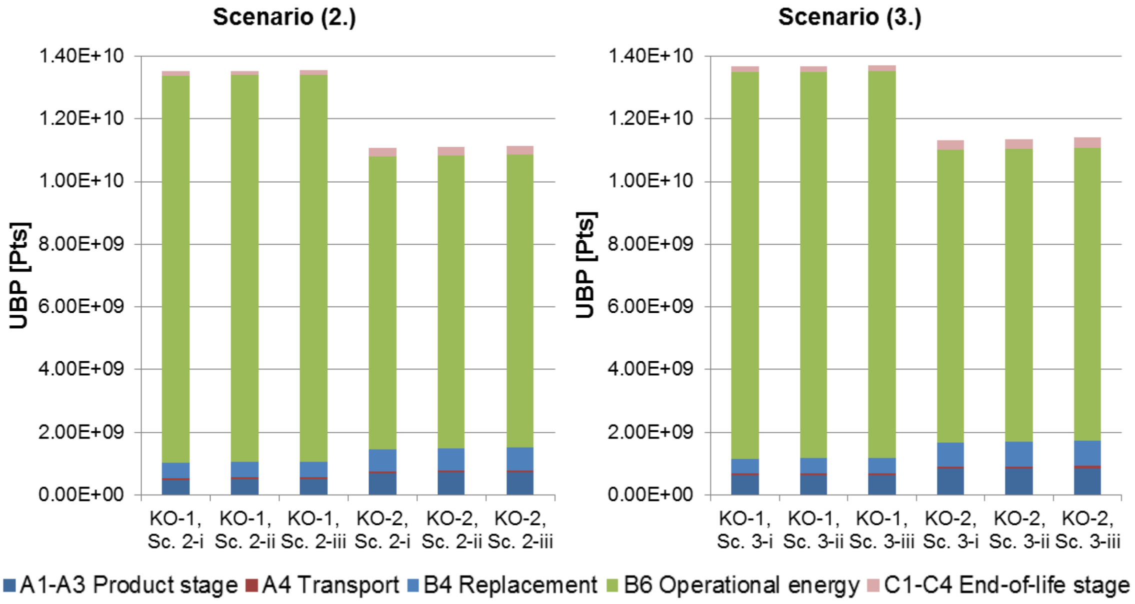
Total environmental impacts of individual KO-1 and KO-2 scenario combinations in CED impact category structured according to Eco-Bat 4.0 tool. 60-year building service life is considered.



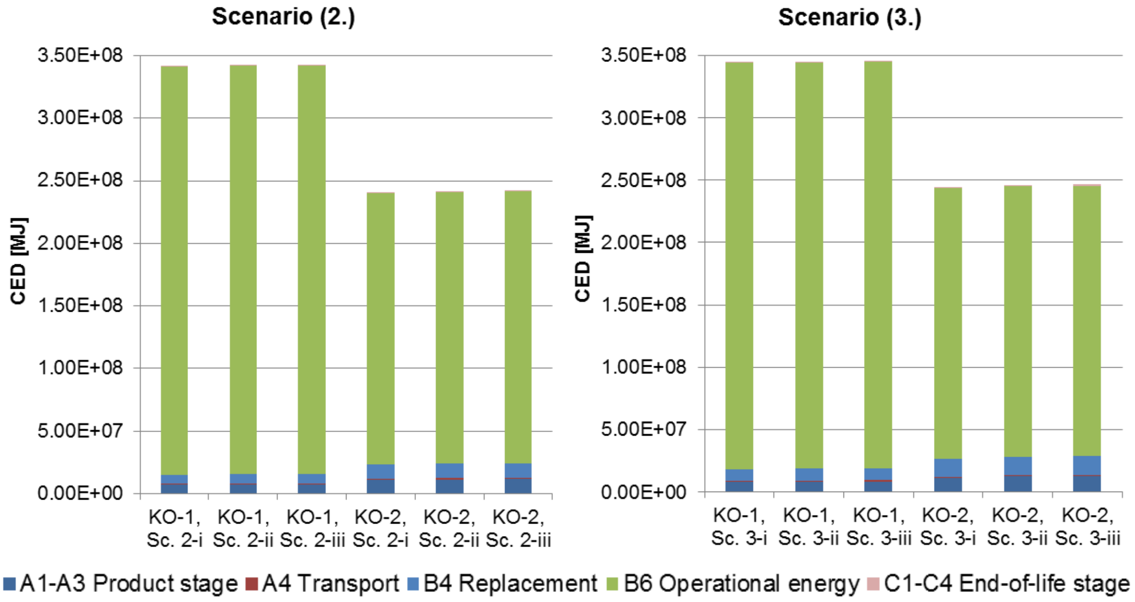
Total environmental impacts of individual KO-1 and KO-2 scenario combinations in NRE impact category structured according to Eco-Bat 4.0 tool. 60-year building service life is considered.



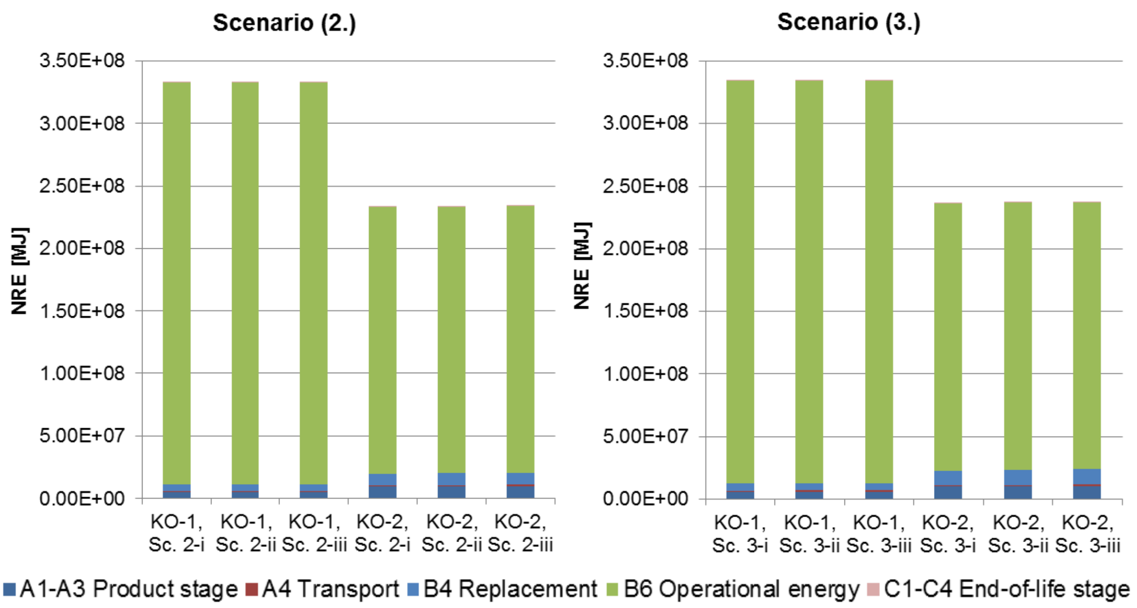
Total environmental impacts of individual KO-1 and KO-2 scenario combinations in GWP impact category structured according to Eco-Bat 4.0 tool. 60-year building service life is considered.



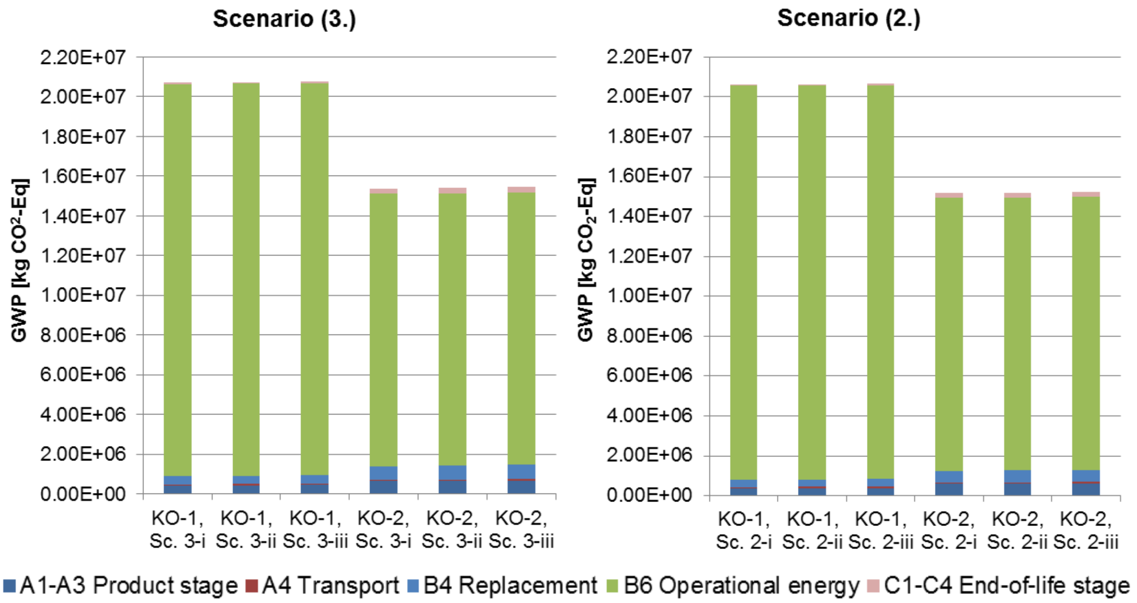
Total environmental impacts of individual KO-1 and KO-2 scenario combinations in UBP impact category structured according to EN 15978. 60-year building service life is considered.



Total environmental impacts of individual KO-1 and KO-2 scenario combinations in CED impact category structured according to EN 15978. 60-year building service life is considered.

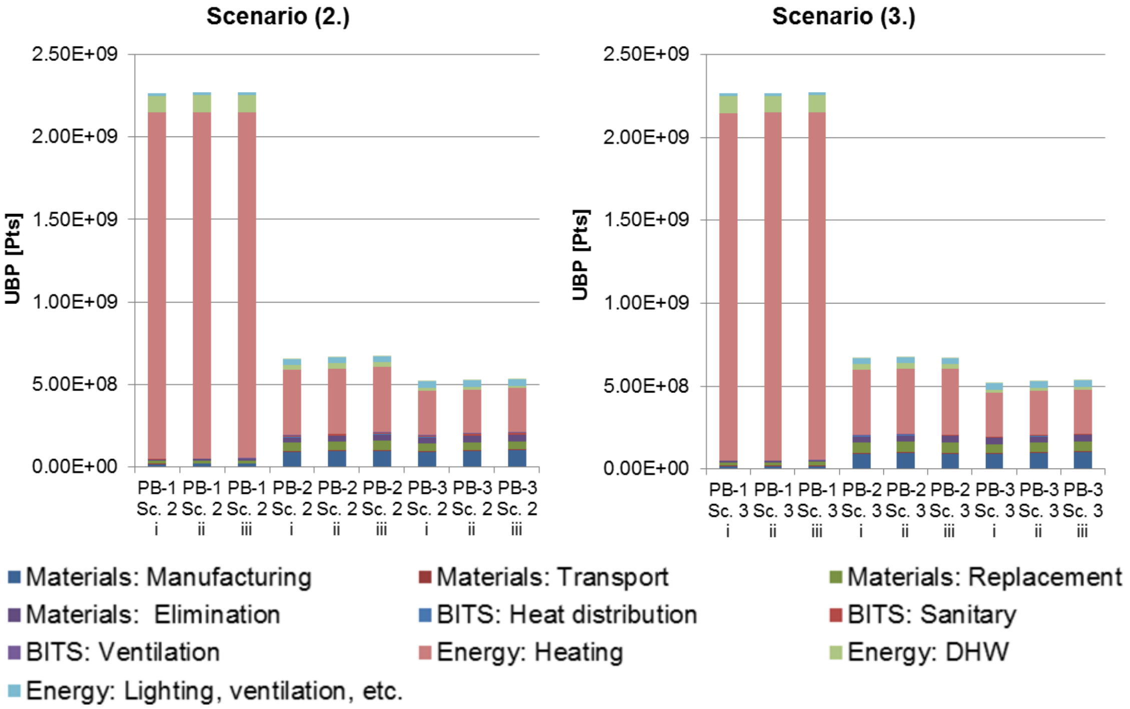


Total environmental impacts of individual KO-1 and KO-2 scenario combinations in NRE impact category structured according to EN 15978. 60-year building service life is considered.

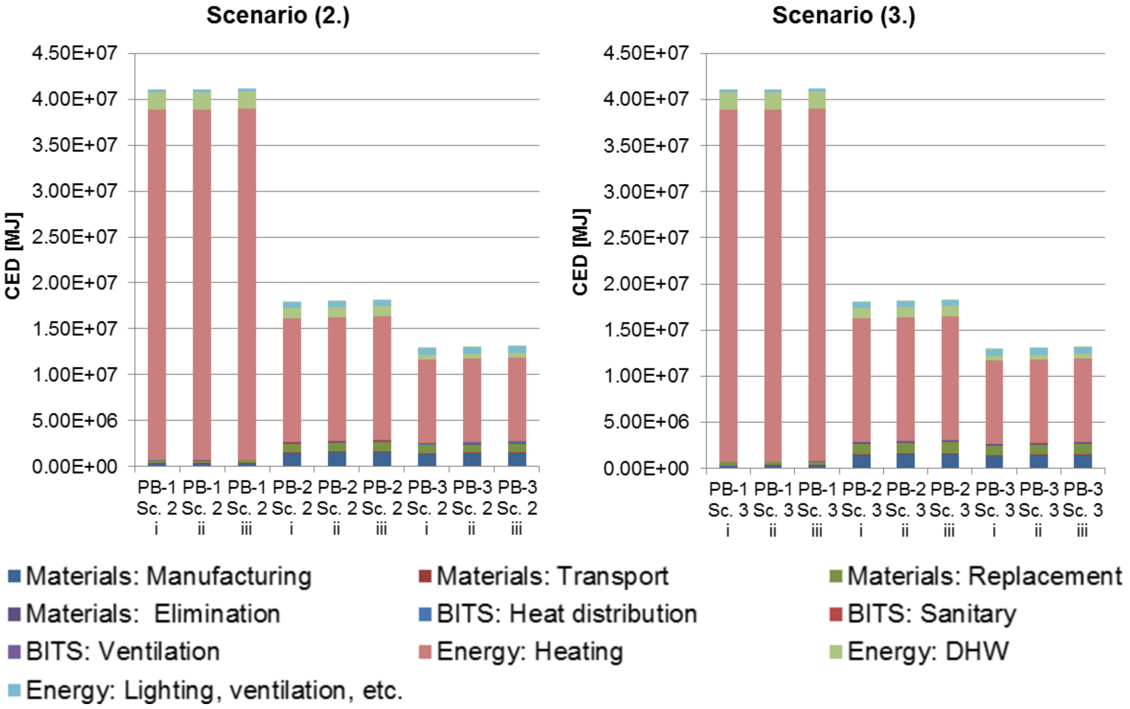


Total environmental impacts of individual KO-1 and KO-2 scenario combinations in GWP impact category structured according to EN 15978. 60-year building service life is considered.

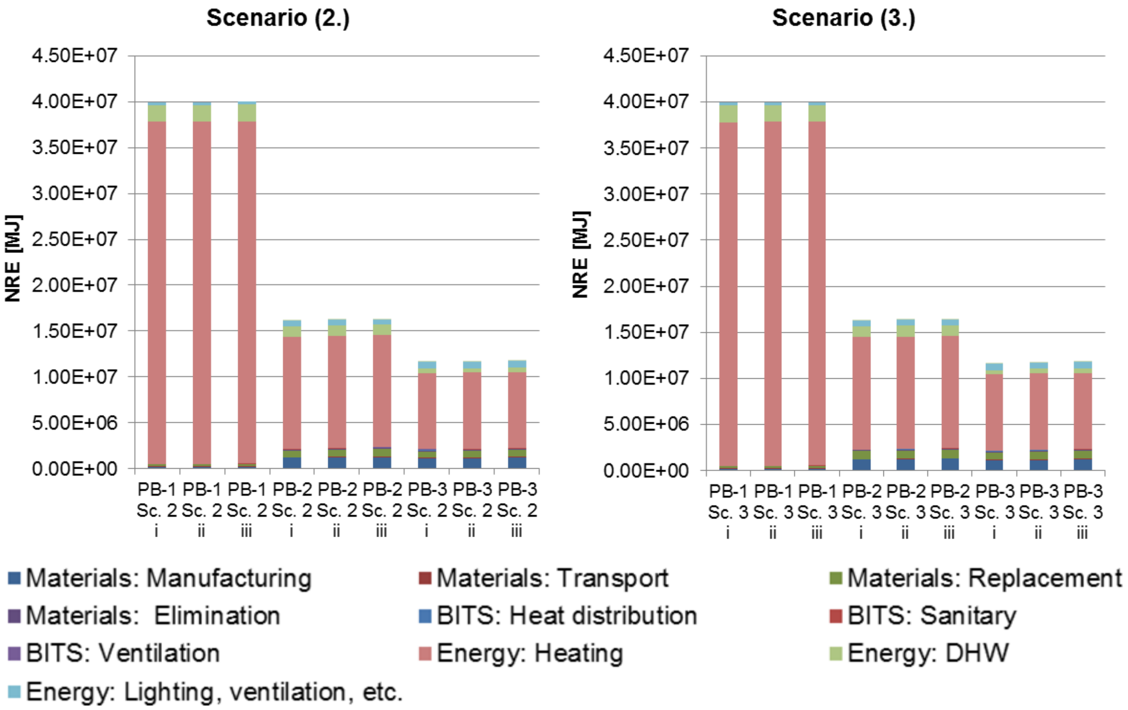
Total environmental impacts of PB-1 to PB-3 (60-year service life)



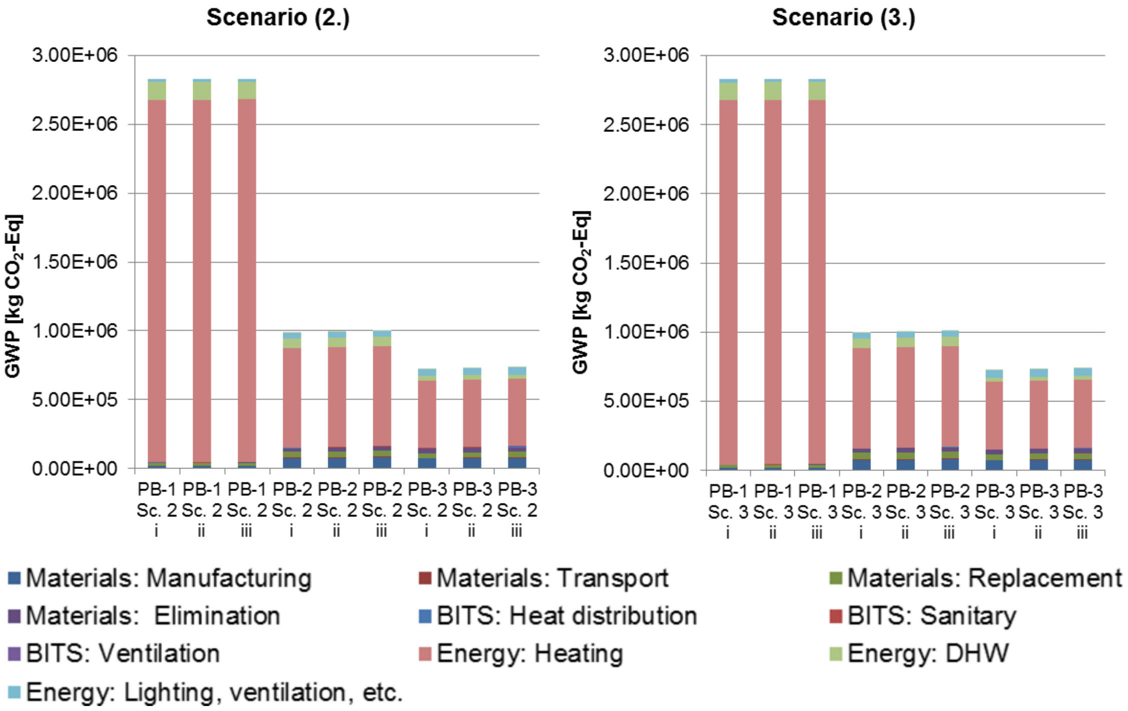
Total environmental impacts of individual PB-1 to PB-3 scenario combinations in UBP impact category structured according to Eco-Bat 4.0 tool. 60-year building service life is considered.



