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Expanding the use of life-cycle assessment to capture induced impacts in the built environment

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Abstract

Current assessments of environmental impacts in the built environment focus on the individual building scale or the urban scale. Scientific evaluation of buildings predominately utilize life-cycle assessments and concentrate on two impacts categories: embodied and operational impacts. At the urban scale, research focuses on entire systems. However, to date the impacts resulting from the interactions between an individual building and the larger urban environment—induced impacts—have not been addressed. For the first time, the work quantitatively assesses induced impacts through analysis of the embodied and operational impacts of buildings at various locations within a metropolitan region. Thereby capturing the attributes of building type, building form, living space density, construction materials, structural systems, shared building walls with neighboring buildings, and area of heat transfer. The interaction with the urban environment through the building residents is subsequently captured through transportation impacts. The research therefore quantifies the embodied and operational impacts of transportation.

The results show that embodied impacts, accounting for building materials, vehicles, and infrastructure materials, constitute over 20% of all impacts. The cumulative results show that the city center has the lowest environmental impacts followed by the periphery and then the districts. Additionally, the work finds that transportation emissions make up 51, 50, and 47% of all emissions for households in the city center, on the city periphery, and outside the city, respectively. Given the significance of transportation emissions, these impacts must be accounted for in all locations within the metropolitan region. Induced impacts are found to make up 50% of total impacts. The detailed analysis of the impact categories for each location reveals that different strategies should be applied to each location within the metropolitan region. Outside the city, focus should be placed on heating demand reduction for single family houses. In the city center, electricity use is of critical importance. Finally, at the city periphery, attention should be paid to heating reduction and transportation. The work illustrates the importance of expanding the analysis framework for environmental performance of the building sector though the inclusion of induced impacts.

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Chapter 1

Introduction

1.1 Background and problem statement

Environmental research in the building sector focuses on two scales—individual buildings and the larger urban context (e.g., cities, metropolitan regions). Research on individual buildings concentrates on embodied impacts (i.e., raw material extraction, transport, production, manufacture, assembly, disassembly, deconstruction) and operational impacts (i.e., heating, cooling, hot water, electricity) [1, 2]. Energy use and greenhouse gas emissions are dominated by the operational phase of the building (approximately 85%) when compared to the embodied phase [1–5]. At the urban scale, research focuses on the impact of urban form, transportation systems, infrastructure, and residential density on environmental impacts [6, 7].

However, individual buildings are not isolated objects. Rather buildings are integrated into the surrounding built environment. Alternatively, focusing on an entire city ignores typical patterns of construction (i.e., renovation and new construction of buildings in existing cities). Environmental impacts from the building sector are thus not fully captured within current methodologies due to the absence of the interactions between the individual buildings and the larger urban environment. Therefore, a new methodology is required to assess actual construction patterns and to capture currently missing environmental outputs. This methodology needs to quantitatively assess the environmental impacts resulting from the interaction of an individual building and the built environment (induced impacts). The ability to meet environmental goals requires the quantitative assessment and evaluation of these induced impacts. The research hypothesis states:

If the environmental performance of a building is influenced by its interactions with the surrounding urban context, then achieving environmental objectives within the built environment requires the identification and life-cycle evaluation of induced impacts.

The hypothesis asserts that induced impacts produce significant life-cycle environmental impacts and must be considered along with the embodied and operational impact categories when analyzing the environmental performance of a building.

1.2 Research objectives

There are three goals of the research. The first goal of the research is to develop a new methodology to expand the use of life-cycle assessment (LCA) to more comprehensively analyze the environmental performance of the built environment. The second objective of the work is to quantify the environmental impacts for an actual scenario using the expanded methodology to capture the new category of induced impacts. The analysis will concentrate on the case study example of the *urban region of Munich*. The work will determine the magnitude of induced impacts compared to the typical impact categories of embodied and operational impacts for buildings. Finally, based on the quantitative results of the research, recommendations are given to improve the environmental performance of the built environment.

The work is of interest as it addresses actual patterns of construction—new buildings or building renovations within an existing urban context. The results of the research provide guidance to building designers, urban planners, and transportation engineers in understanding the environmental influences between individual buildings and the urban context. Further, the findings are of use to politicians, policy-makers, and citizens in setting and achieving environmental goals.

1.3 Organization of the thesis

The thesis is organized into nine chapters as follows. This chapter, Chapter 1: *Introduction*, provides the research objectives, and the organization of the thesis. Chapter 2: *Problem statement* presents the research motivation and the detailed problem definition. The chapter summarizes the state-of-the-art of scientific research in the area of building life-cycle assessment and energy analysis in urban systems. The assessment methodologies for both scales of research are also presented. From the literature review, the detailed problem definition for the research is formalized.

Subsequently, Chapter 3: *Methodology* presents the research methodology used for the work. Expanding upon the traditional methodology for life-cycle assessment of buildings, the research introduces the category of induced impacts to capture currently absent environmental impacts resulting from the interaction of a building and the surrounding built environment. The theoretical background for life-cycle assessment and the different assessments methods (i.e., economic input-output based, process-based, and hybrid) are then discussed. Finally, the life-cycle equations used in the work are presented.