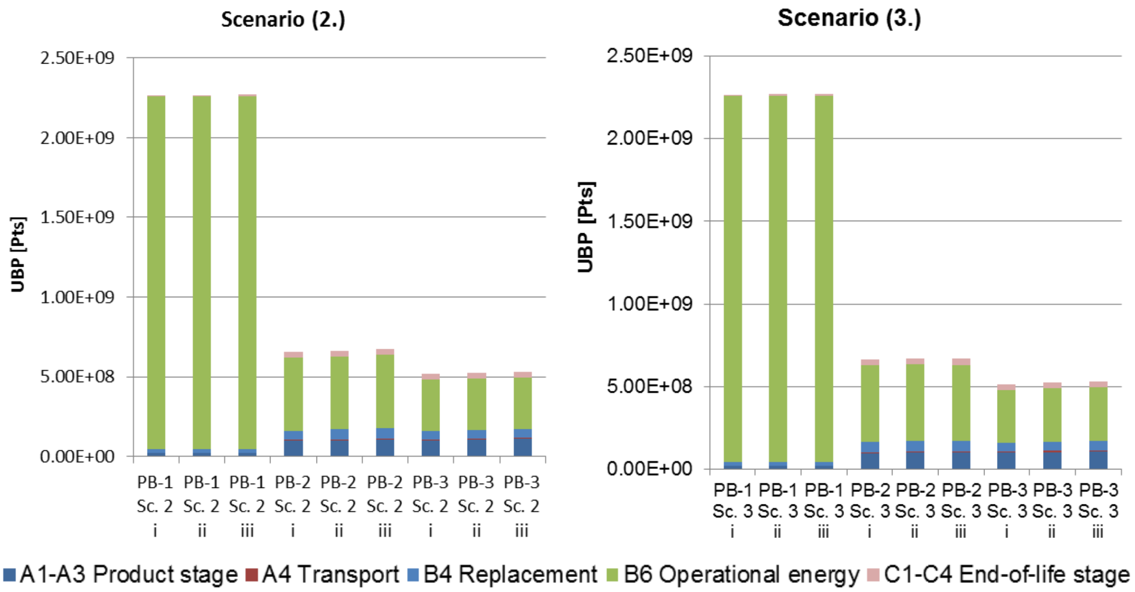
Total environmental impacts of individual PB-1 to PB-3 scenario combinations in CED impact category structured according to Eco-Bat 4.0 tool. 60-year building service life is considered.



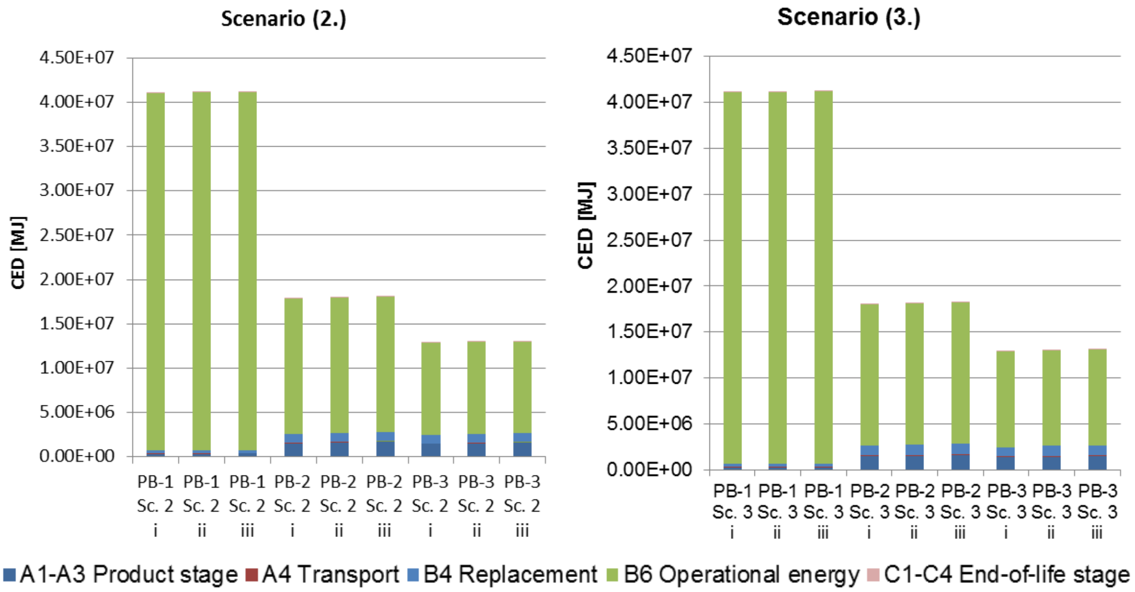
Total environmental impacts of individual PB-1 to PB-3 scenario combinations in NRE impact category structured according to Eco-Bat 4.0 tool. 60-year building service life is considered.



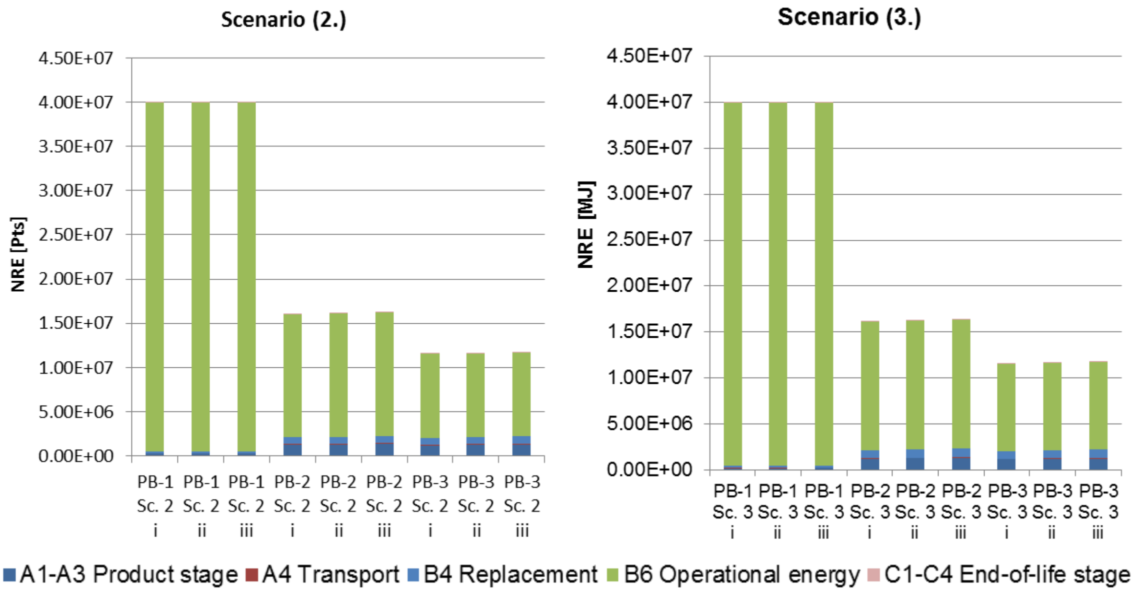
Total environmental impacts of individual PB-1 to PB-3 scenario combinations in GWP impact category structured according to Eco-Bat 4.0 tool. 60-year building service life is considered.



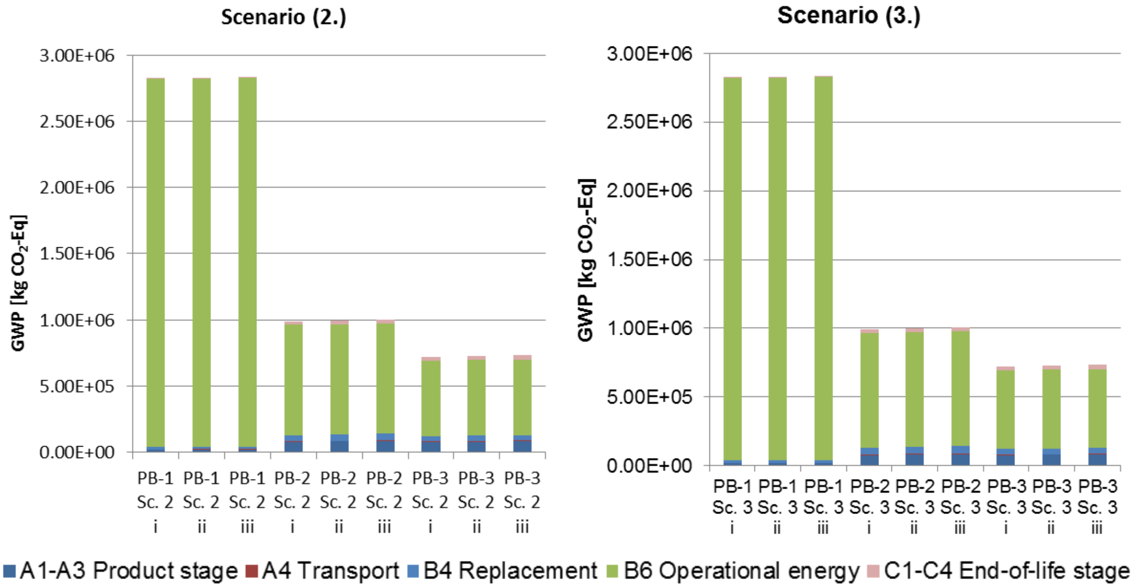
Total environmental impacts of individual PB-1 to PB-3 scenario combinations in UBP impact category structured according to EN 15978. 60-year building service life is considered.



Total environmental impacts of individual PB-1 to PB-3 scenario combinations in CED impact category structured according to EN 15978. 60-year building service life is considered.

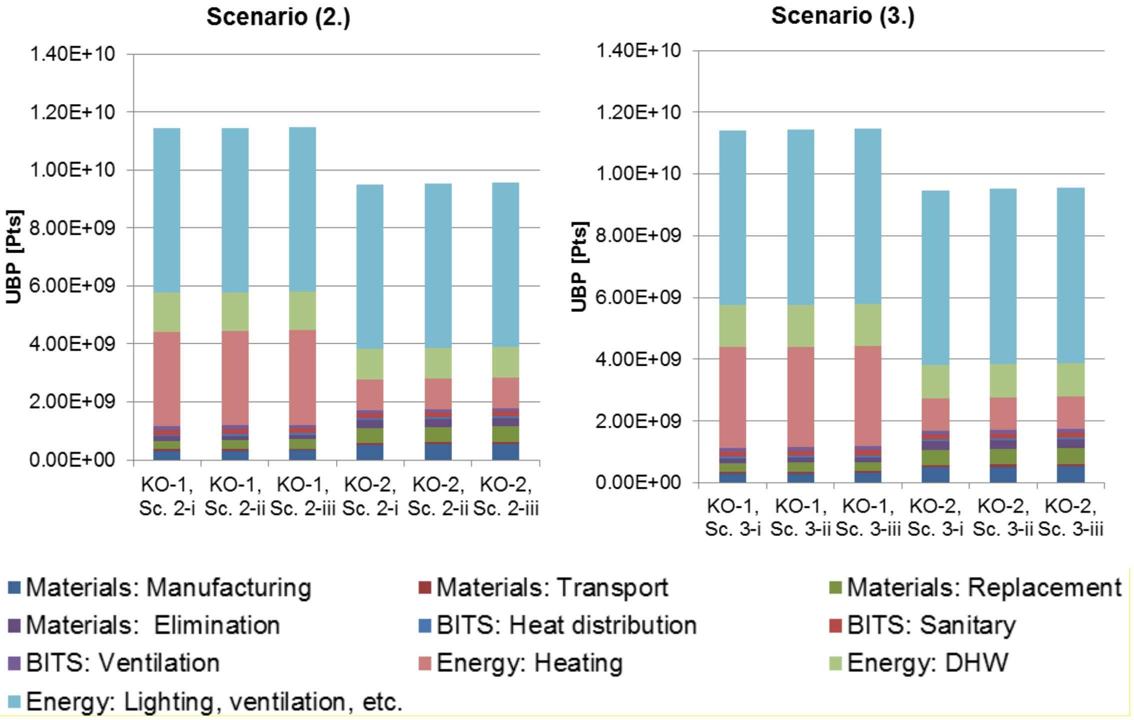


Total environmental impacts of individual PB-1 to PB-3 scenario combinations in NRE impact category structured according to EN 15978. 60-year building service life is considered.

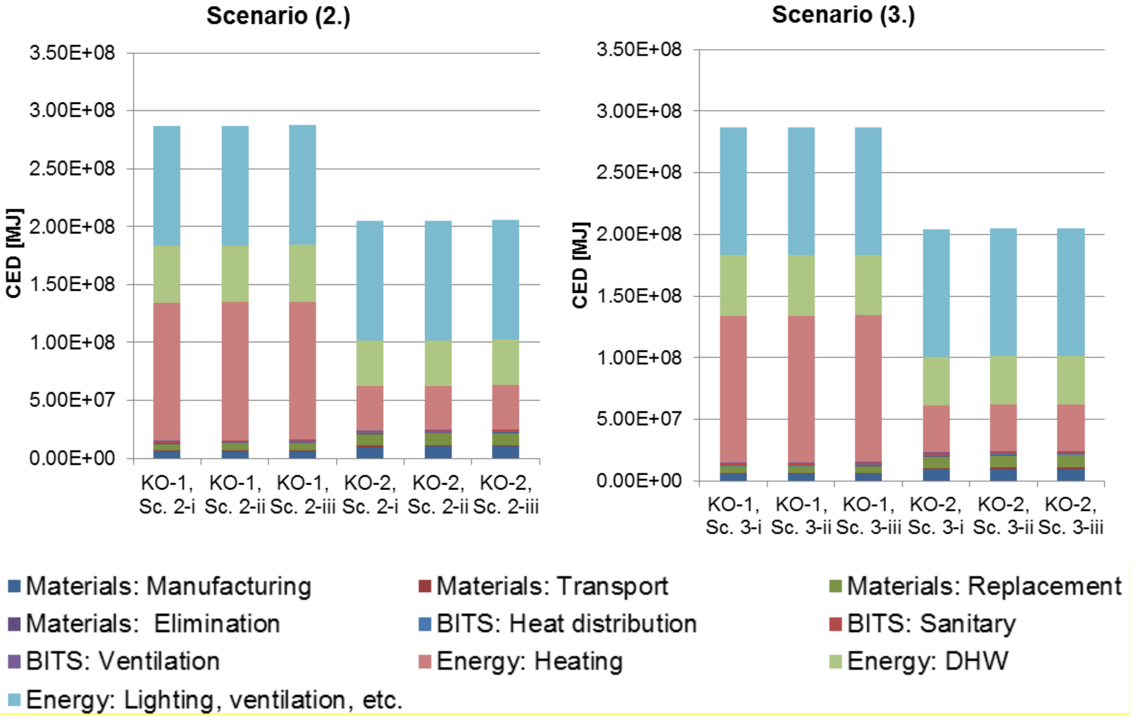


Total environmental impacts of individual PB-1 to PB-3 scenario combinations in GWP impact category structured according to EN 15978. 60-year building service life is considered.

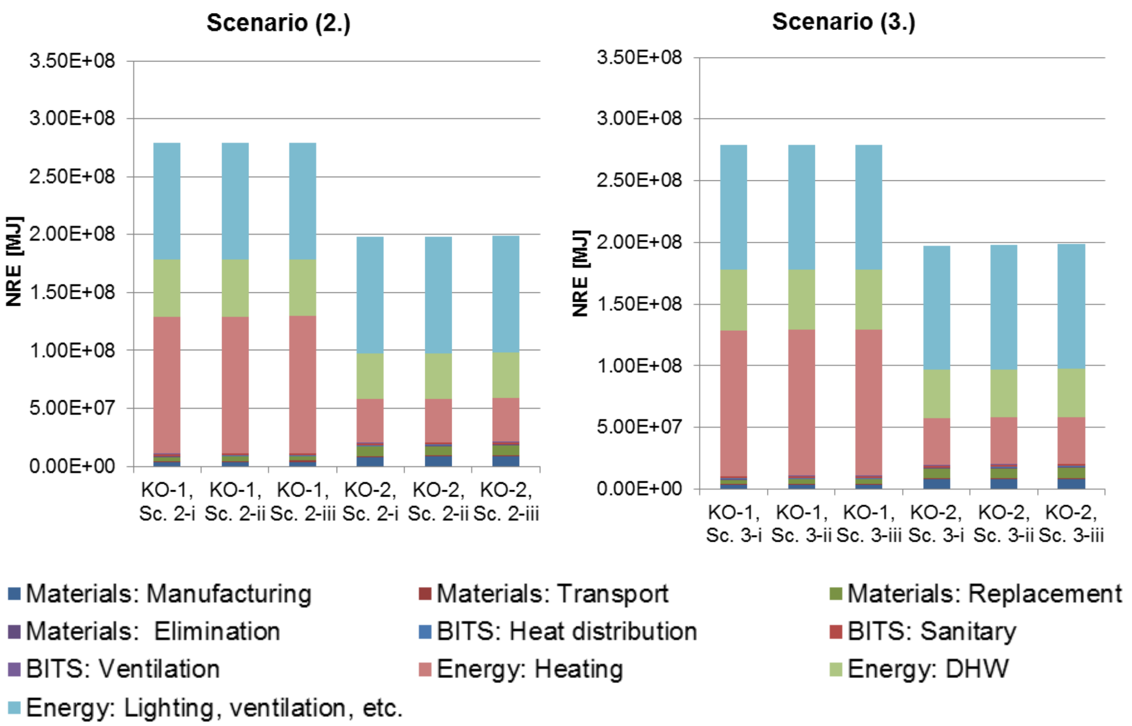
Total environmental impacts of KO-1, KO-2 (50-year service life)



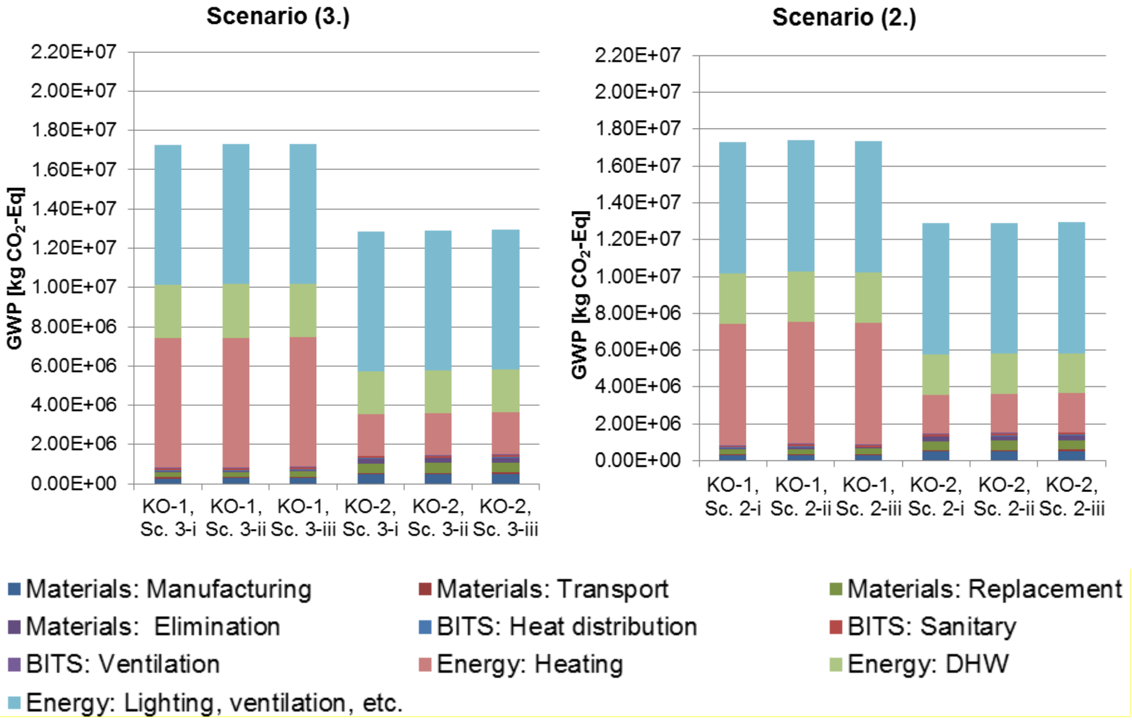
Total environmental impacts of individual KO-1 and KO-2 scenario combinations in UBP impact category structured according to Eco-Bat 4.0 tool. 50-year building service life is considered.



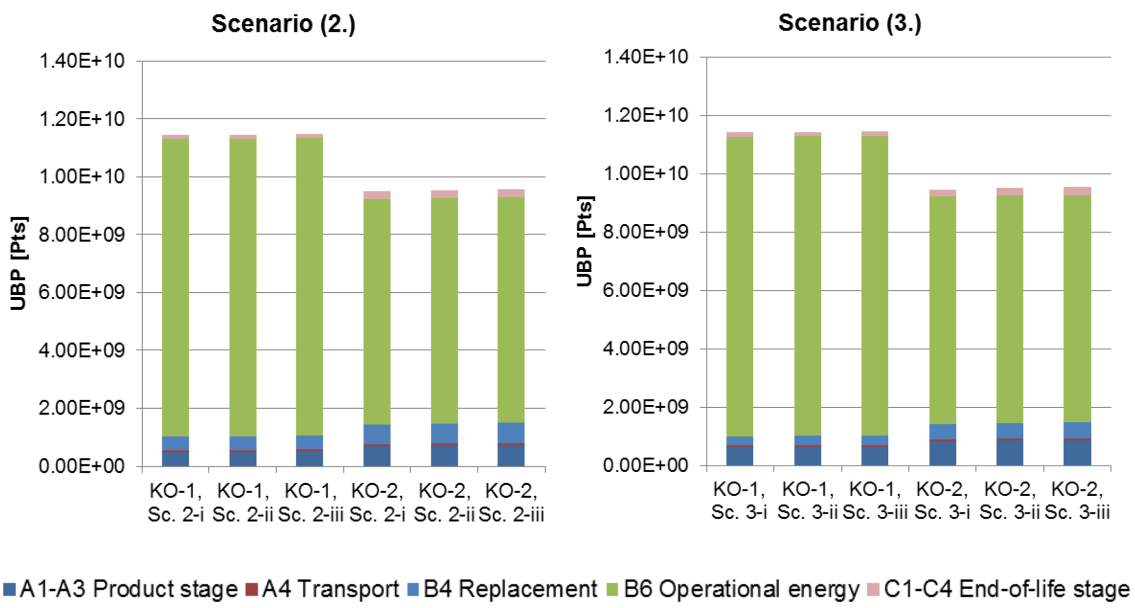
Total environmental impacts of individual KO-1 and KO-2 scenario combinations in CED impact category structured according to Eco-Bat 4.0 tool. 50-year building service life is considered.



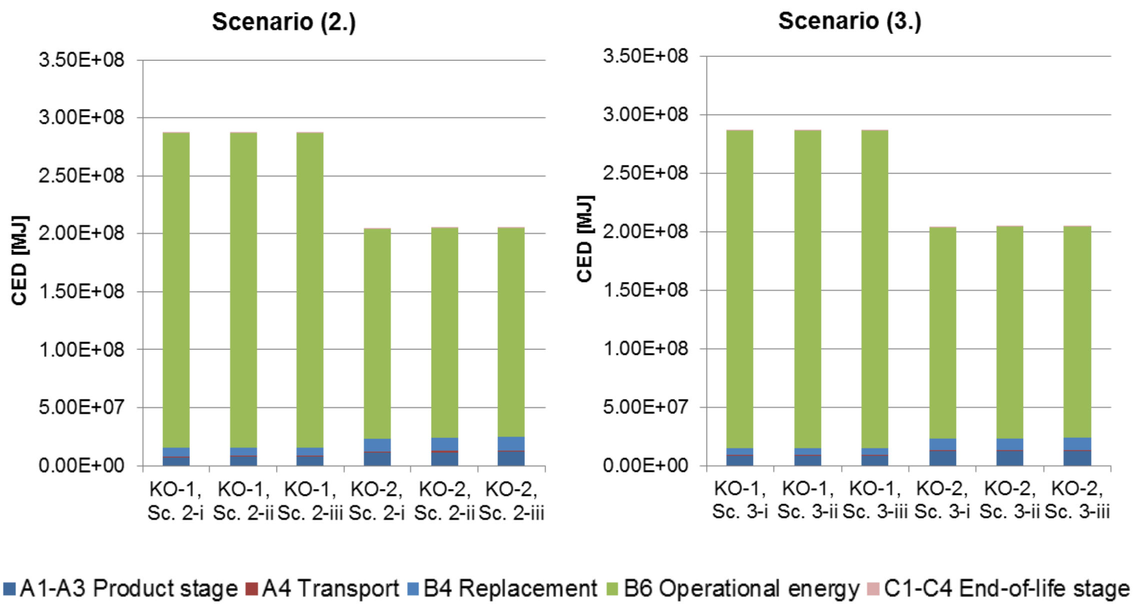
Total environmental impacts of individual KO-1 and KO-2 scenario combinations in NRE impact category structured according to Eco-Bat 4.0 tool. 50-year building service life is considered.



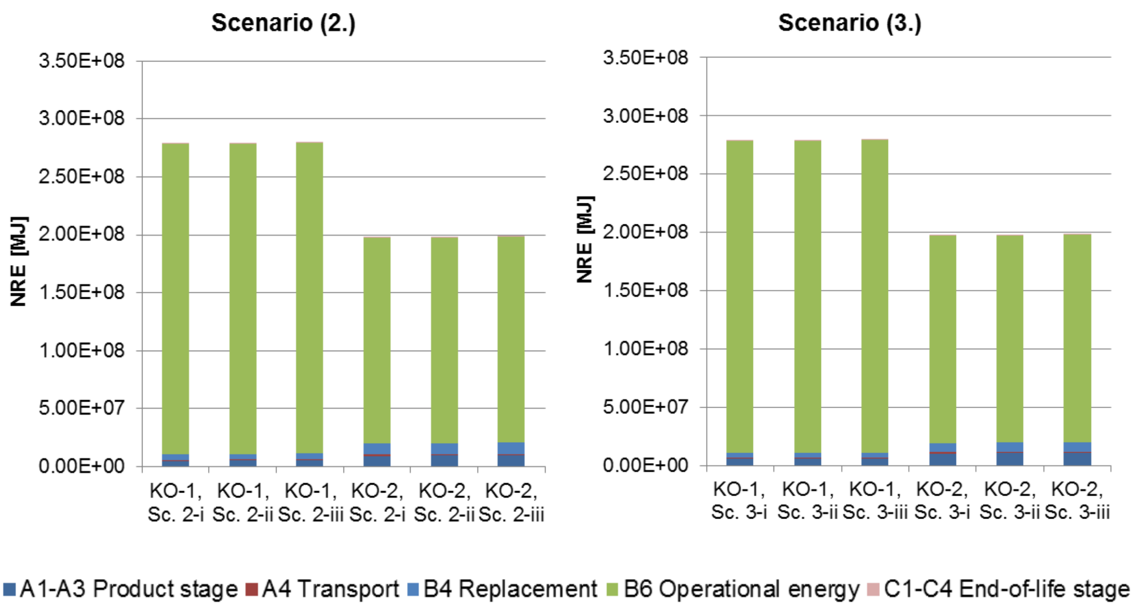
Total environmental impacts of individual KO-1 and KO-2 scenario combinations in GWP impact category structured according to Eco-Bat 4.0 tool. 50-year building service life is considered.



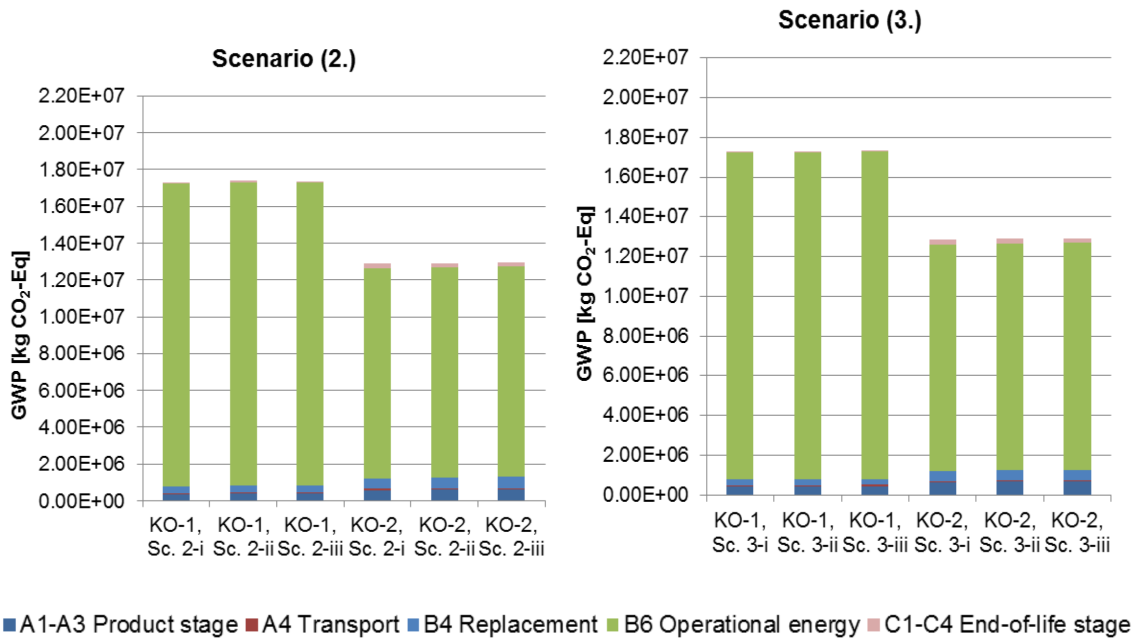
Total environmental impacts of individual KO-1 and KO-2 scenario combinations in UBP impact category structured according to EN 15978. 50-year building service life is considered.



Total environmental impacts of individual KO-1 and KO-2 scenario combinations in CED impact category structured according to EN 15978. 50-year building service life is considered.

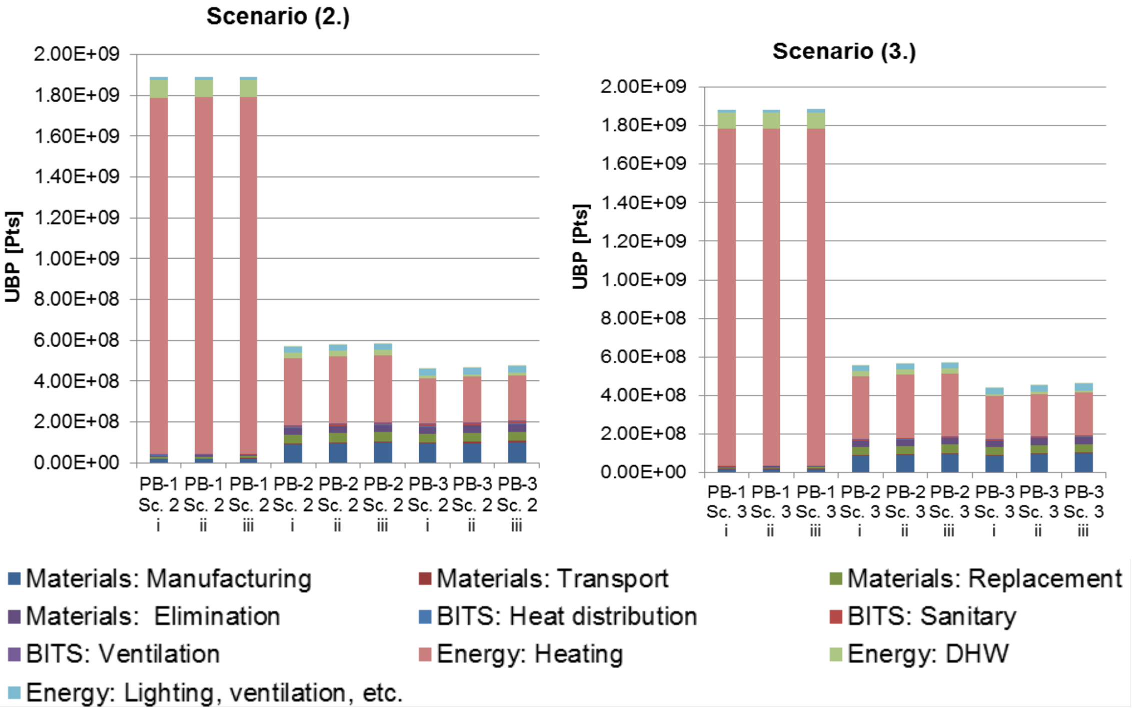


Total environmental impacts of individual KO-1 and KO-2 scenario combinations in NRE impact category structured according to EN 15978. 50-year building service life is considered.

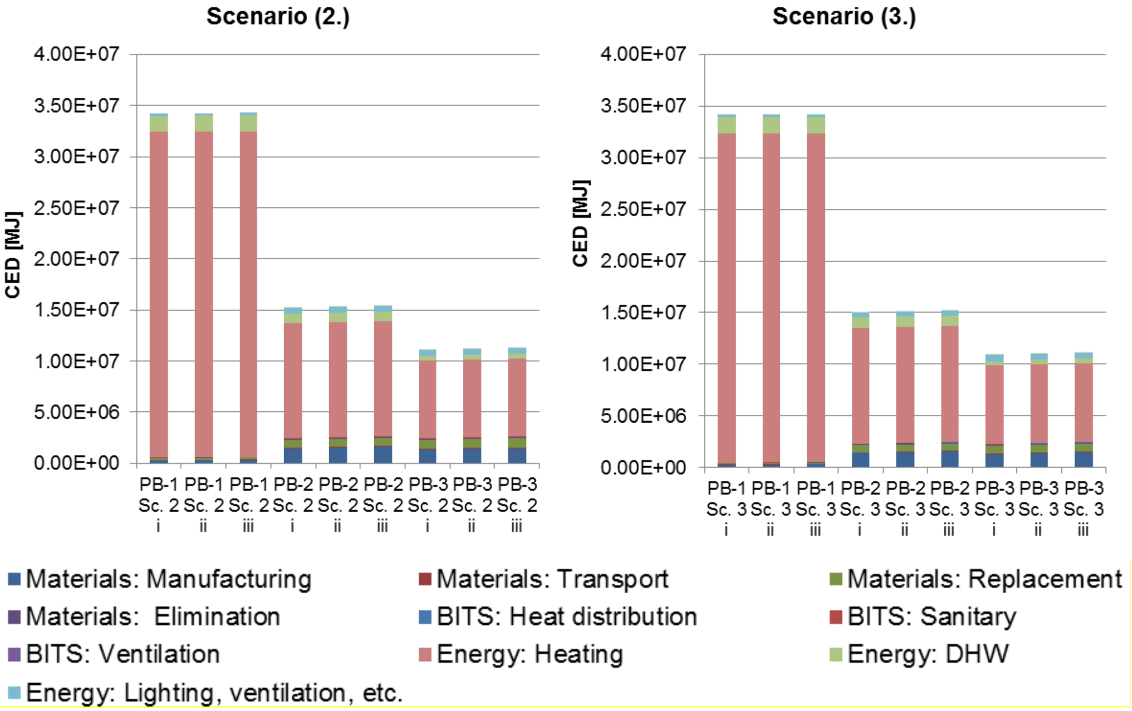


Total environmental impacts of individual KO-1 and KO-2 scenario combinations in GWP impact category structured according to EN 15978. 50-year building service life is considered.

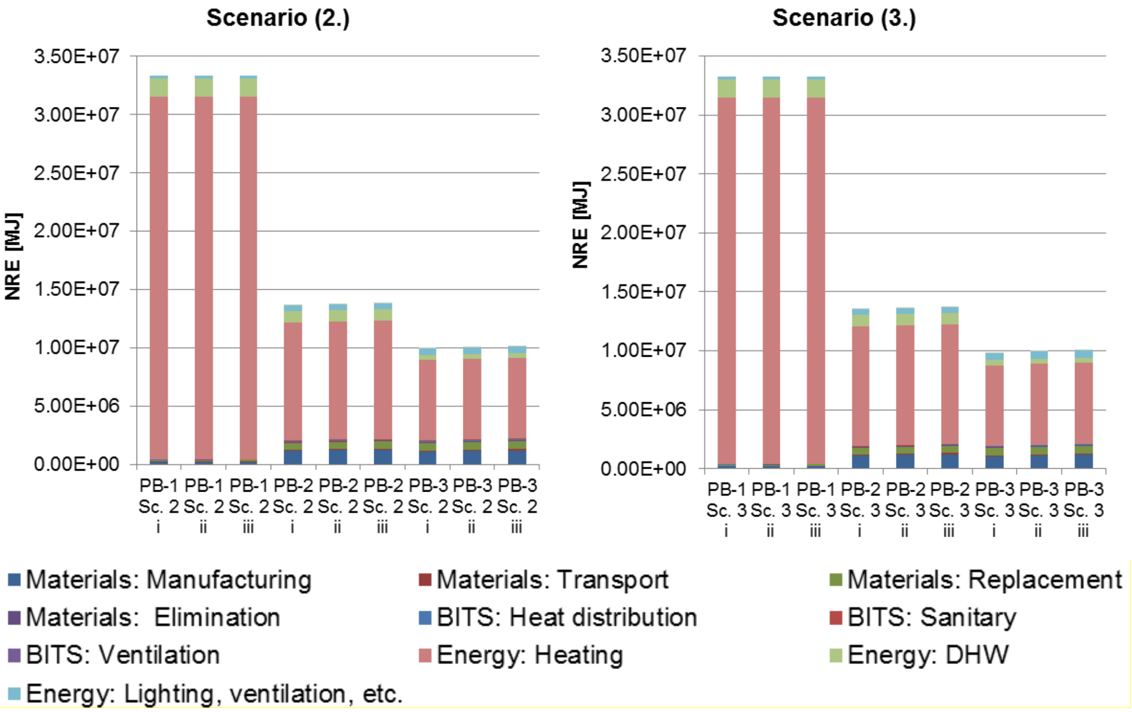
Total environmental impacts of PB-1 to PB-3 (50-year service life)



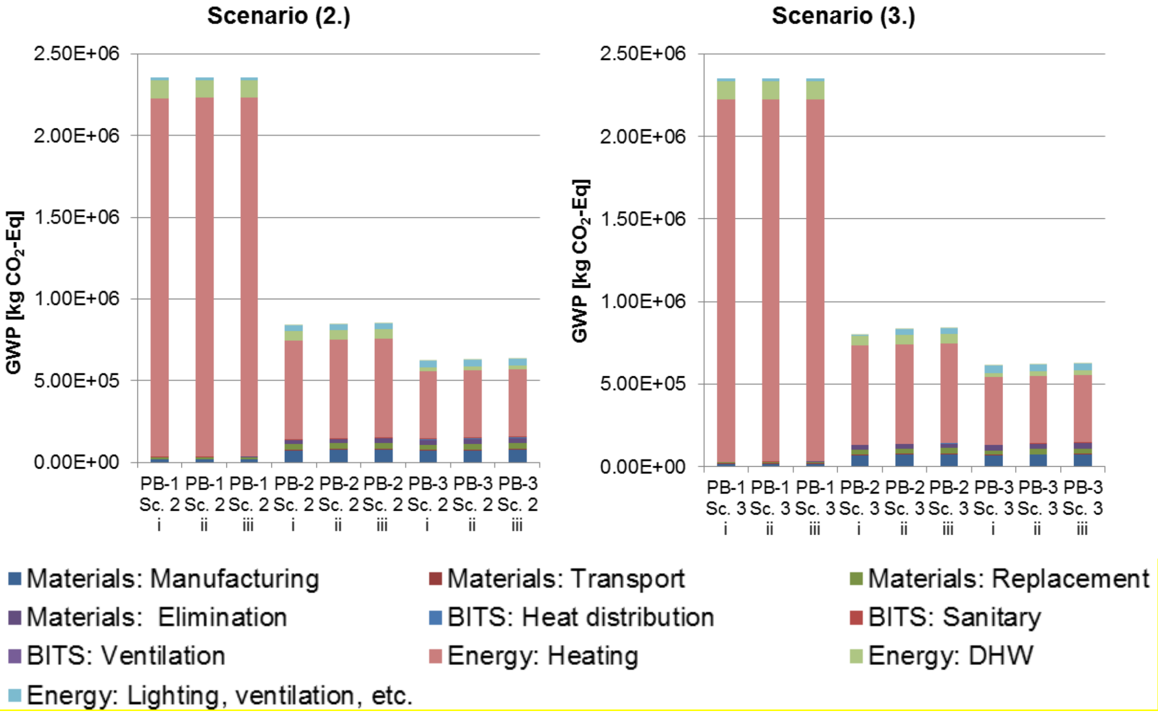
Total environmental impacts of individual PB-1 to PB-3 scenario combinations in UBP impact category structured according to Eco-Bat 4.0 tool. 50-year building service life is considered.



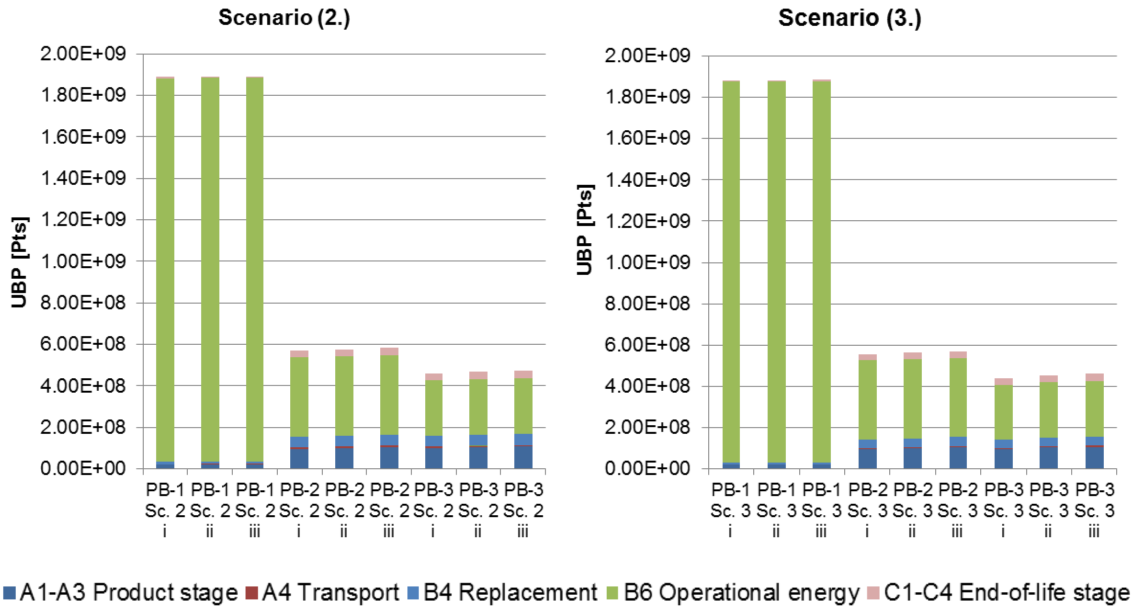
Total environmental impacts of individual PB-1 to PB-3 scenario combinations in CED impact category structured according to Eco-Bat 4.0 tool. 50-year building service life is considered.