The analysis and results for the embodied impacts of residential buildings are presented in Chapter 4: *Building embodied impacts*. The motivation and justification for the selection of three building case studies are presented. Statistical data and a market survey provide guidelines for the selection of the case studies. The case study buildings are then presented in detail. The first case study is a multi-family house, the second is a row house, and the third is a single family house. For the row house option, two scenarios are evaluated: a middle house with only two exterior walls, and an edge house with three exterior walls. This is due to the different material demands and the anticipated varying heating demands of the two buildings. The life-cycle assessment methodology for the building evaluations is then summarized, and the analysis software is presented. The chapter then gives the life-cycle assessment results for each case study, followed by a discussion, and a conclusion of the results.

Chapter 5: *Building operational impacts* covers the analysis and results of the operational use-phase of the case study buildings. The chapter begins with a review of energy standards in Germany and energy calculation equations. The required building characteristics to determine the operational demand of the buildings are then given. The calculation methodology, assumptions, and simulation results for building heating and hot water demand are then shown. This is followed by information on electricity demand. The operational results are then given and discussed. Finally, a sensitivity analysis examining the impact of renovation on both operational and embodied impacts is presented.

The embodied impacts for transportation are subsequently outlined in Chapter 6: *Transportation embodied impacts*. The chapter begins with the embodied emissions for transportation vehicles. This includes both private automobiles and public transportation vehicles (i.e., bus, tram, subway train, and suburban train). The chapter continues with the embodied impacts for the road network within the City of Munich. These results are then extrapolated to the surrounding districts to obtain the embodied impacts for the road network outside of Munich. Next, the impacts for the public transportation infrastructure are discussed. The chapter analyzes the tram, subway, and suburban train systems. The chapter then compares the infrastructure results for private and public infrastructure networks. Finally, the chapter combines the vehicle and infrastructure demands to compare the total embodied impacts of transportation.

The operational impacts from transportation are given in Chapter 7: *Transportation operational impacts*. The chapter discusses the data, an existing transportation survey conducted in Munich and published in 2008, used for the analysis. All steps of the data preprocessing are then presented, and any assumptions made are discussed. After reviewing the data preprocessing, the chapter summarizes the analysis methodology. A software program is written in *Python* to evaluate the extensive dataset and combine the transportation data with environmental impacts. This is followed by the results of the transportation operation assessment. The findings are verified with existing information from the original dataset. Then the travel distances and CO_2 emissions are given at the traffic cell, neighborhood, and the district level. Sensitivity analyses are then done for future emissions and the inclusion of long distance aircraft travel. The chapter ends with the conclusions of the analysis and a summary of the findings.

Chapter 8: *Results and discussion* combines and compares the results from all impact categories as determined in the previous chapters. Impact results are summarized for building embodied impacts, building operational impacts, transportation embodied impacts, and transportation operational impacts. The chapter summarizes the main findings of the cumulative results for three locations: the city center, the city periphery, and the districts outside the city. The major findings and points of interest are presented and discussed. The chapter then presents the results for the building renovation scenario. Sensitivity analyses are done for varying location of each building type and for specific household scenarios.

Finally, Chapter 9: *Conclusion* summarizes the research. The background motivation, problem statement, and research hypothesis are reviewed. The methodology for the research is given, as well as the data sources used in the work. The results for each impact category and the combined results are then discussed. The key findings and take-away points of the work are subsequently summarized. In concluding, the outlook for the current research is given. Recommendations for reducing environmental impacts from the built environment based on the research are presented, and suggestions for future research and areas for further study are given.

Chapter 2

Problem statement

2.1 Introduction

The built environment—accounting for the building and transportation sectors—is responsible for 62% of global final energy consumption (2009) [8] and 55% of greenhouse gas emissions (2004) [9]. Furthermore, the final energy consumption of these sectors is anticipated to increase between 20 and 44% from 2009 to 2035 for climate mitigation and business-as-usual scenarios, respectively [8]. In addition to the building and transportation sectors, the embodied energy and embodied emissions associated with materials (i.e., mining, manufacturing, processing, and transportation) must also be included to determine the full impacts of the built environment—the summation of all human-made structures, infrastructure, and transportation systems. The industry sector, which includes embodied material impacts among other sources, is responsible for 27% of final energy consumption (2009) [8] and generates 24% of greenhouse gas emissions (2004) [9]. Within the industry sector, cement and steel alone are responsible for around 5% (2003) [9, 10] and 6–7% of global CO_2 emissions (2002) [9], respectively. The built environment is consequently the dominate driver of global energy consumption and greenhouse gas emissions.

Addressing the ecological impacts from the built environment requires understanding global trends in this sector. In 2011, the world urban population was 52.1% and is forecast to increase to 58.0% by 2025 and 67.2% by 2050 [11]. The projected mass migration to urban areas illustrates the increasing importance of the built environment on total ecological impacts (e.g., climate change). This "second wave of urbanism" [12] will consequently demand new buildings and infrastructure. However, changes in the built environment will vary across regions. Worldwide construction (as a share of global construction spending) is anticipated to shift from Western Europe and North America to Asia [13]. The share of global construction spending will decrease from 35 to 24% in Western Europe and from 25 to 17% in North America, and will increase in Asia from 31 to 46% [13]. In Asia, annual construction spending will be the highest in India (8.9%), China (7.6%), and Japan (7.6%) [14].