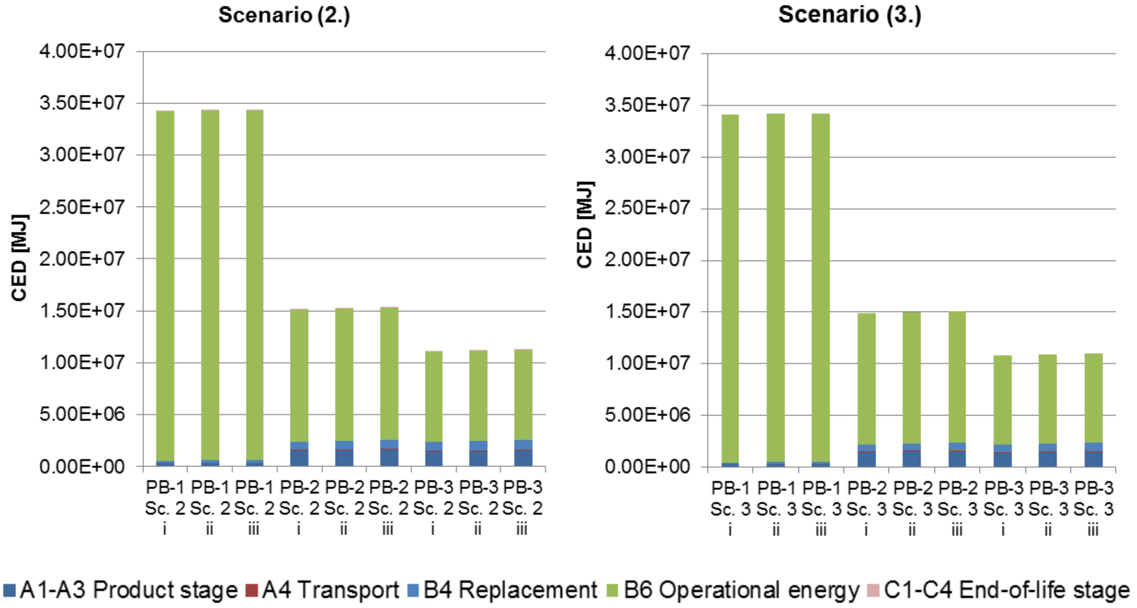
Total environmental impacts of individual PB-1 to PB-3 scenario combinations in NRE impact category structured according to Eco-Bat 4.0 tool. 50-year building service life is considered.



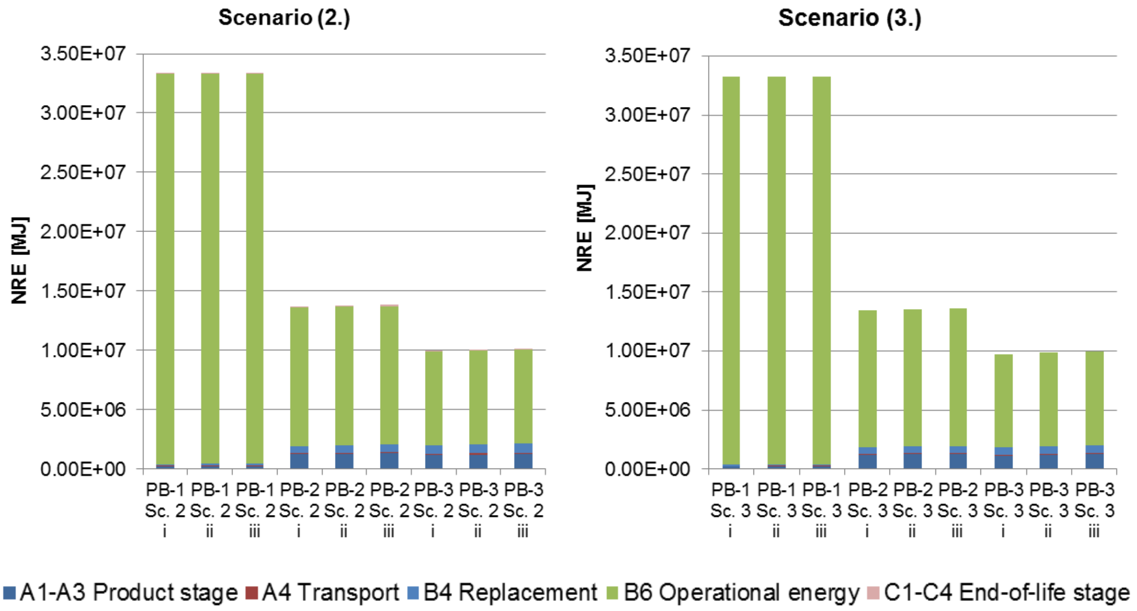
Total environmental impacts of individual PB-1 to PB-3 scenario combinations in GWP impact category structured according to Eco-Bat 4.0 tool. 50-year building service life is considered.



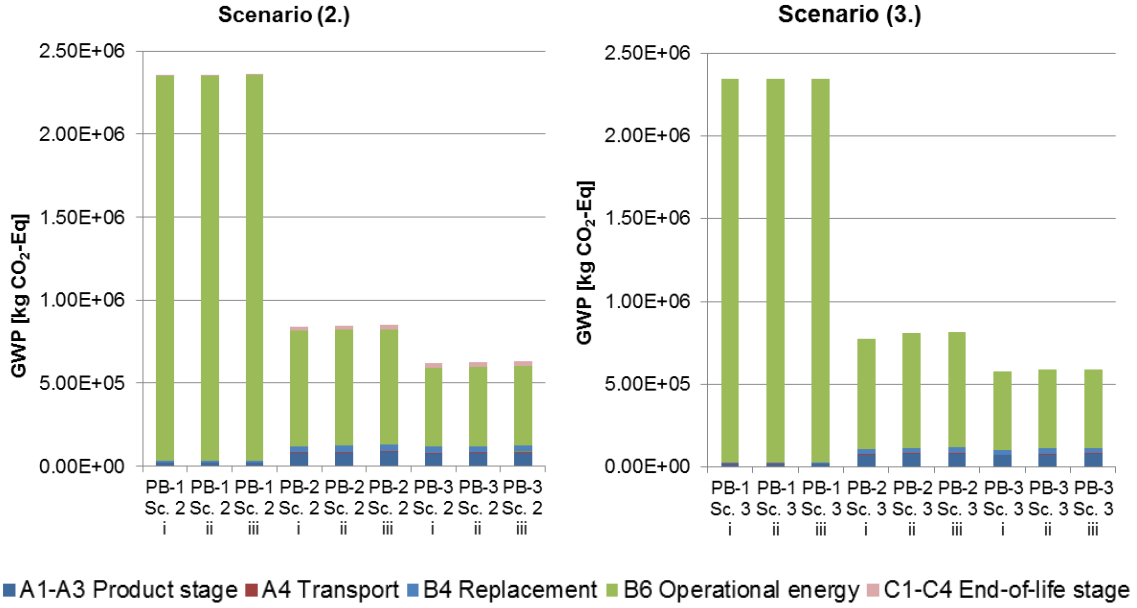
Total environmental impacts of individual PB-1 to PB-3 scenario combinations in UBP impact category structured according to EN 15978. 50-year building service life is considered.



Total environmental impacts of individual PB-1 to PB-3 scenario combinations in CED impact category structured according to EN 15978. 50-year building service life is considered.

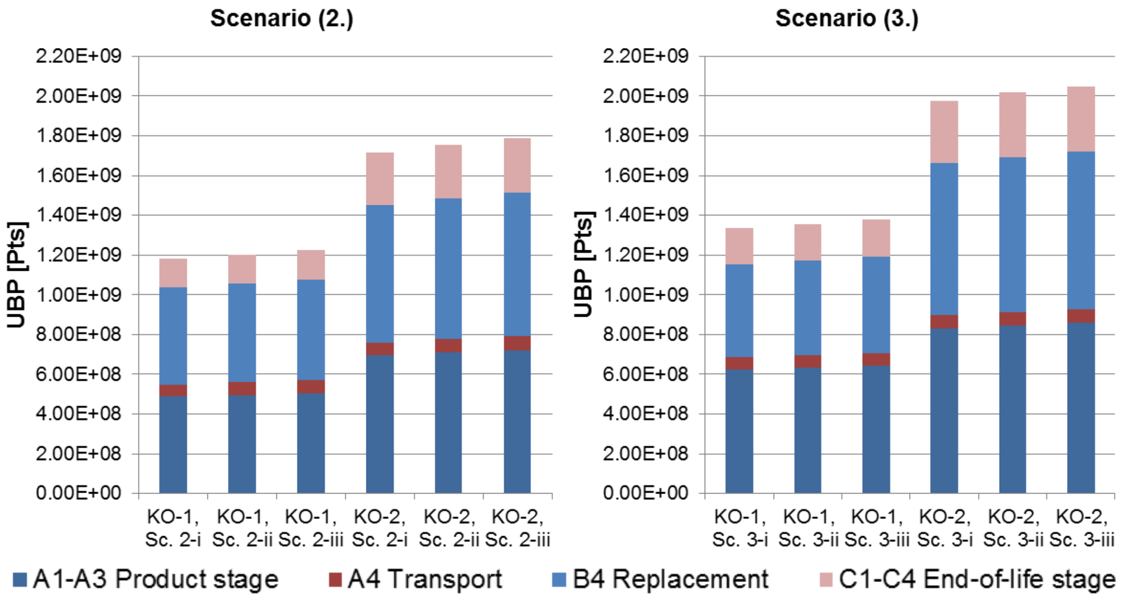


Total environmental impacts of individual PB-1 to PB-3 scenario combinations in NRE impact category structured according to EN 15978. 50-year building service life is considered.

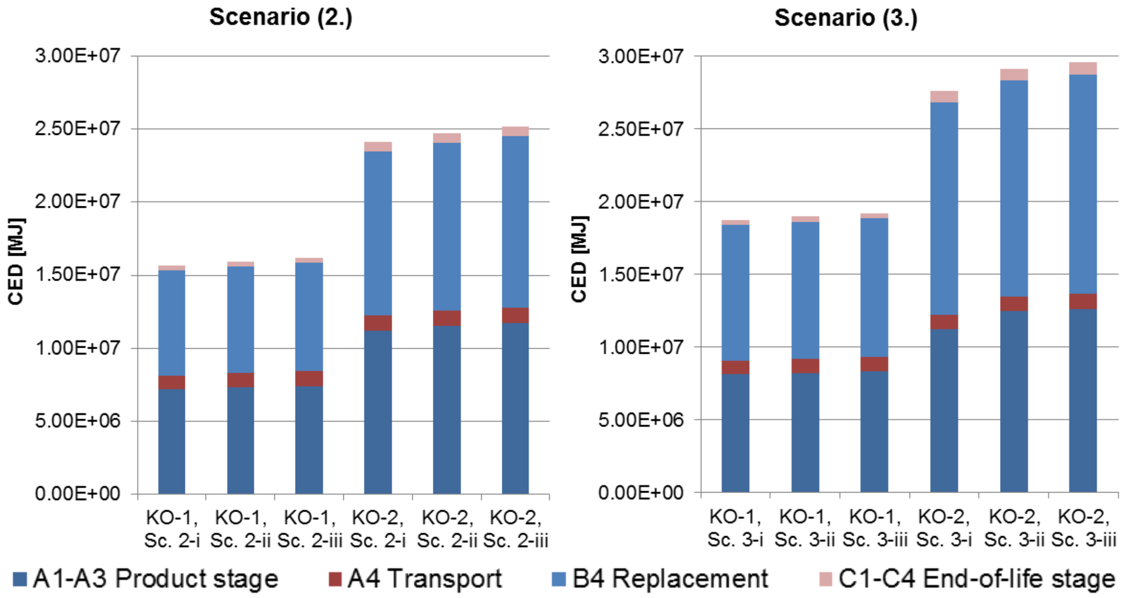


Total environmental impacts of individual PB-1 to PB-3 scenario combinations in GWP impact category structured according to EN 15978. 50-year building service life is considered.

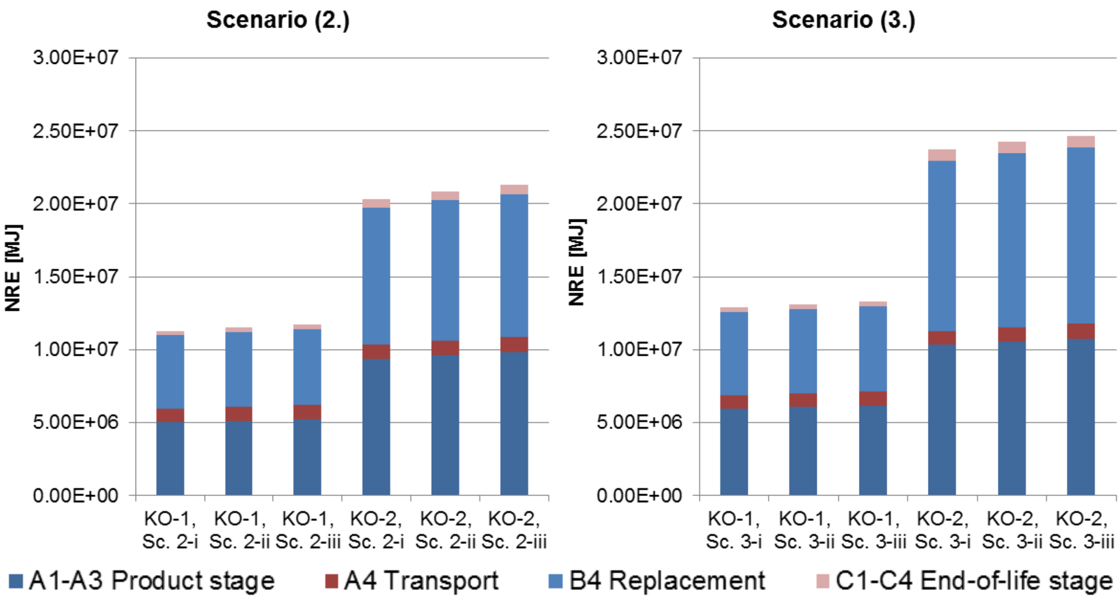
Embodied environmental impacts of KO-1, KO-2 (60-year service life)



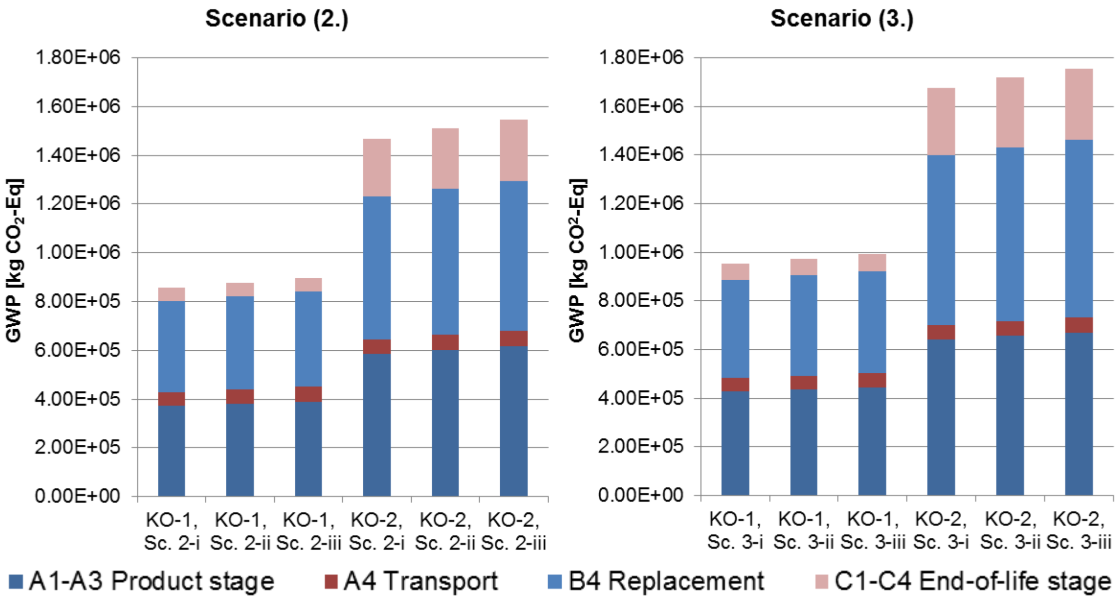
EEIs of individual KO-1 and KO-2 scenario combinations in UBP impact category structured according to EN 15978. 60-year building service life is considered.



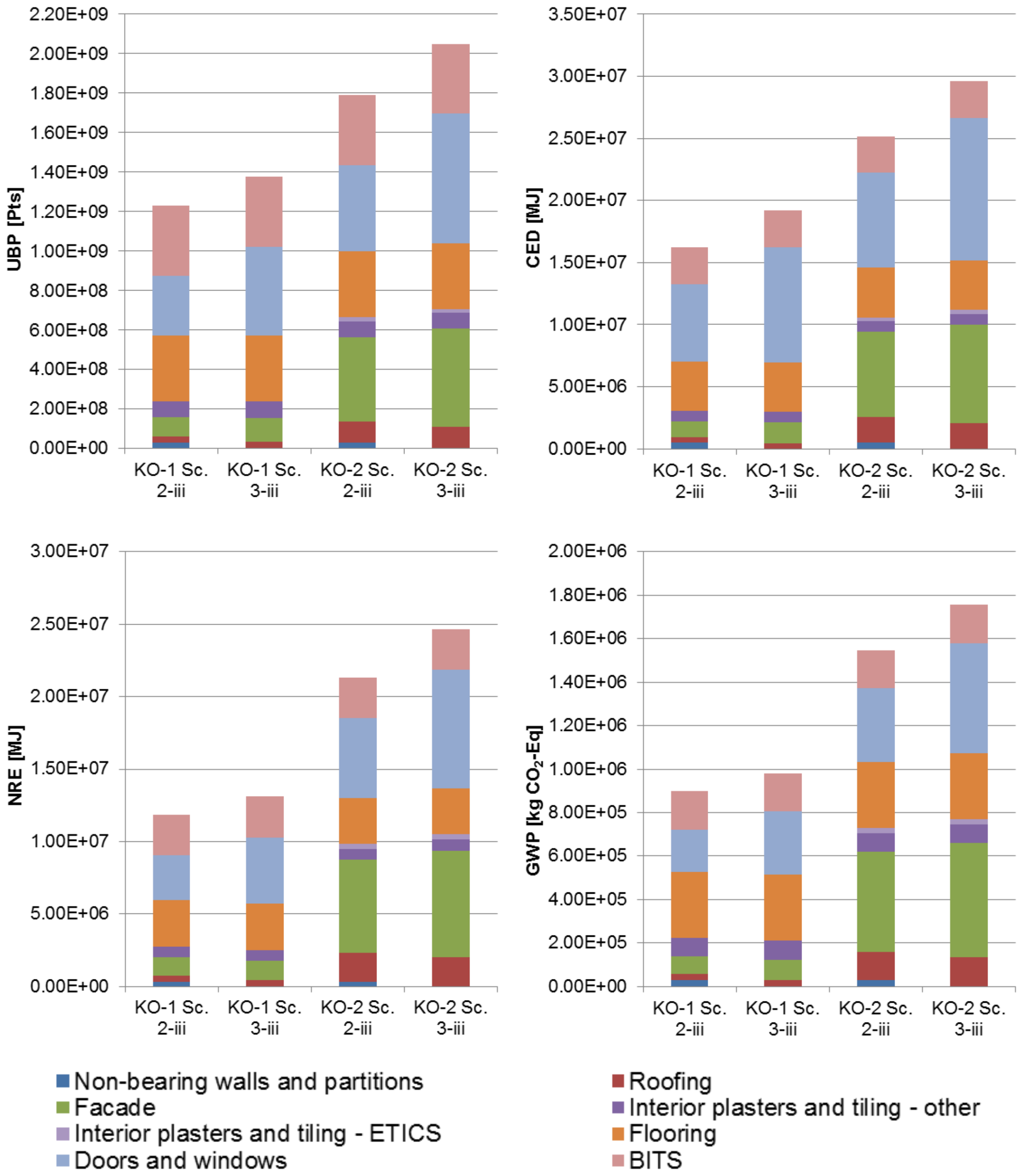
EEIs of individual KO-1 and KO-2 scenario combinations in CED impact category structured according to EN 15978. 60-year building service life is considered.