In addition to the global trend of urbanization and construction shifting to Asia, specific changes in the global built environment are relevant for energy demand. First, mass urban migration will lead to African and Asian cities having the highest growth rates [12]. However, not every city will have linearly increasing growth in these regions, nor will all cities grow from small to big to mega-cities [12]. In fact, 40% of developing cities shrunk during the 1990s [12]. Second, this wave of urbanism results in the build-up of existing cities rather than creating new cities from scratch, yielding small and intermediate cities instead of mega-cities [12]. Between 1990 and 2000, 694 small cities (less than 100,000 persons prior to 1990) were established [12]. From these cities, 510 grew to small cities (population less than 500,000), 132 to intermediate cities (500,000 to 1 Mio.), and finally 52 to big cities (1 to 5 Mio.) [12]. The data show that 52% of urban populations live in small cities (less than 500,000 persons), further illustrating the importance of small and medium size cities [12].

In developed countries (i.e., countries in Europe and North America) increasing growth in the built environment occurs mainly in peri-urbanization areas (the space between urban and rural areas) [15]. While suburbanization is typically held to be a North American phenomenon, in Europe the growth rate in peri-urbanization is 3.7 times higher than growth in urban areas [15]. This trend holds dramatic implications for energy use in the built environment as the peri-urbanization is half as dense as urban areas. Peri-urban annual growth rates in Europe are 1.4–2.5% compared to 0.5–0.6% for urban areas [15]. In addition to illustrating where growth occurs in developed countries, these figures highlight the low overall growth rates in developed countries. These low growth rates are also captured in the small percentage of buildings constructed after 1990 in Europe (14% on average; varying from 8 to 22%) [16]. Consequently, developed countries exhibit low urban growth rates, growth in the low density periphery of existing urban centers, and a large supply of existing buildings.

The built environment is shown to be the dominate source of energy use and greenhouse gas emissions. Trends show that there will be significant growth to existing cities rather than construction of new cities. This paper answers critical outstanding questions regarding the future of environmental impacts in the built environment. A detailed analysis will present the major research areas, findings, and methodologies in this research field. The work identifies critical areas requiring further research, and finally offers insights into the future of research of environmental impacts in the built environment.

2.2 Energy use in the built environment—a question of scales

There is an extensive body of research concerned with energy use in the built environment. Energy use is discussed here as a proxy for numerous additional environmental impacts (e.g., CO_2 emissions). The research covers numerous disciplines including, but not limited to, architecture, city and regional planning, civil engineering, economics, environmental assessment and planning, sociology, and transportation planning. The theme of energy use in the built environment is often directly addressed (e.g., spatial analysis of urban energy [17]), but it is also indirectly analyzed (e.g., transportation demand and urban form [18]). Despite the breath of scientific inquiry in energy and the built environment, several main areas of investigation are identified.

The main research themes are *materials*, *architectural design*, *operational systems*, *structural systems*, *construction*, *density*, *transportation*, *infrastructure*, *urban form*, *consumption*, and *analysis methods*. The first topic area, *materials*, investigates the environmental impacts from construction materials [19], [20]. Focus is placed on evaluating the embodied impacts from traditional, new, alternative, and innovative materials (e.g., concrete with low CO_2 emissions) [21]. In addition, research covers material performance during the use-phase of a building [19, 20]. The second research area is *architectural design*. This field is concerned with the integration of renewable energy systems into buildings ([22, 23]) and the influence of building form on energy use [24]. Designing buildings to minimize operational energy demands (i.e., heating, cooling, lighting, ventilation, electricity) is covered under the third category: *operational systems*. This topic addresses both active systems and passive strategies for the operational energy demands of a building. Diverse research in this field include low-energy and passive buildings [25], new and innovative building operational systems [24], automation of building systems, and numerous other subfields. The area *structural systems* is concerned with the evaluation of different structural engineering solutions for buildings and their associated impact on the building's embodied energy [19, 20, 26]. *Construction* studies the energy resulting from constructing a building [27].

The research area *urban form* is one of the largest in the field of energy and the built environment. The wide spectrum of this field covers general city planning and compares alternative urban forms (i.e., cities, suburbs) [28]. The composition of urban space (i.e., mixed-use, single-use) is another main topic [29]. The area of *urban form* also covers the interplay and interaction with several other research areas: urban form and density [17], urban form and infrastructure, and urban form and consumption [30]. The next research field, *density*, addresses the topic of density within the built environment. Here, focus is typically placed on residential density [28, 30–33], but also encapsulates other density metrics (e.g., job density [34]). *Transportation* is the next research area in energy and the built environment. Focus here is on transportation infrastructure for various modes [35, 36], transportation system operations [37], and how urban form influences transportation [18, 38, 39]. The research topic *infrastructure* covers all non-transportation infrastructure found in the built environment. This includes water, telecommunications, sewage, heating distribution, and electricity distribution among others [40–42]. An emerging research field is the role of *consumption* in energy and the built environment. Here, the research boundaries of energy and the built environment are expanded to capture the consumption impacts from individuals [30, 43, 44]. Finally, the last research area is *analysis methods*. This vast research topic covers the identification, evaluation, review, and verification of assessment methodologies in capturing and quantifying environmental impacts [45–50].

Consequently, there is a wide spectrum of research investigating energy and the built environment, which can be classified into eleven overarching research areas. Upon review, the research areas are clearly delineated based on the scale of analysis: individual buildings and the larger urban scale. The first scale of analysis, the individual building scale, is concerned only with the building itself and omits any relationship of the building to the larger built environment. The research areas covered by the building scale are *materials*, *architectural design*, *operational systems*, *structural systems*, *construction*, and *analysis methods*. The second scale of analysis, the urban scale, focuses on entire systems within the built environment rather than individual elements such as buildings. The topics at the urban scale are *urban form*, *density*, *transportation*, *infrastructure*, *consumption*, and *analysis methods*. The research areas and their scale of analysis are summarized in figure 2.1. The analysis of the main research areas reveals that there is a stark differentiation between the level of analysis for research in energy and the built environment. Only the research field of *analysis methods* spans the building and urban scale divide. This field is concerned with assessment methods for quantitatively determining environmental impacts.

Research Areas	Scale of Analysis
Materials Architectural design Operational systems Structural systems Construction Analysis methods	Building scale
Urban form Density Transportation Infrastructure Consumption Analysis methods	Urban scale

Figure 2.1: Overarching research areas within energy and the built environment illustrate a clear delineation based on the scale of analysis.

Through summarizing the main areas of research in energy and the built environment, a stark separation between the scales of analysis is identified. Building upon this revelation, the next section explores the major findings at each scale of analysis in detail. Next, a detailed review of analysis methodologies is given for the building and urban level. Finally, having found an absence of research bridging the individual building and urban scales, the paper identifies new areas for research on energy and the built environment.

2.3 Major findings

This section presents the critical findings from research in the field of energy and the built environment. Instead of listing all findings of this vast research topic, focus is placed on presenting the key results to identify critical issues and illuminate where future research should focus. The analysis is presented for both the building and the urban scale.

2.3.1 Building scale

Research on energy use and the built environment at the building scale is summarized in six categories: *materials*, *architectural design*, *operational systems*, *structural systems*, *construction*, and *analysis methods*. *Materials* research concentrates on new, alternative, innovative, and renewable materials for building construction [19], [20]. Research shows that attention should be paid to structural materials rather than architectural materials, as these materials dominate (77%) the total material energy demand [51]. Accordingly, significant research focuses on reducing carbon dioxide emissions in cement production—the binding material in concrete [10]. The vast quantities of concrete used annually, the high emissions from cement production (5% of anthropogenic CO_2 emissions), and the reliance of the construction industry on concrete are other key motivations for this research [10]. The findings show that attention should be placed on cement substitutions (e.g., fly ash) [21, 26]. By 2050 the cement industry could reduce its direct emissions by 18% [10]. Bridging the areas of *materials* and *structural systems*, analysis of structural systems (e.g., moment frames, shear walls) avoids the illogical comparison of materials on a simple weight basis. The literature shows that irrespective of the building's structural material (i.e., steel, concrete, or wood) and structural system, the relative percentage and total energy is largely consistent [19, 20] (figure 2.2 on the next page and figure 2.3 on page 11).

Research in *architectural design* and energy use covers a wide spectrum of issues including building shape (e.g., compactness, shape factor), orientation, building envelope, shading, passive systems (cooling, heating), and glazing [24]. Useful strategies are traditional design methods: courtyards [52], daylighting, [53], natural ventilation [54], building orientation [55], and thermal mass [56]. Findings are dependent on the local climate conditions and thus uniform results are not possible. However, it has been found that building orientation, shape, and the surface-area-to-volume-ratio are the most important factors [24].

Operational systems cover active and passive systems used for climate control in buildings. The overriding take-away message from this research area is the relative importance of operational energy compared to embodied energy over the lifespan of the building. Material research compares the embodied energy from different structural materials (e.g., concrete, steel, wood), and also the operational energy for a building with a given structural system [21, 57–63]. The literature mainly shows that the primary energy of a building is dominated by the operational phase compared to the embodied phase (i.e., 85% versus 15%) [1, 19, 20, 27, 64] (figure 2.4 on page 11). However, more extensive assessment methods have shown that embodied emissions can make up to 45% of total energy demand over a building's lifespan [65]. As expected, low-energy (i.e., operational energy) buildings are found to transfer energy use from the operational to the embodied phase [25]. *Structural systems* were discussed above and are strongly tied to materials. The energy for the construction phase shows the very minor impact (around 2%) from building construction [27]. Thus, the research area *construction* is of only minor significance in total energy use.