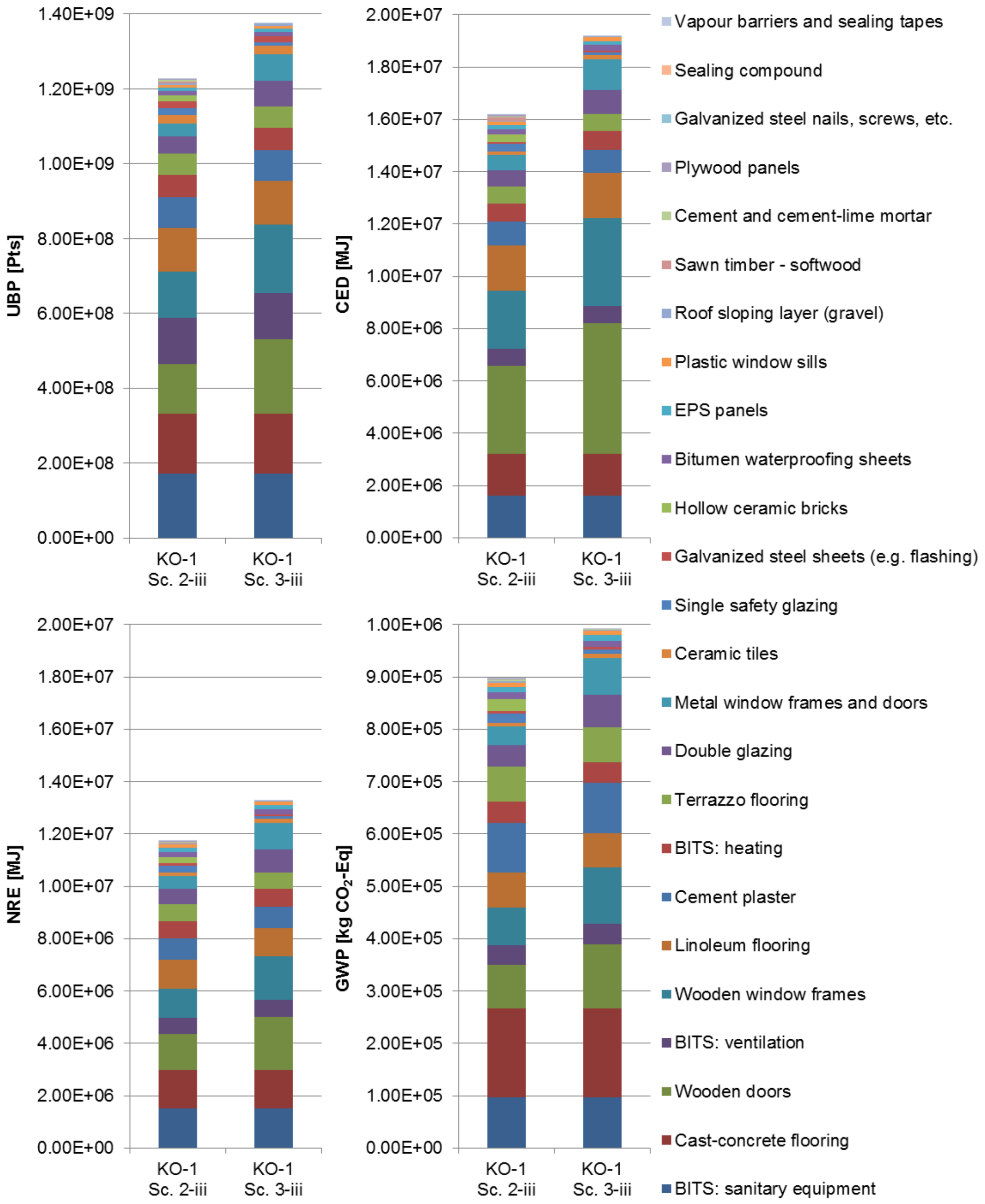
EEIs of individual KO-1 and KO-2 scenario combinations in NRE impact category structured according to EN 15978. 60-year building service life is considered.



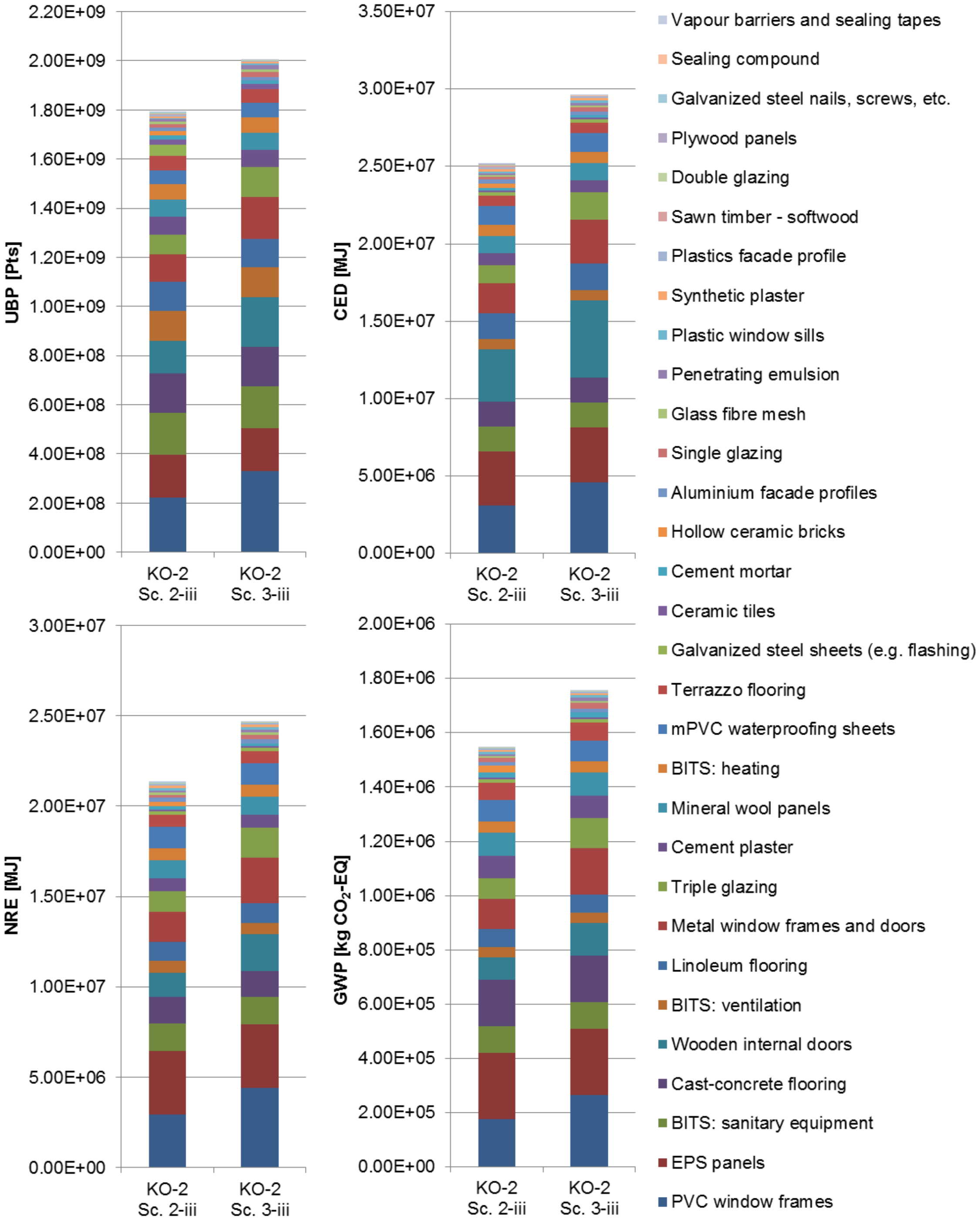
EEIs of individual KO-1 and KO-2 scenario combinations in GWP impact category structured according to EN 15978. 60-year building service life is considered.



EEIs of the worst-case scenario combinations in KO-1 and KO-2 in all four impact categories. The EEIs are divided among individual building elements based on grouping in inventory tables.

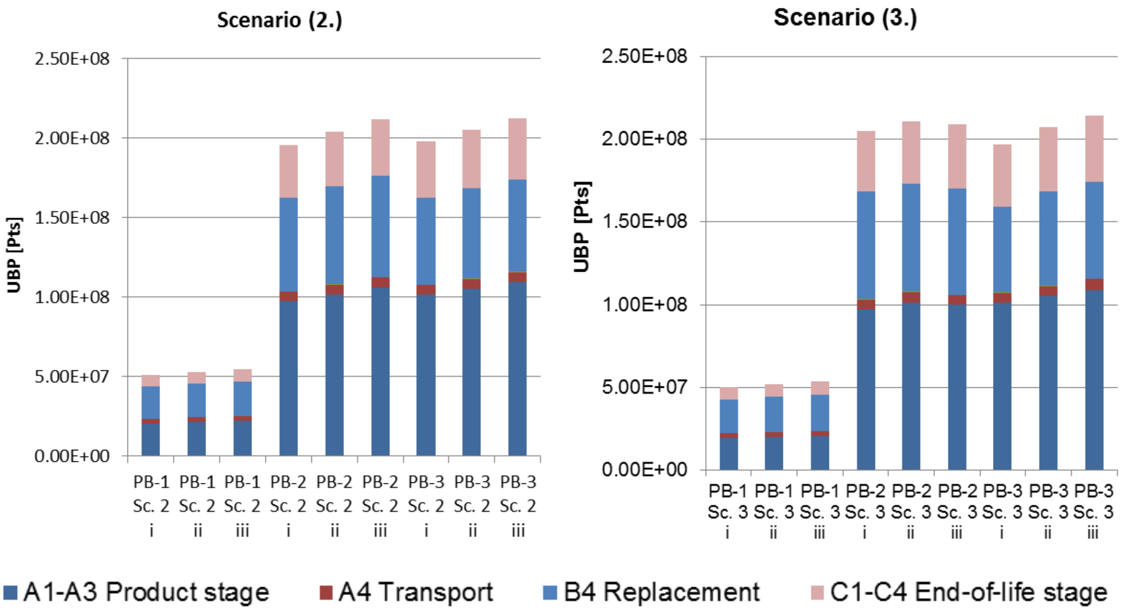


EEIs of the worst-case scenario combinations in KO-1 in all four impact categories. The EEIs are divided among individual building materials listed in inventory tables.

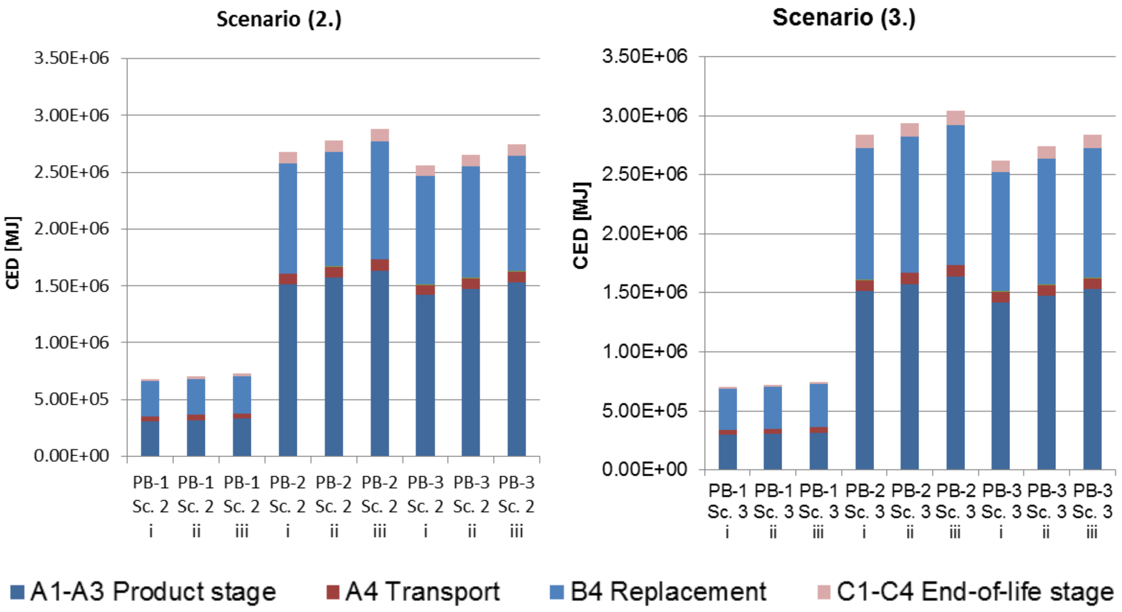


EEIs of the worst-case scenario combinations in KO-2 in all four impact categories. The EEIs are divided among individual building materials listed in inventory tables.

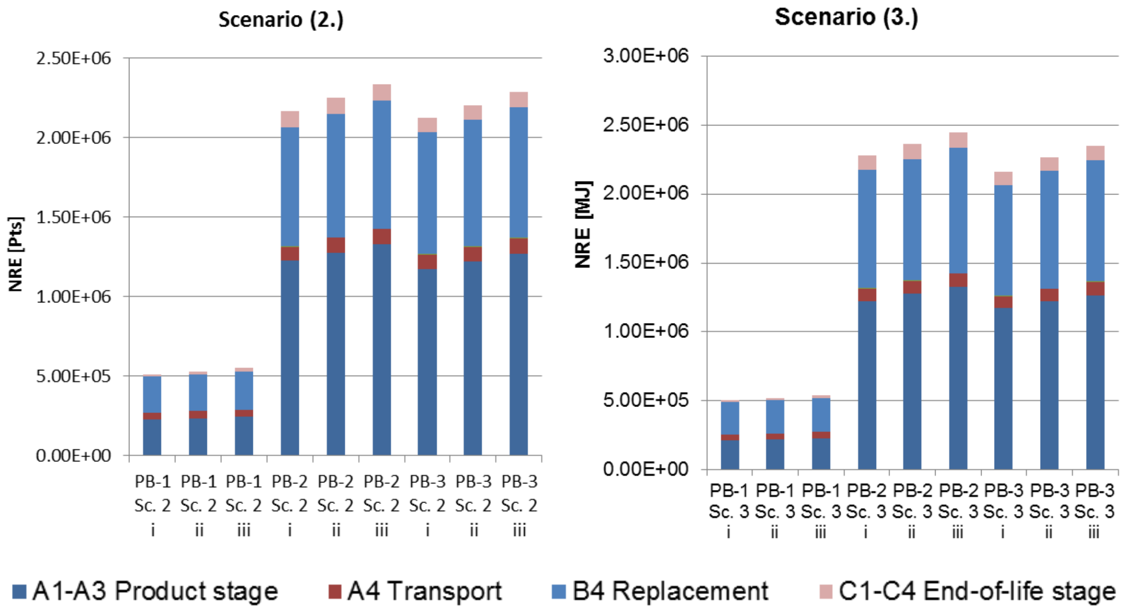
Embodied environmental impacts of PB-1 to PB-3 (60-year service life)



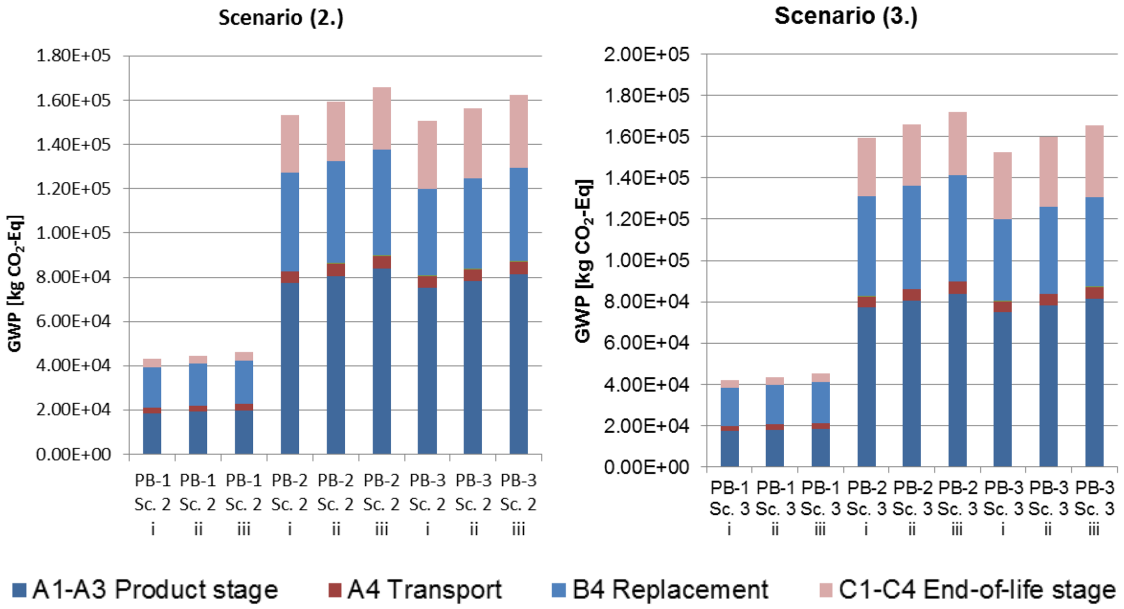
EEIs of individual PB-1 to PB-3 scenario combinations in UBP impact category structured according to EN 15978. 60-year building service life is considered.



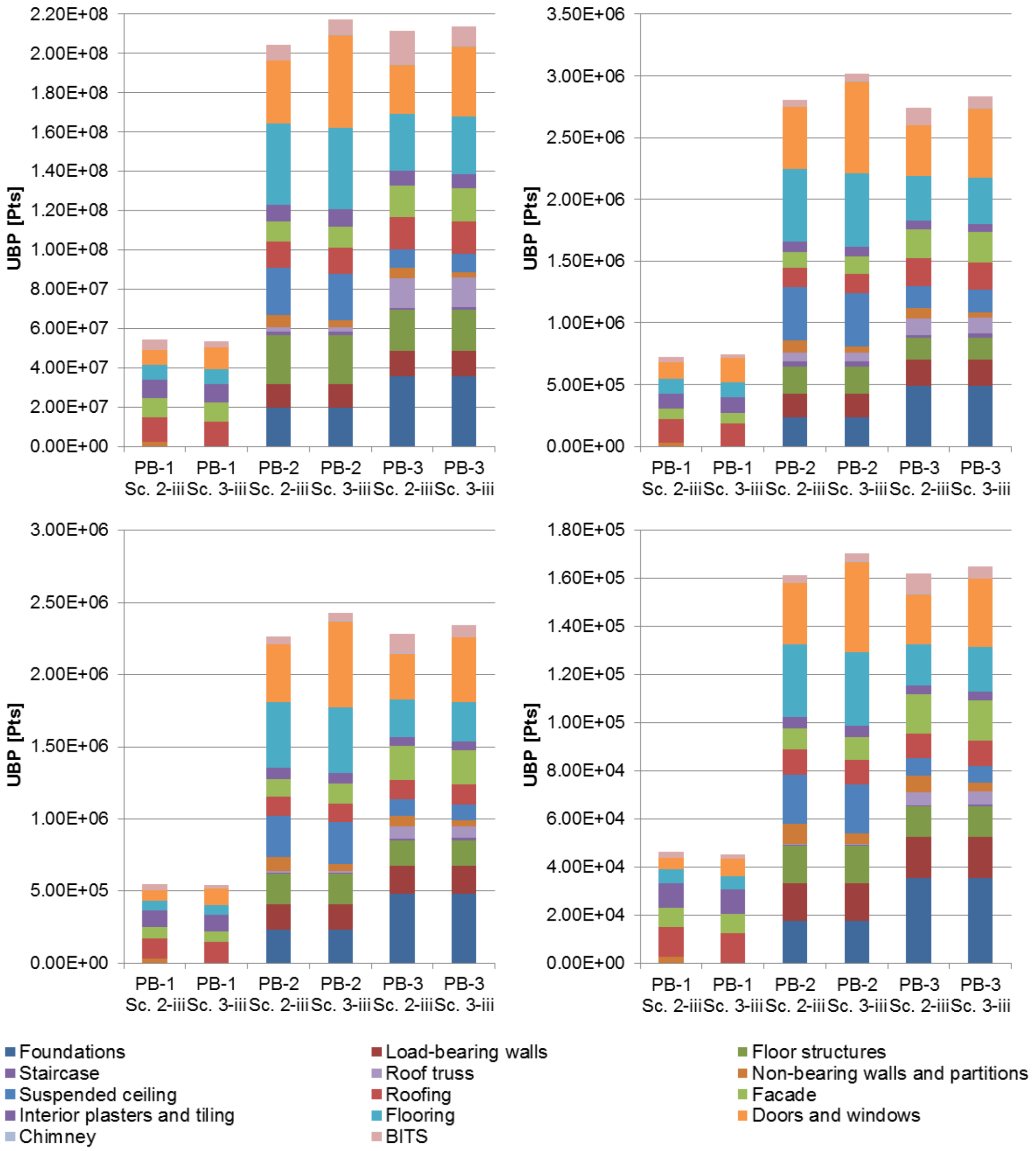
EEIs of individual PB-1 to PB-3 scenario combinations in CED impact category structured according to EN 15978. 60-year building service life is considered.