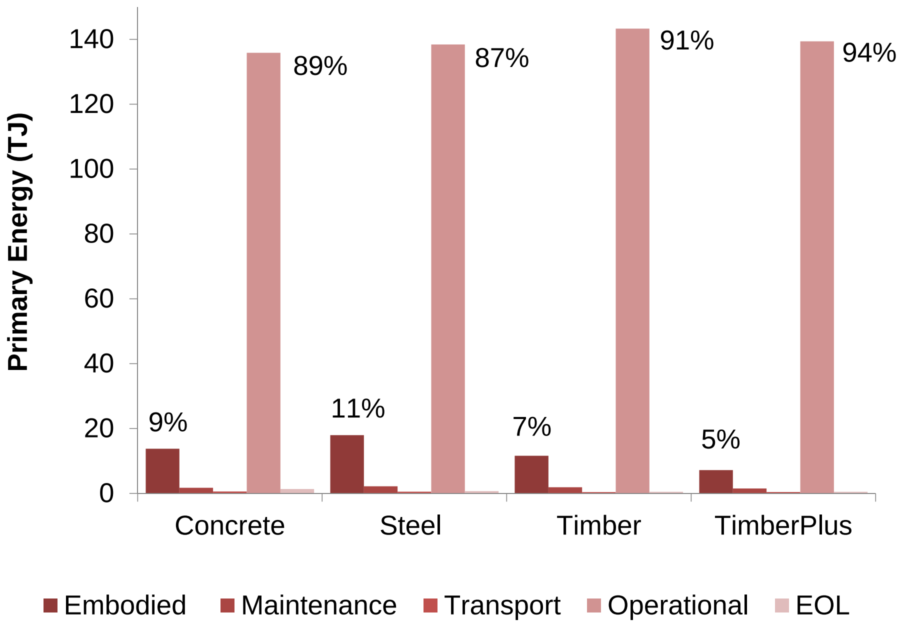

Figure 2.2: The choice of the structural material and associated structural system has a negligible influence on primary energy for the embodied, maintenance, transport, operational, and end-of-life (EOL) phase of a building [19]. Values not shown are under 1%. TimberPlus has a timber structure similar to Timber, but also incorporates wood products for architectural features (e.g., exterior claddings, windows, ceilings).

The final major research area at the building scale, *analysis methods*, concentrates on methodological development and quantification of impacts. Methodology development is concerned with improving the accuracy and computational time of assessments, capturing indirect outputs, and verifying results among numerous additional goals [66–69]. Applying these methods to case studies to determine actual results and recommendations for energy use reduction are captured in quantification analysis studies [27, 51, 70–72]. While there are numerous assessment methods (e.g., statistical models, eco-footprints, simulations) [73, 74], life-cycle assessment is the predominate methodology for quantitative assessment of buildings over their entire lifespan accounting for upstream impacts [42]. The exact methodologies will be discussed in the subsequent section.

In addition to specific research results, the energy categories assessed at the building level are illustrative. Energy use in the built environment at the building scale is classified as either embodied or operational energy. Embodied impacts are the impacts from raw material extraction, transport, production, manufacture, assembly, disassembly, and deconstruction. The materials, their transport, and the construction process of any repair, retrofit, or renovation are also included in the embodied impacts. Operational impacts result from the daily use of the building including electricity, water, water-heating, ventilation, heating, and cooling. These

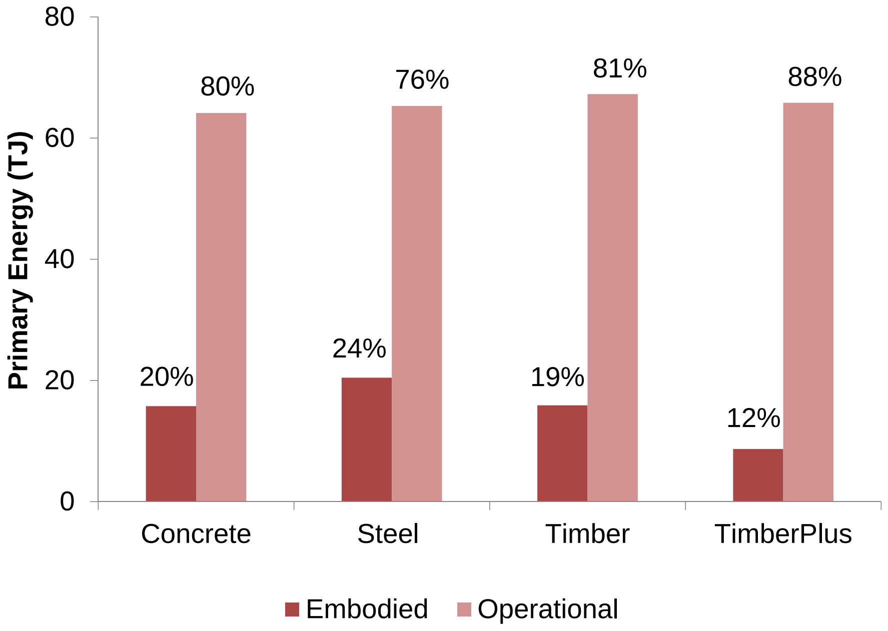

Figure 2.3: Results showing the minor impact of the structural material and associated structural system on primary energy for embodied and operational impacts [20].

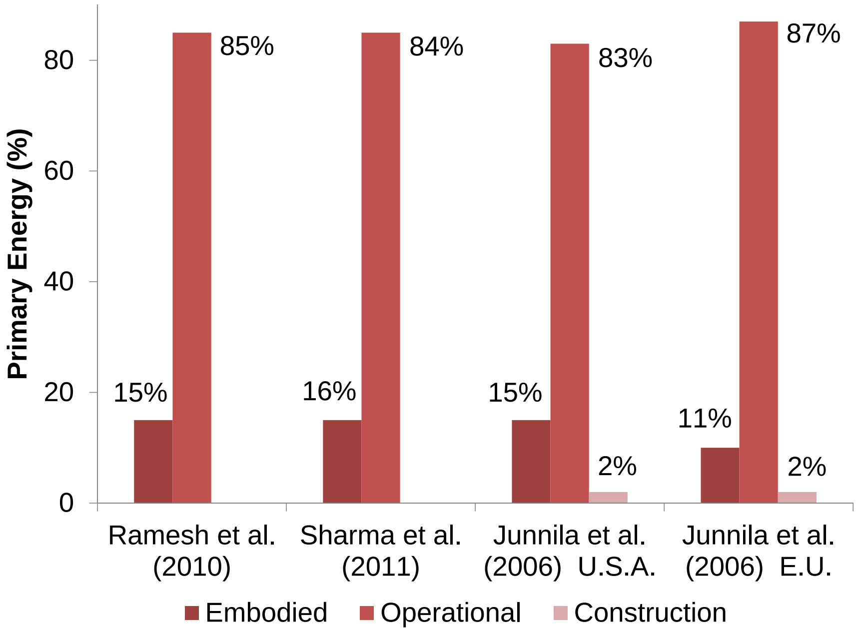

Figure 2.4: Operational energy dominates life-cycle energy compared to life-cycle embodied energy [1, 27, 64].

categories are useful in comparing the relative importance of each as noted above, and to provide recommendations for reducing the energy demand in buildings.

2.3.2 Urban scale

The second level of analysis for energy use and the built environment is the urban scale. Research at the urban scale is summarized in six areas: *urban form*, *density*, *transportation*, *infrastructure*, *consumption*, and *analysis methods*. The first research topic, *urban form*, is extensive and covers all topics relating to the influence of urban form on energy use. Key findings show that households in urban centers have lower carbon dioxide emissions (a proxy for energy use) than suburban locations [17, 32, 75, 76]. However, it has been shown that the vast amounts of suburbanization in large metropolitans can cancel out any reductions in emissions in the urban core [17]. Another major finding is that urban areas contain households with both the highest and lowest carbon dioxide emissions, which are strongly based on socio-demographic factors [75].

The second research area, *density*, focuses primarily on the impact of residential density on energy use within urban regions [28, 30–34, 38, 77, 78]. While these studies tend to show that low-density neighborhoods are more energy intensive than high-density neighborhoods, qualifications are required (see table 2.1 on the facing page). In general, detailed analysis shows that the influence of density on carbon dioxide is limited and can vary significantly among households in similar density locations due to socio-economic factors [75].

The third area of research at the urban scale is *transportation*. This covers transportation infrastructure, transportation system operations, and the interplay between urban form and transportation. In addition to the traditional focus on the operation stage of transportation, infrastructure for transportation systems is shown to have a significant impact on overall environmental impacts [35]. Transportation infrastructure is responsible for an additional 63% for on-road, 155% for rail, and 31% for air systems energy compared to operational energy [35]. However, operational energy demand continues to play a significant role in research and practice. Transportation system operations focuses on operational emissions of different systems (e.g., public transportation) [37], and emission modeling allows for comparisons between systems [79]. Finally, *transportation* researches the interplay between urban form and transportation. This includes diverse topics including, but not limited to, vehicle miles traveled, mode use, driving behavior, self-selection, and neighborhood type [29, 38, 80–88]. The major findings from this extensive research field will be briefly discussed. First, research has found a strong correlation between urban development densities and transportation energy use across different global cities [82]. A detailed review of travel and the built environment found that travel distance is most strongly correlated to accessibility and secondarily to street network design [89]. Unexpectedly, only a weak correlation between population and job density and travel behavior was found once other factors had been accounted for [89].