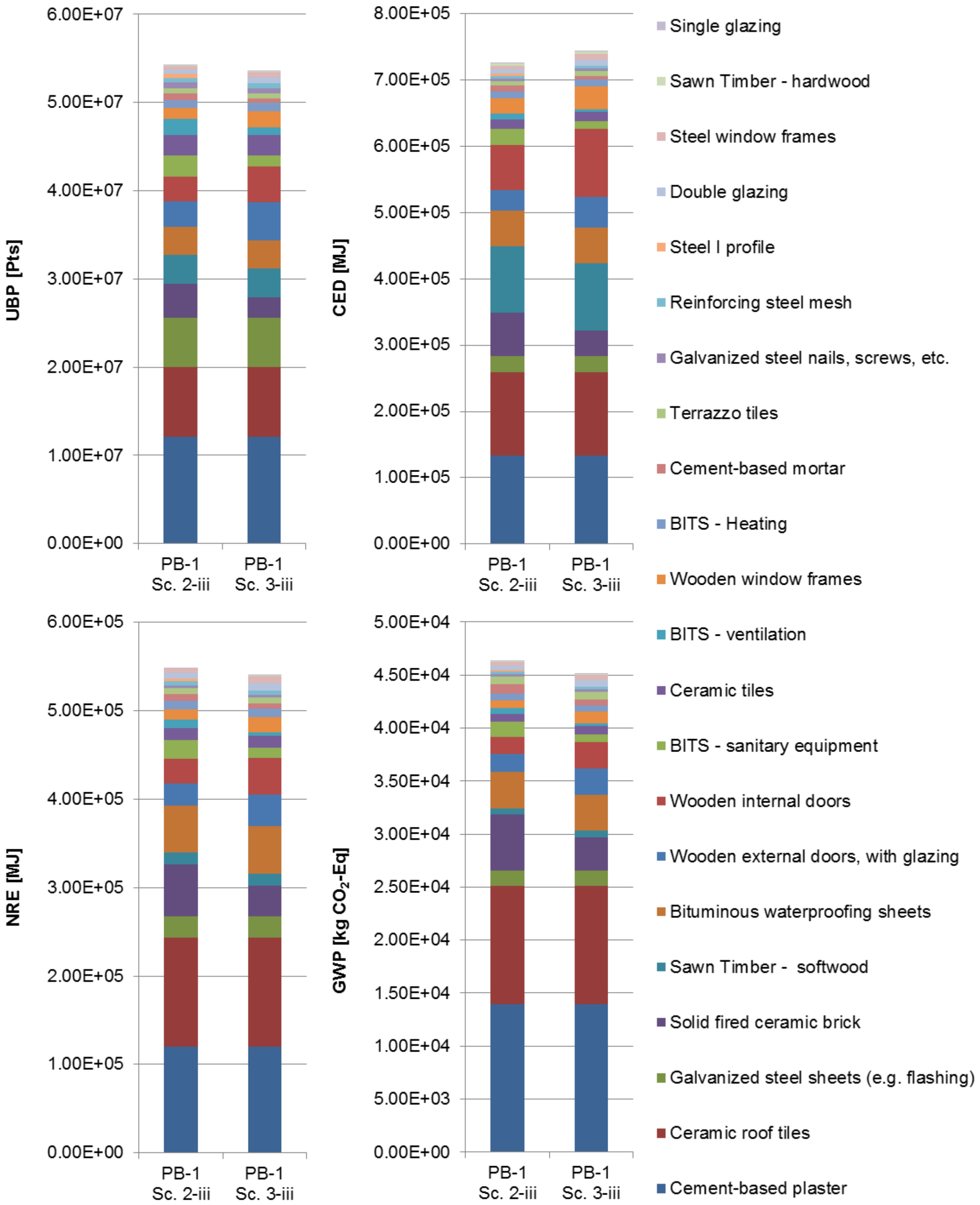
EEIs of individual PB-1 to PB-3 scenario combinations in NRE impact category structured according to EN 15978. 60-year building service life is considered.



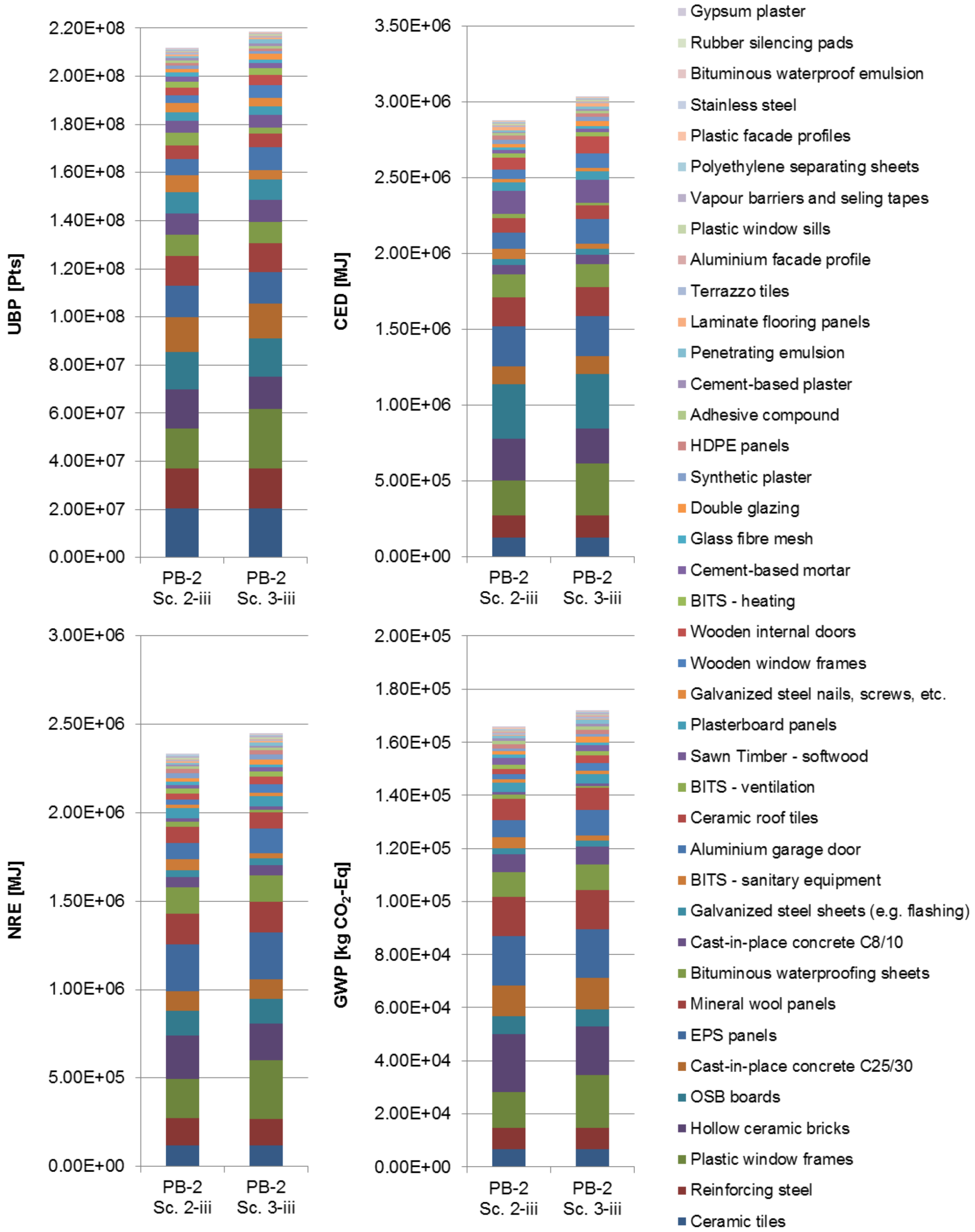
EEIs of individual PB-1 to PB-3 scenario combinations in GWP impact category structured according to EN 15978. 60-year building service life is considered.



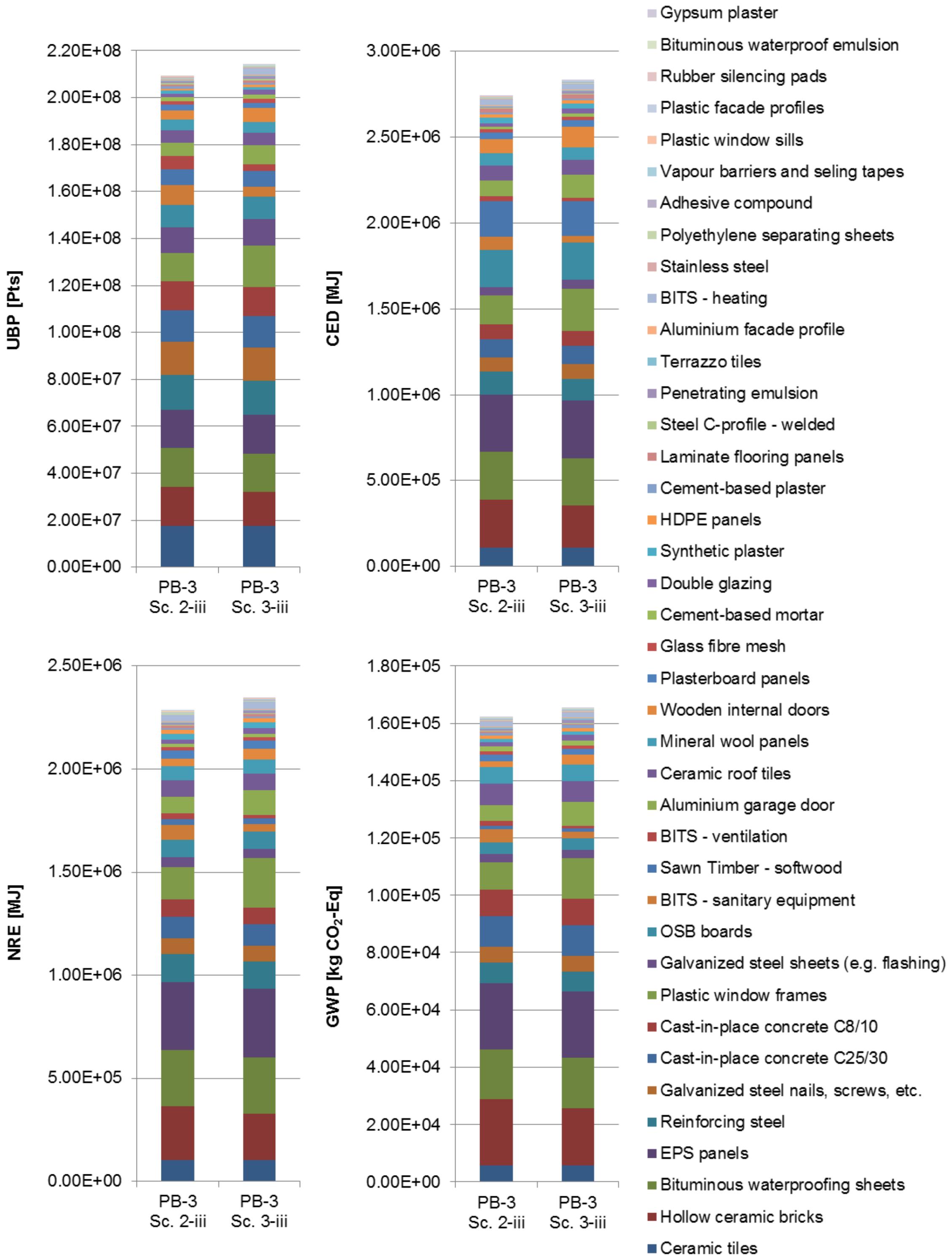
EEIs of the worst-case scenario combinations in PB-1 to PB-3 in all four impact categories. The EEIs are divided among individual building elements based on grouping in inventory tables.



EEIs of the worst-case scenario combinations in PB-1 in all four impact categories. The EEIs are divided among individual building materials listed in inventory tables.



EEIs of the worst-case scenario combinations in PB-2 in all four impact categories. The EEIs are divided among individual building materials listed in inventory tables.



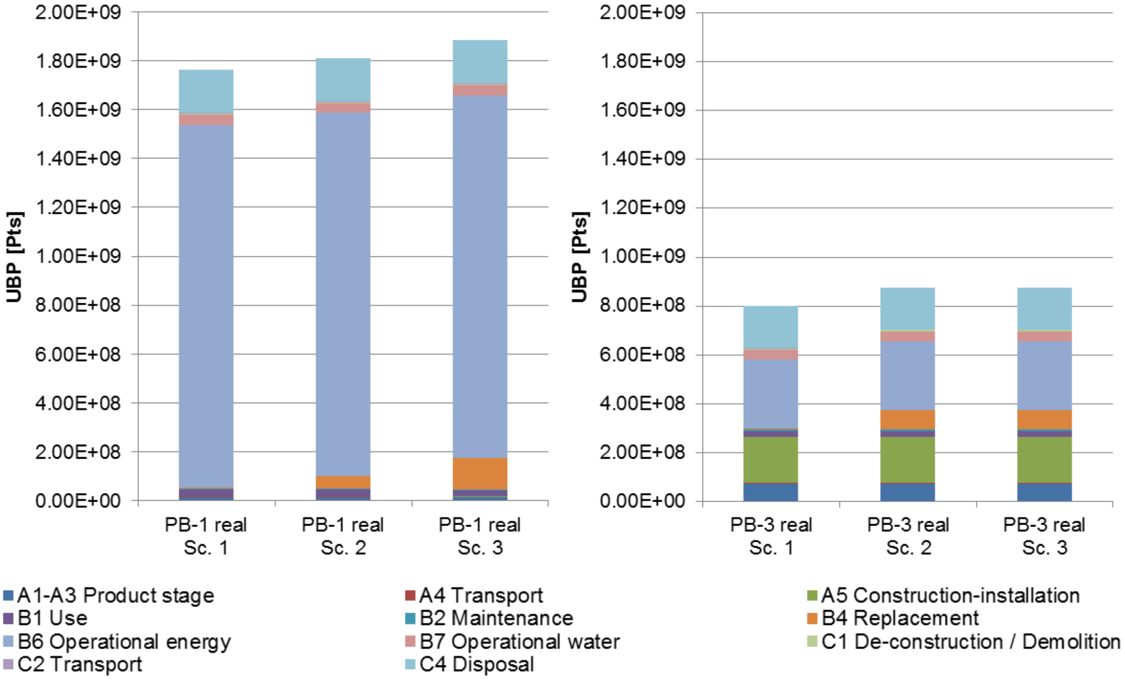
EEIs of the worst-case scenario combinations in PB-3 in all four impact categories. The EEIs are divided among individual building materials listed in inventory tables.

Appendix E. GaBi 4 results

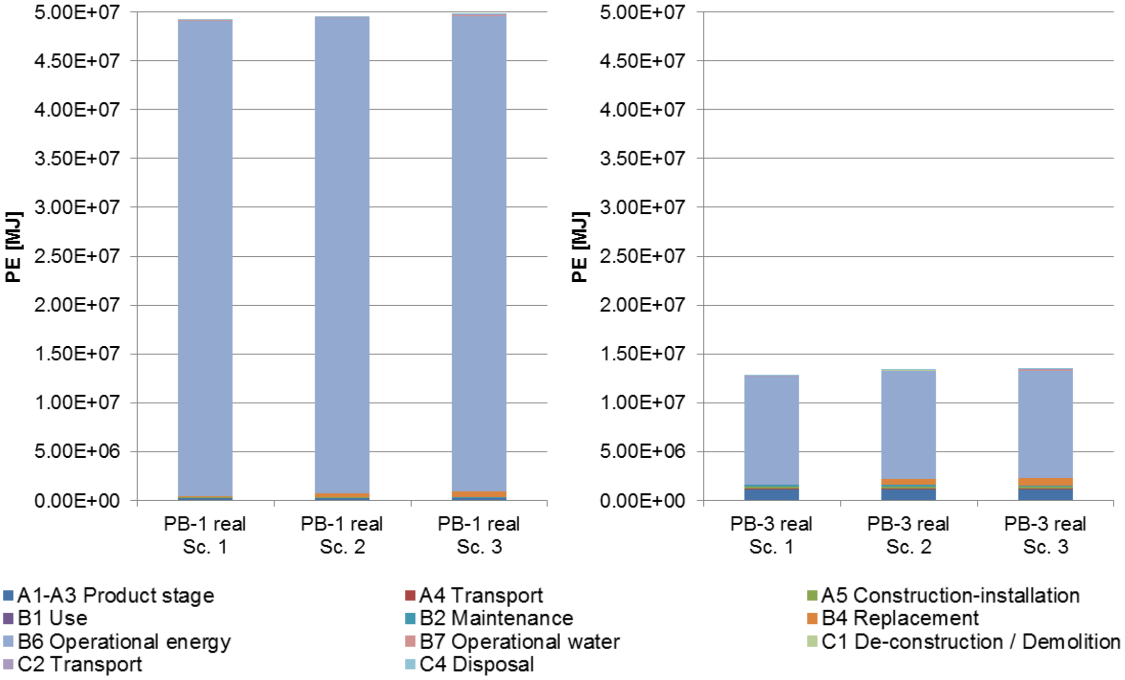
This appendix presents charts with results of GaBi 4 calculations supplementing the results in Section 6.2. Full numerical results are archived by the author and are available on request. The charts in the appendix show:

- Total environmental impacts of PB-1 and PB-3 scenario combinations most resembling reality in all four impact categories structured according to EN 15978. Only 60-year building service life is considered,
- EEIs of PB-1 and PB-3 scenario combinations most resembling reality structured according to EN 15978 – excerpt of the total results. Only 60-year service life is considered,
- EEIs (in modules A1-A3) of PB-1 and PB-3 scenario combinations most resembling reality divided per individual structures,
- EEIs (in modules A1-A3) of PB-1 and PB-3 scenario combinations most resembling reality divided per individual materials,
- total environmental impacts of PB-1 and PB-3 scenario combinations with highest and lowest environmental impacts (in UBP impact category) in all four impact categories structured according to EN 15978. Only 60-year building service life is considered,
- EEIs of PB-1 and PB-3 scenario combinations with highest and lowest environmental impacts (in UBP impact category) structured according to EN 15978 – excerpt of the total results. Only 60-year service life is considered.

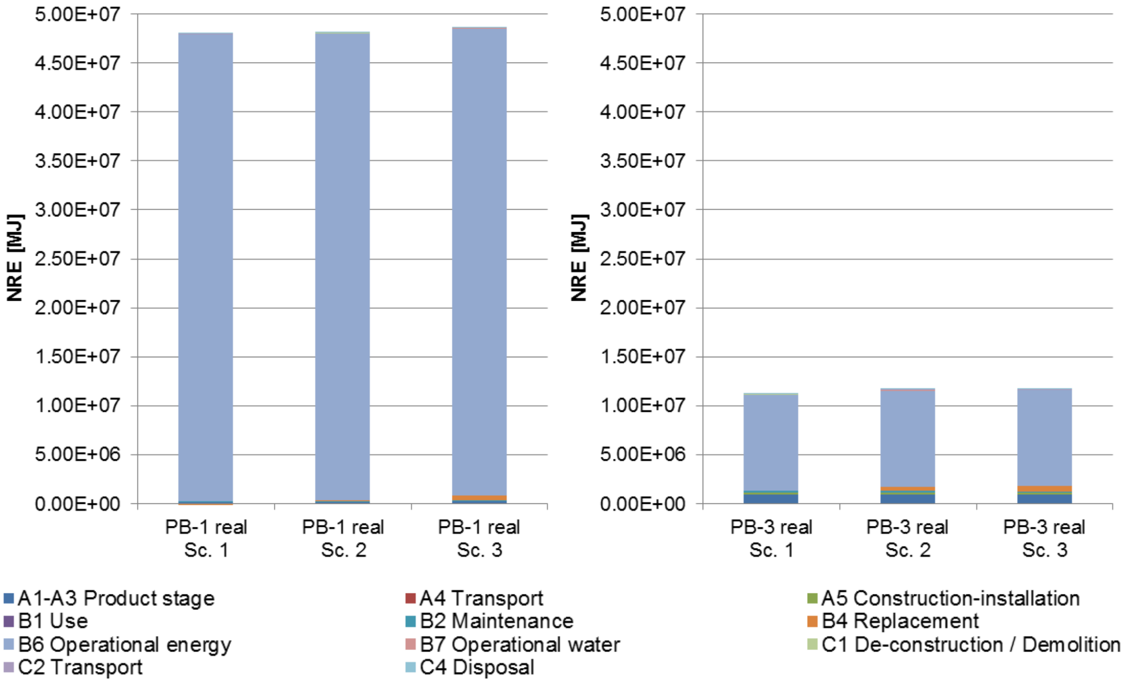
Environmental impacts of PB-1 and PB-3 scenario combinations most resembling reality



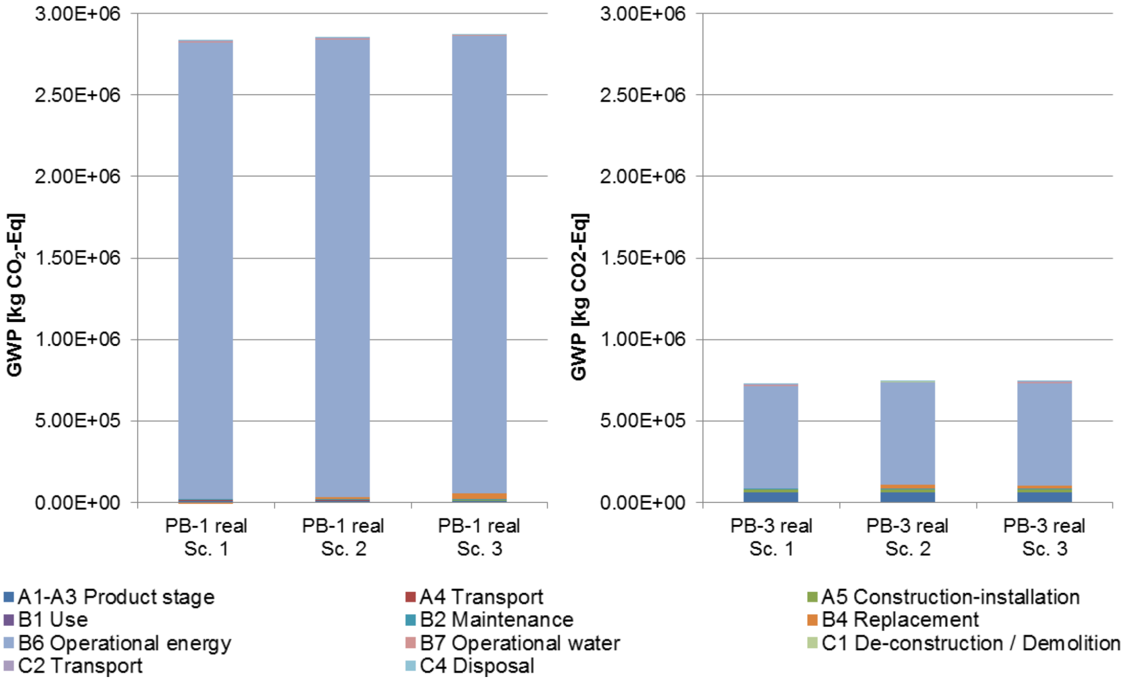
Total environmental impacts (structured according to EN 15978) related with PB-1 and PB-3 scenario combination most resembling reality in UBP impact category.