In addition to transportation infrastructure, the research area of *infrastructure* is an emerging field covering all other forms of physical infrastructure within urban environments. Two main research focuses here are water infrastructure [40, 41] and energy production systems [42]. Energy consumption from urban water systems shows that 80% of total primary energy is due to water heating and only 20% is required for waterworks and treatment [41]. Infrastruc-

Table 2.1: Urban scale energy use—summary of significant findings regarding density

Urban variable	Location	Key findings	Ref.
Residential density (low and high)	Toronto, Canada	Low-density more energy and GHG intensive (factor of 2.0–2.5 per capita), (factor of 1.0–1.5 per m^2)	[31]
Residential density (low, medium, and high)	Adelaide, Australia	Urban form characteristics of dwelling type and density are not sufficient to ensure lower energy use or GHG emissions.	[77]
Residential and commercial density	N.A.	Increasing residential density may increase emissions if it causes relocation of firms.	[34]
Residential density (low and high)	U.S.	1) Nationwide data illustrates a small difference in energy between compact and urban residential. 2) Energy savings from compact living were mitigated through increased spending on other goods. 3) Sprawl is 17–19% more energy intensive than compact living.	[33]
Residential density (low and high)	Helsinki, Finland	GHG emissions in the suburbs are lower than the city center (per capita) due to the higher standard of living and higher consumption.	[30]
Residential density (low and high)	U.S.	1) Cities have lower emissions than suburbs. 2) The city–suburb gap is largest in older areas (e.g., New York City).	[32]
Residential density (low and high)	Sydney, Australia	1) High density has lower transit energy per capita. 2) Effect of housing density on residential energy use is unclear.	[45]

ture for energy systems (e.g., wind turbines) focus on the embodied energy required for such systems, which allows for a comprehensive analysis in combination with operational impacts [42].

The fifth research area is *consumption*. Moving beyond the materials of the built environment, the focus on consumption determines the energy implications of building users through their consumption patterns. These studies illustrate the large energy impacts of consumption [90–93]. Life-style choices through consumption are shown to be sufficient to override energy savings from dense living [30, 44]. This research has been expanded to assess how urban form affects lifestyles and, consequently, greenhouse gas emissions [94, 95]. While emissions from transportation and housing energy decrease slightly with higher density, these reductions can be easily offset by indirect lifestyle emissions [94]. Further, on a per capita basis, in less dense areas larger family size can offset the advantage of denser living [95].

The sixth, and final, area of research at the urban scale is *analysis methods*. Analysis includes the quantification of energy use for the urban setting [32, 96–98], transportation infrastructure [35, 36, 99, 100], water infrastructure [91], and the construction sector [101]. This area also includes research into the modeling of energy use of the urban system [45–50], and innovative methodologies to expand the scope of analysis [102]. Specific methods used for energy assessment at the urban scale are presented in the following section.

Similar to the building level, the major findings at the urban scale can be summarized into six energy categories. At the urban level the energy categories are embodied, operational, transportation, and consumption. Attributes of the urban context which affect energy use are buildings (embodied and operational energy), transportation (transportation energy), infrastructure (embodied and operational energy), and consumption (consumption energy). There is an overlap of embodied and operational energy from the building level, and a simultaneous expansion to the categories of transportation and consumption.

2.4 Analysis methods

As noted, research in *analysis methods* is the one common area of research between the building and the urban scale. This is due to the fact that methodological development for environmental analysis is applicable at various scales. The main difference between the building and the urban scale is the analysis boundaries. This section presents the common analysis methods for both levels and summarizes dominate and proven methodologies.

2.4.1 Building scale

While there are numerous analysis methods for the environmental performance of buildings, life-cycle assessment has proven to be the predominate methodology. Life-cycle assessment assesses the environmental impacts over the entirely of a product's lifespan. The international standard ISO 14040 provides the principles and framework and ISO 14044 gives the requirements and guidelines for conducting an LCA [103, 104]. For the analysis of buildings, LCA is the clearly accepted scientific methodology [21, 27, 51, 58, 59, 61–63, 70, 105, 106]. LCA is used both for embodied energy of construction materials, as well as the operational phase where energy sources are evaluated for all upstream impacts.

Research in *analysis methods* has led to the development of several different types of life-cycle assessment. Economic input-output LCA utilizes economic relationships between sectors to capture all impacts [69], [106]. Research also covers tiered hybrid LCI [107] and hybrid LCI models [65]. Process-based LCA, economic input-output LCA, and hybrid LCA are all used to determine energy use [21, 27, 51, 58, 59, 61–63, 70]. In order to determine the amount of energy demand during the operational phase of a building, energy modeling is utilized prior to LCA analysis [68]. The major energy analysis methods at the building scale and associated critical references are given in table 2.2.

Table 2.2: Building scale methodologies.

Methodology	References
Life-cycle assessment (incl. life-cycle energy analysis) (process-based, input-output, hybrid)	[65, 108–111]
High resolution statistical model	[112]
Life-cycle eco-footprint	[113]
Climate simulations	[73]
Simulation/ data set analysis	[68]
Integrated criteria weighting framework	[74]

2.4.2 Urban scale

Assessment methodologies for urban scale energy use are very similar to the methods used at the building scale. Life-cycle assessment is again a dominate method for urban level analysis. The range of life-cycle assessment methods is vast and includes hybrid global multi-region input-output models [75], environmentally extended input-output LCA (EE IO LCA) [94], input-output LCA [95, 114], hybrid LCA [43], IO analysis and spatially resolved household expenditure data [76], and consumption based EE IO models with expenditure data [115, 116].

In addition to life-cycle assessment, energy at the urban scale is analyzed indirectly with urban simulation models [49, 50] and agent-based transportation simulation models [88]. Heat island modeling is another assessment tool used at the urban scale, which illustrates a first approach to integrating individual buildings and the larger urban context [117, 118]. The predominate analysis methods for energy and the built environment at the urban scale are summarized in table 2.3.