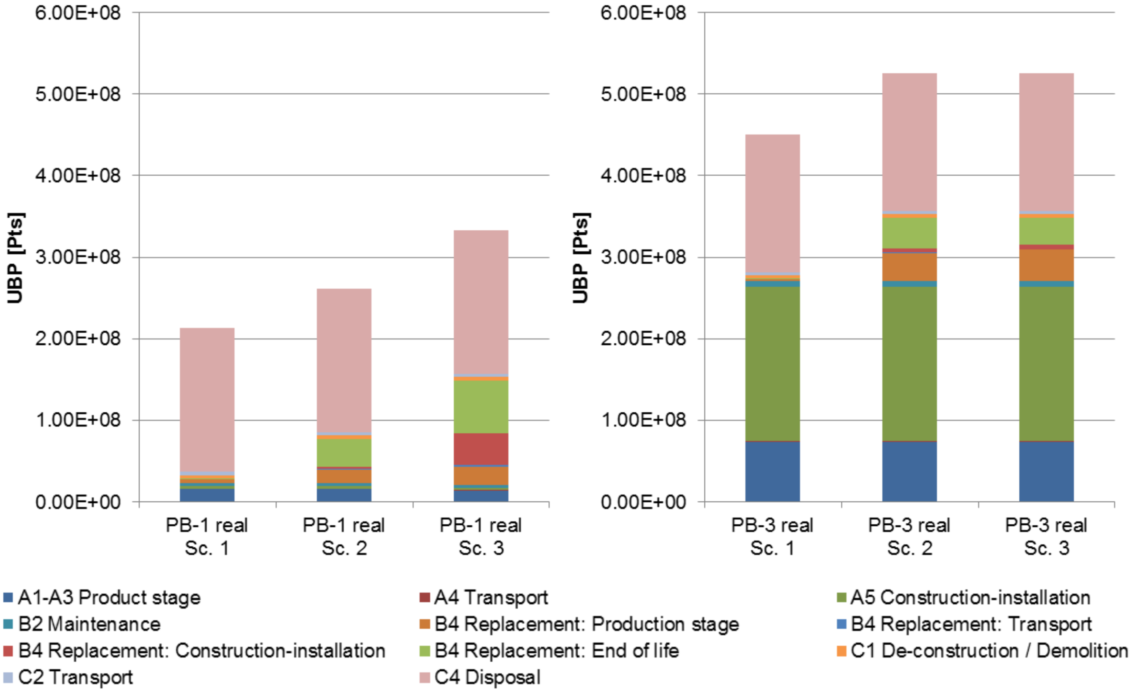
Total environmental impacts (structured according to EN 15978) related with PB-1 and PB-3 scenario combination most resembling reality in PE impact category.



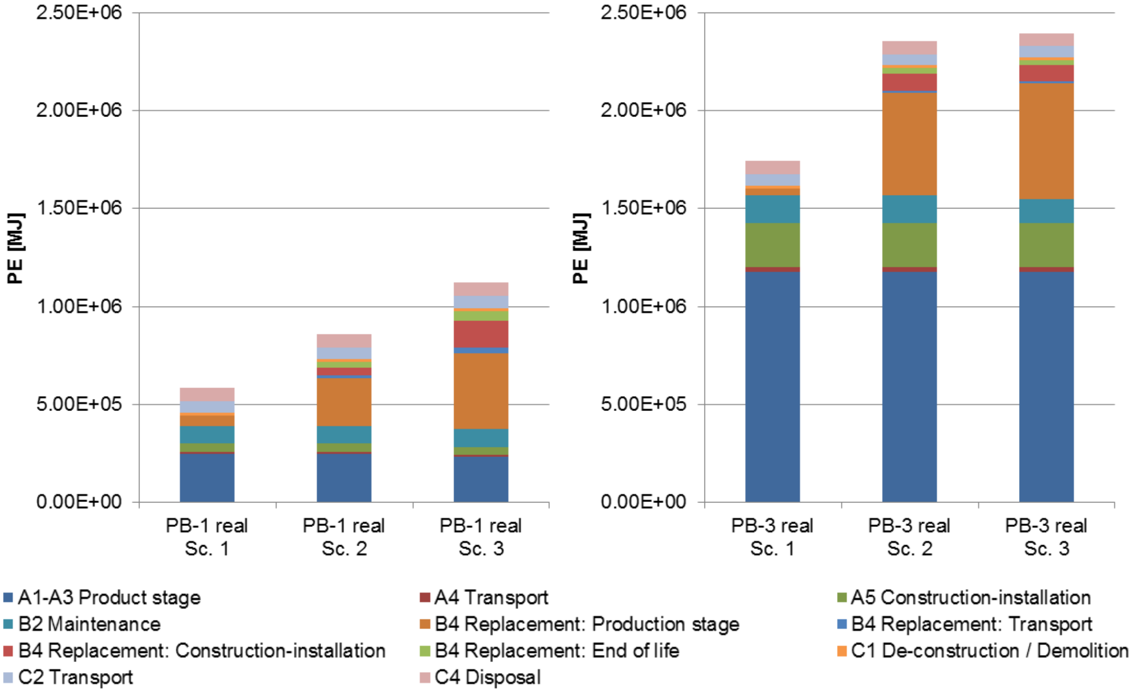
Total environmental impacts (structured according to EN 15978) related with PB-1 and PB-3 scenario combination most resembling reality in NRE impact category.



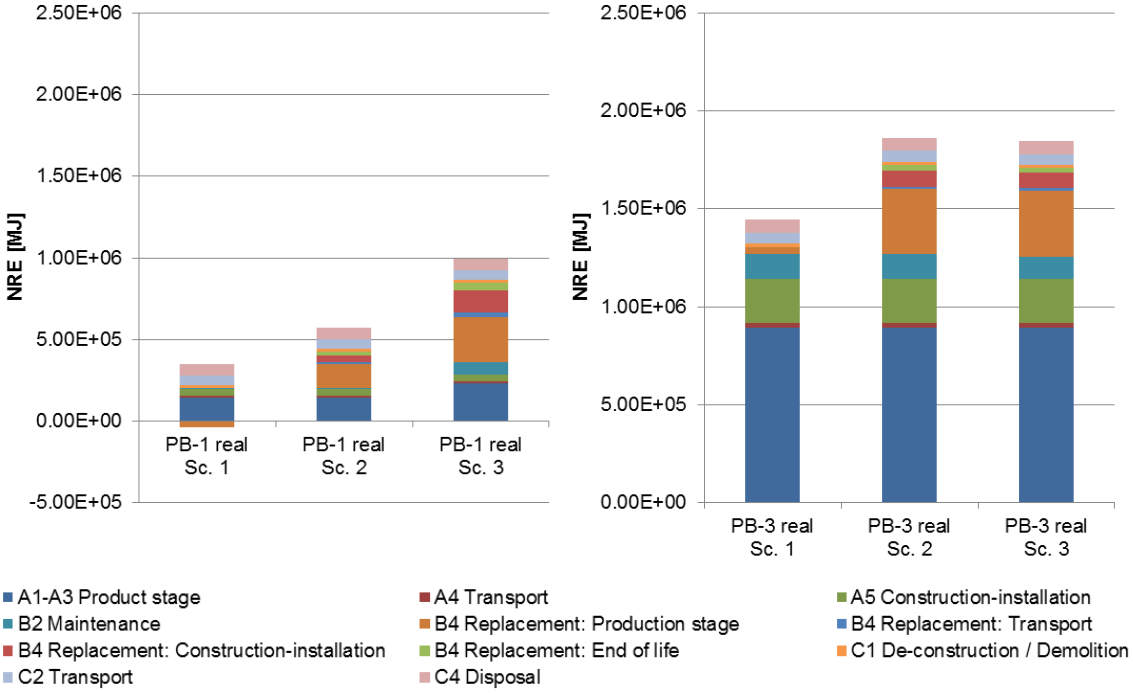
Total environmental impacts (structured according to EN 15978) related with PB-1 and PB-3 scenario combination most resembling reality in GWP impact category.



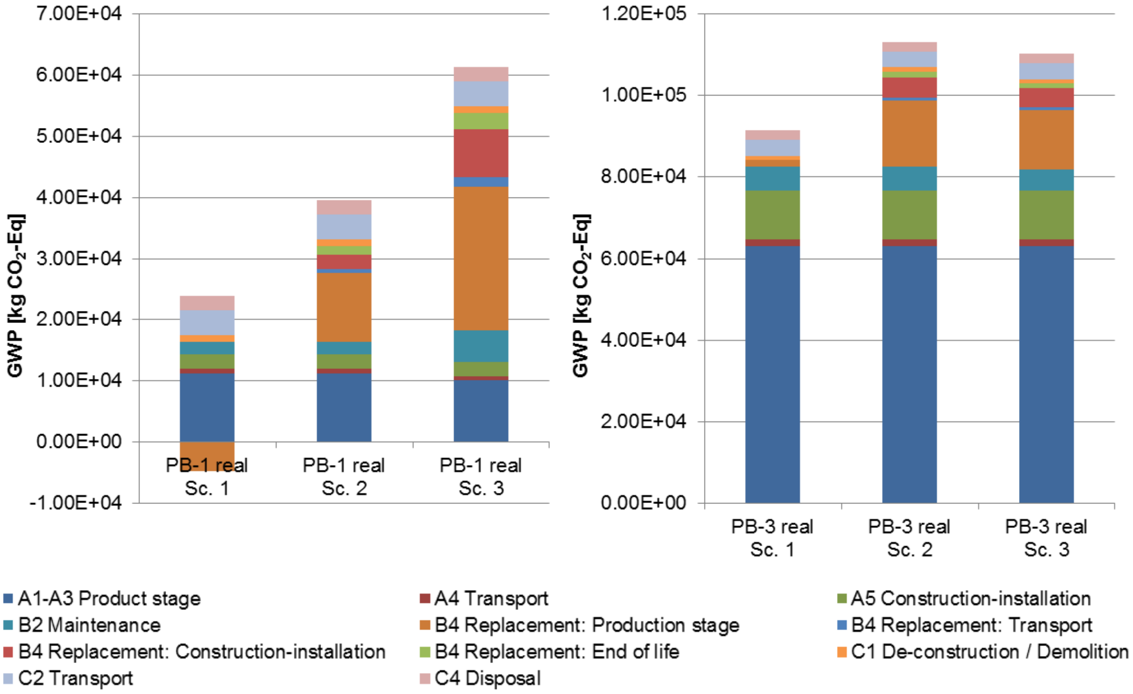
EEIs of PB-1 and PB-3 scenario combinations most resembling reality in UBP impact category. EEIs are structured according to EN 15978 with B4 module is further divided to increase clarity.



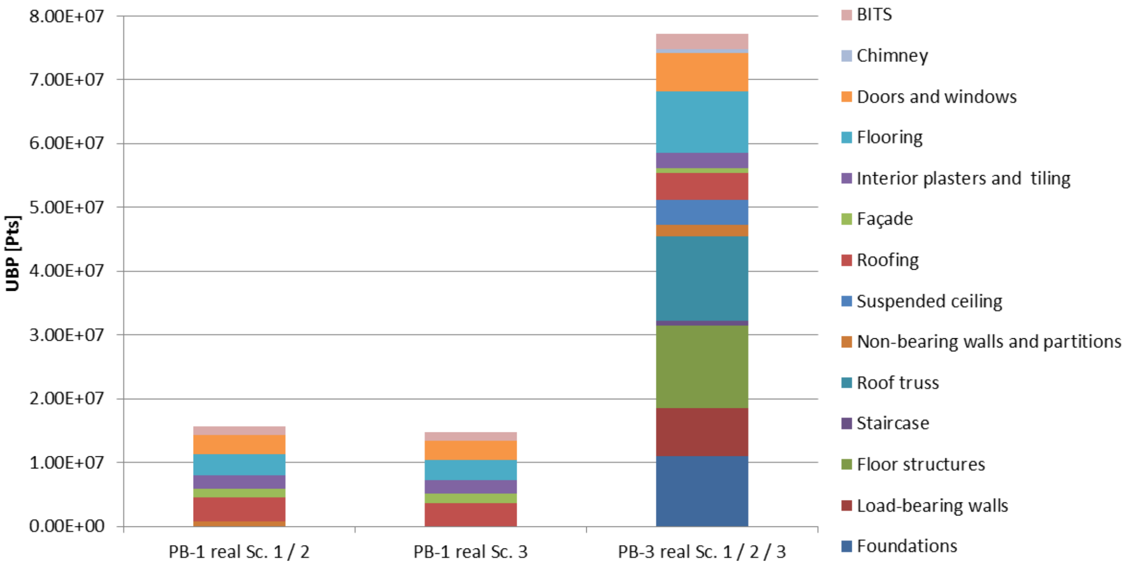
EEIs of PB-1 and PB-3 scenario combinations most resembling reality in PE impact category. EEIs are structured according to EN 15978 with B4 module is further divided to increase clarity.



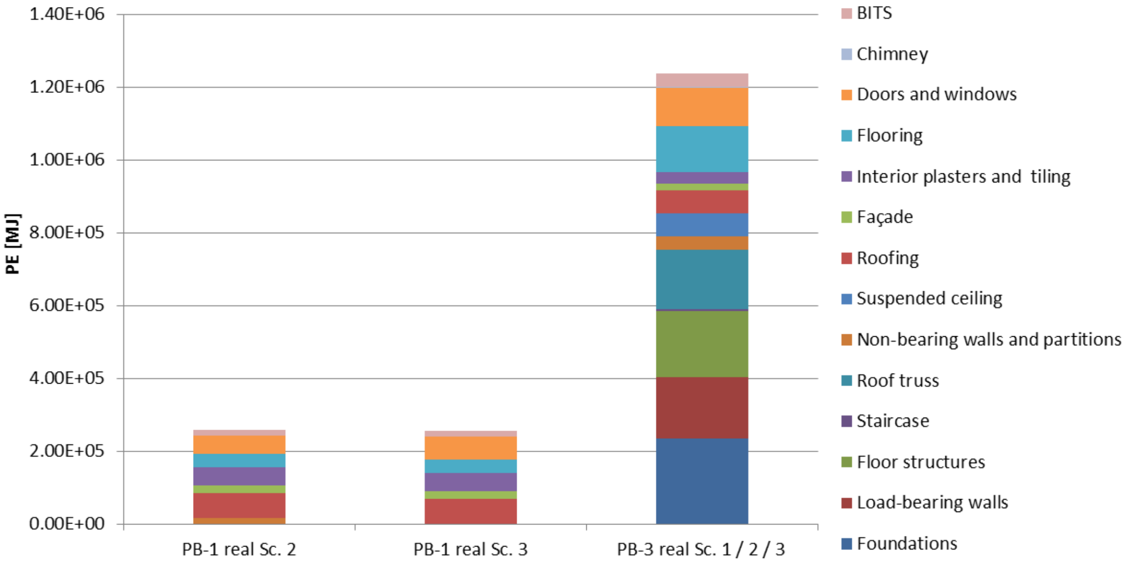
EEIs of PB-1 and PB-3 scenario combinations most resembling reality in NRE impact category. EEIs are structured according to EN 15978 with B4 module is further divided to increase clarity.



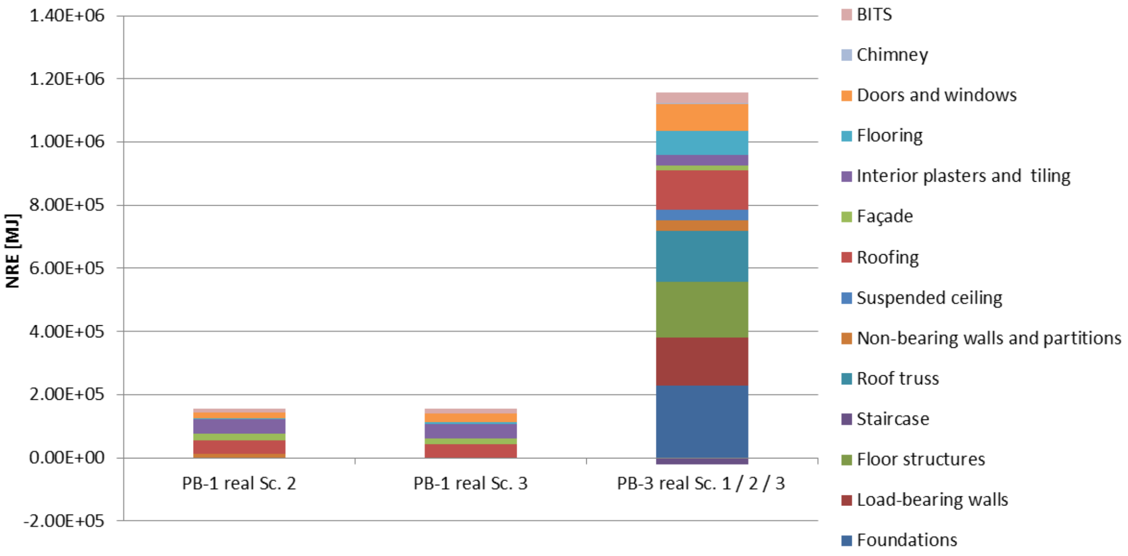
EEIs of PB-1 and PB-3 scenario combinations most resembling reality in GWP impact category. EEIs are structured according to EN 15978 with B4 module is further divided to increase clarity.



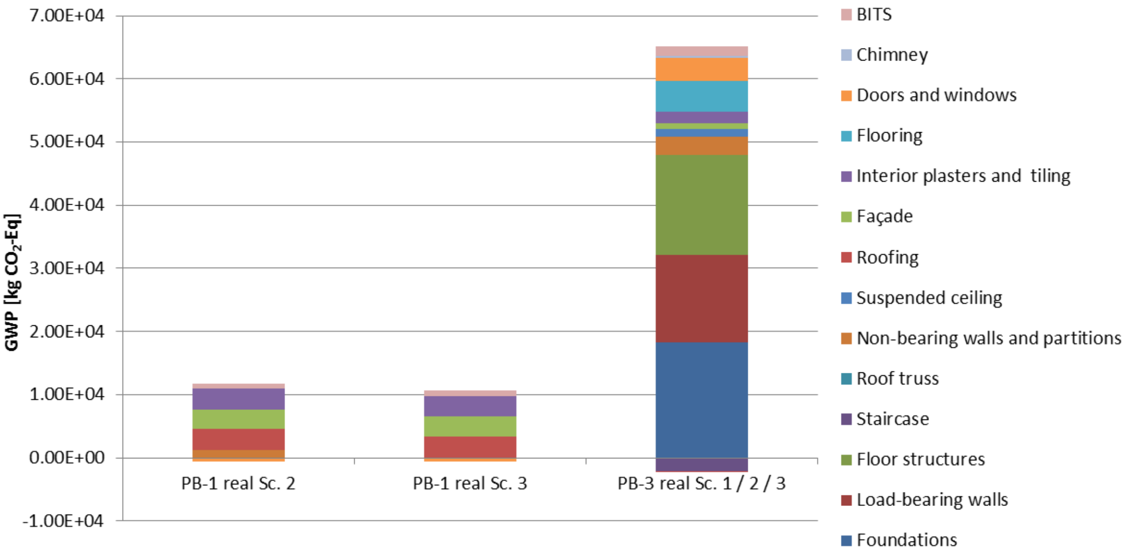
EEIs in UBP related with production of construction materials (modules A1-A3) considered in PB-1 and PB-3 scenario combinations most resembling reality. EEIs are divided between individual building elements. The chart is ordered according to Appendix A.



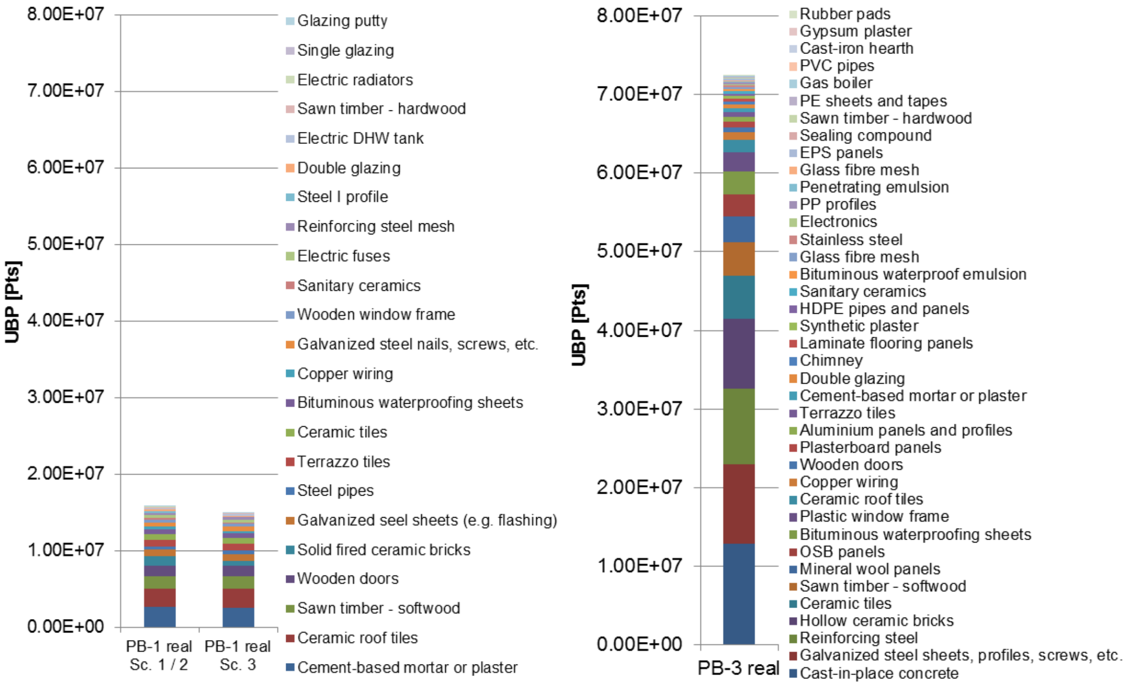
EEIs in PE related with production of construction materials (modules A1-A3) considered in PB-1 and PB-3 scenario combinations most resembling reality. EEIs are divided between individual building elements. The chart is ordered according to Appendix A.



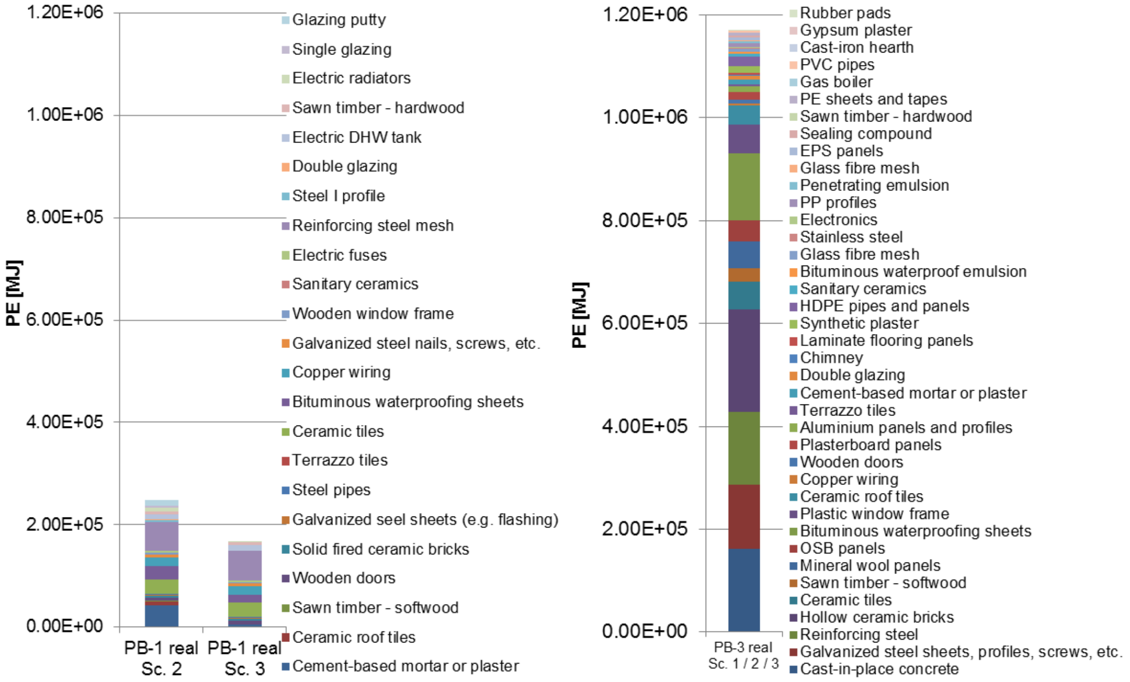
EEIs in NRE related with production of construction materials (modules A1-A3) considered in PB-1 and PB-3 scenario combinations most resembling reality. EEIs are divided between individual building elements. The chart is ordered according to Appendix A.



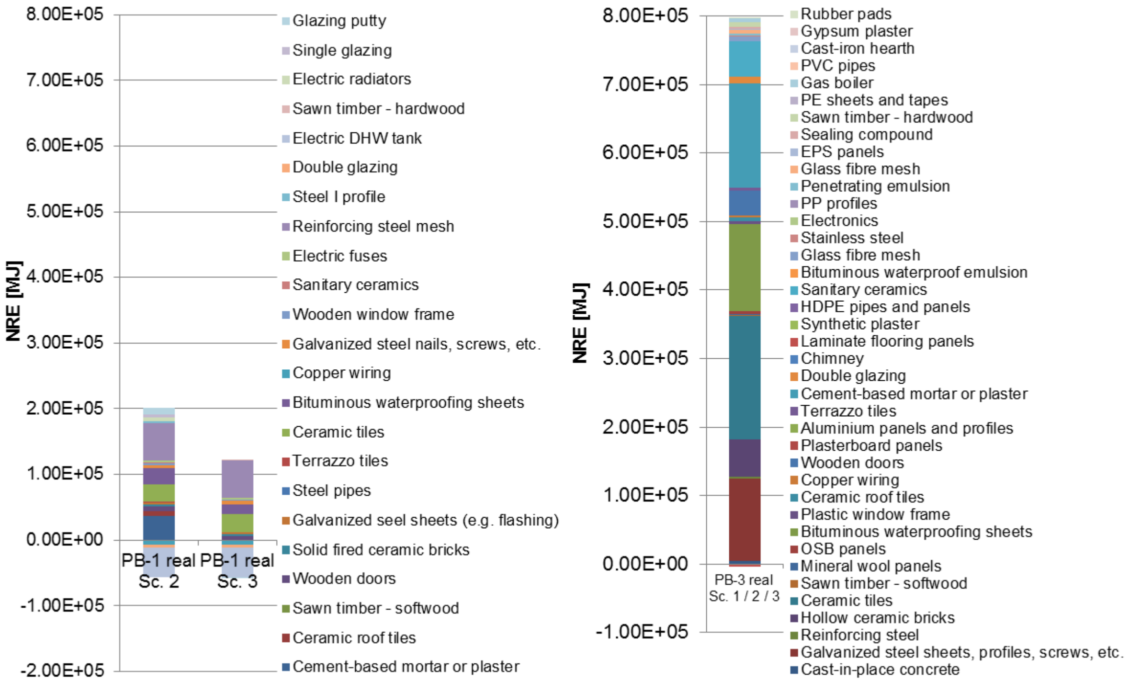
EEIs in GWP related with production of construction materials (modules A1-A3) considered in PB-1 and PB-3 scenario combinations most resembling reality. EEIs are divided between individual building elements. The chart is ordered according to Appendix A.



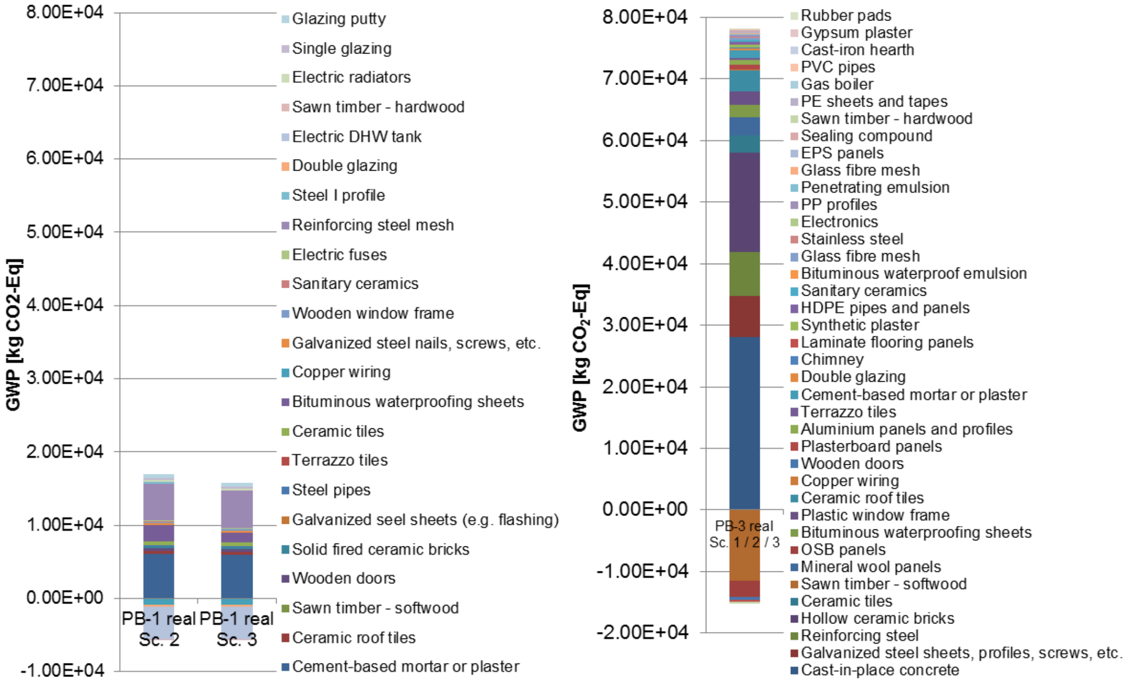
EEIs in UBP related with production of construction materials (modules A1-A3) considered in PB-1 and PB-3 scenario combinations most resembling reality. EEIs are divided between individual materials, which are ordered according to their shares on the total EEIs: highest to lowest.



EEIs in PE related with production of construction materials (modules A1-A3) considered in PB-1 and PB-3 scenario combinations most resembling reality. EEIs are divided between individual materials, which are ordered according to their shares on the total EEIs: highest to lowest.

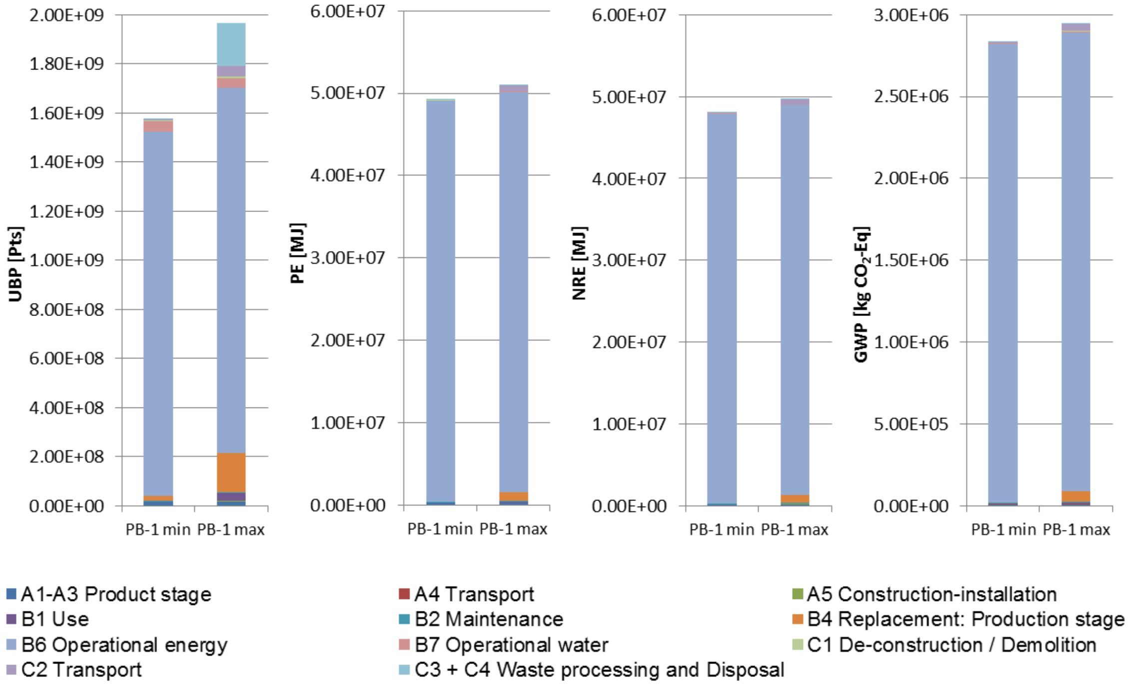


EEIs in NRE related with production of construction materials (modules A1-A3) considered in PB-1 and PB-3 scenario combinations most resembling reality. EEIs are divided between individual materials, which are ordered according to their shares on the total EEIs: highest to lowest.

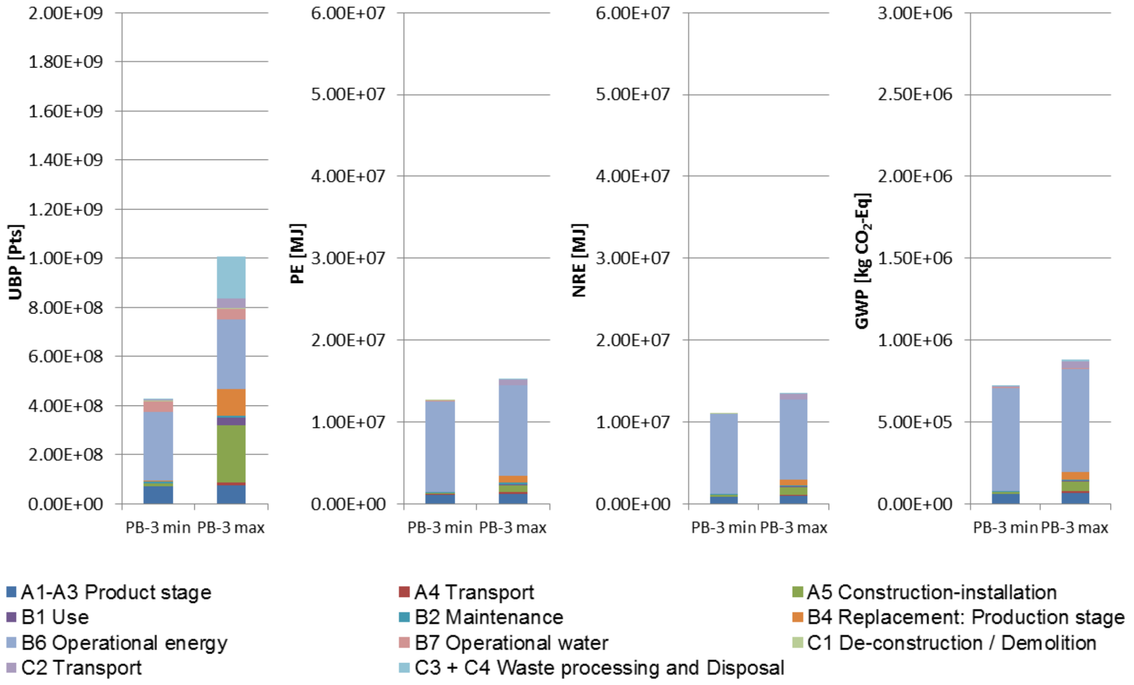


EEIs in GWP related with production of construction materials (modules A1-A3) considered in PB-1 and PB-3 scenario combinations most resembling reality. EEIs are divided between individual materials, which are ordered according to their shares on the total EEIs: highest to lowest.

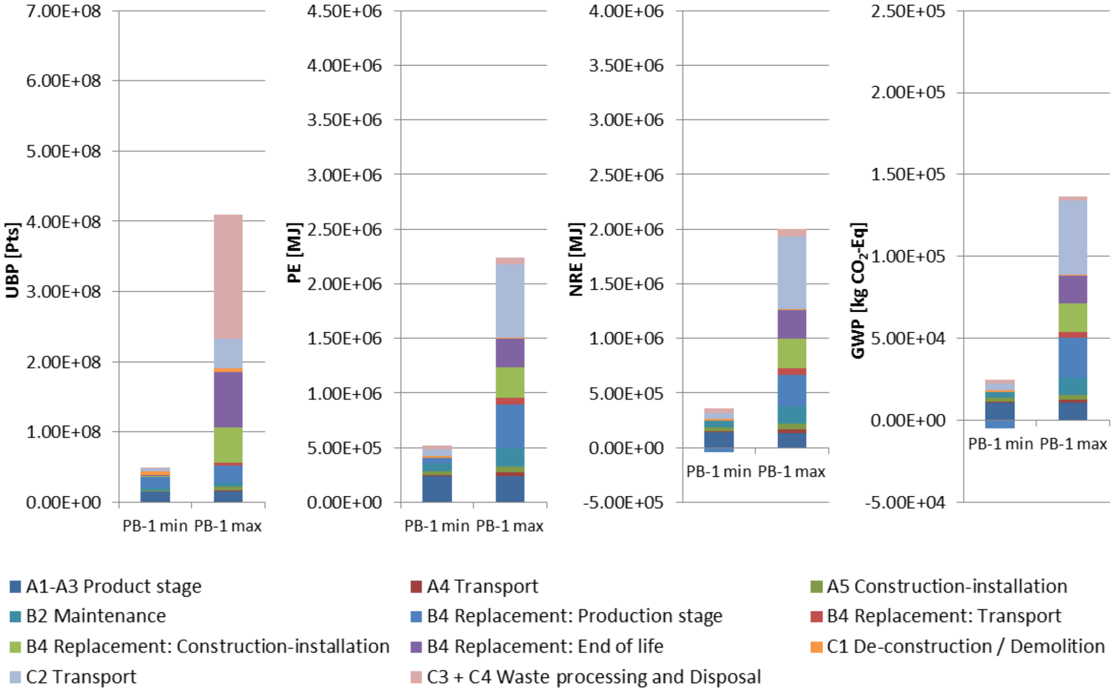
Environmental impacts of the best and the worst (in UBP) PB-1 and PB-3 scenario combinations



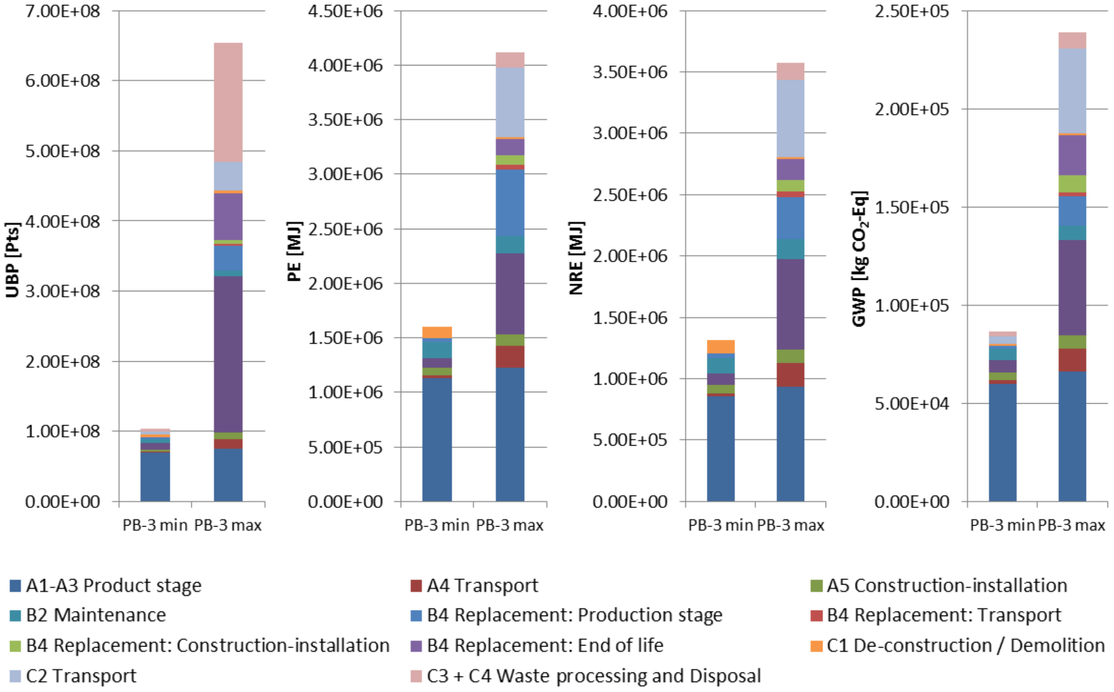
Total environmental impacts of the best (lowest) and the worst (highest) scenario combinations in PB-1 LCA study. The environmental impacts are structured according to EN 15978.



Total environmental impacts of the best (lowest) and the worst (highest) scenario combinations in PB-3 LCA study. The environmental impacts are structured according to EN 15978.



EEIs of the best (lowest) and the worst (highest) scenario combinations in PB-1 LCA study. The environmental impacts are structured according to EN 15978.



EEIs of the best (lowest) and the worst (highest) scenario combinations in PB-3 LCA study. The environmental impacts are structured according to EN 15978.