Table 2.3: Urban scale methodologies.

Methodology	References
Input-output life-cycle assessment	[43, 75, 76, 94, 95, 114–116, 119]
Econometric models	[17]
Scenario analysis	[120–122]
Structural equation modeling	[89]
Survey data analysis	[82, 98]
Urban metabolism	[115, 123]
Complex systems approach	[115]
Comparative multivariate analysis	[124]
Survey based GHG accounting	[125]
GHG inventory analysis	[96]
Spatial analysis	[17, 126]
Community wide GHG accounting	[127]
Material flow	[128]
Eco-efficiency	[129]
Computed elastices, weighted average	[18, 39]
Building stock model	[130]

2.5 Problem definition

Research on energy use and the built environment focuses on the individual building or the larger urban context. While this division is useful for creating analysis boundaries for the complex system that is the built environment, two fundamental problems arise. First, analysis at the individual building level treats the building as a stand-alone object, isolated from its context within the built environment. In reality buildings are connected to their surroundings through physical means (e.g., infrastructure) as well as through their users (e.g., residents, workers). These interactions need to be quantitatively evaluated for environmental implications. Second, research at the urban scale recommends actions appropriate for the urban scale (e.g., large urban retrofits, constructing new cities), which are rare in undertaking.

A new methodology is therefore needed which addresses actual patterns of construction: construction of new buildings within an existing urban context. This work focuses on the interactions between an individual building and its larger urban context. A new methodology is required to assess a new impact category, *induced impacts*, in addition to the standard categories of embodied and operational impacts. The new category of induced impacts represents the impacts resulting from the interactions between an individual building the larger urban environment. The quantitative analysis of these interactions using established assessment tools ensures that all impacts are captured and that environmental goals can be met. Having identified a potentially critical, and currently missing, impact category, the next chapter presents an expanded methodology to quantitatively assess induced impacts.

2.6 Conclusion

The built environment is the dominate source of energy consumption and greenhouse gas emissions. Further, the construction sector will continue to grow and global trends indicate the increasing importance of urban areas, particularly in developing countries. The data shows that construction growth will focus on the expansion of existing cities. Significant research has accordingly been conducted investigating the role of the built environment in energy use. The main research areas in this field are *materials*, *architectural design*, *operational systems*, *structural systems*, *construction*, *urban form*, *density*, *transportation*, *infrastructure*, *consumption*, and *analysis methods*. The analysis shows that these topics are strongly divided into two scales of analysis: the building scale and the urban scale.

Consequently, a new research methodology is required to bridge the knowledge gap between the building and urban scale. An expanded analysis framework to account for the interplay between the building and city level can be captured through a new impact category: induced impacts. A new methodology to quantitatively determine induced impacts in the built environment is outlined in the following chapter. Using this expanded methodology and a case study, the assessment of induced impacts will reveal their significance on total environmental impacts.

Chapter 3

Methodology

This chapter addresses the research problem statement by proposing an expanded methodology to identify and capture the new impact category of induced impacts within the built environment. The work contributes to existing scientific research by both defining induced impacts and identifying a means to capture them in the built environment. The methodology expands upon the well-accepted life-cycle assessment framework for environmental analysis. Induced impacts are captured through two means. Indirect induced impacts are determined through varying household locations within an urban region, specifically, in the city center, city periphery, and outer districts. Direct induced impacts are assessed through transportation embodied impacts and transportation operational impacts.

Through an integrated approach, the methodology quantifies building embodied, building operational, transportation embodied, and transportation operational impacts using a life-cycle assessment. The methodology is then applied for the case study of the *urban region of Munich*. Background information on the various types of life-cycle assessments is presented, in addition to the formulas used for the subsequent case study analysis.

3.1 Introduction

The previous chapter illustrated the central importance of the built environment in global environmental impacts. Of particular note is the projected future growth in the built environment. However, the previous chapter also identified the problem that current assessments of the built environment are strongly divided between building level and urban level analysis. Based on this, environmental impacts in the built environment omit the interaction of individual buildings with the surrounding urban context. Thus a new impact category, induced impacts, is required to capture the additional environmental impacts between the individual building and urban context levels. Having identified a potentially critical, and currently missing, impact category, an expanded and integrated methodology to quantitatively assess induced impacts is required.

3.2 Expanding the use of life-cycle assessment

As discussed in Chapter 2: *Problem statement*, research to date focuses on the individual building or the larger urban context. However, this is problematic because it treats buildings as objects isolated from their urban context and ignores actual construction patterns. Therefore, a new category of impacts, induced impacts—the interactions between an individual building the larger urban environment, must be captured through an expanded methodology.

In developing a new methodology to quantify induced impacts, the traditional impact categories of embodied and operational impacts are retained. However, these impacts are dependent on many attributes: building type, building form, living space demand, construction materials, structural systems, shared building walls with neighboring buildings, and area of heat transfer. All these attributes of a building have a potentially significant influence on the embodied and operational impacts of a building. These attributes represent indirect induced impacts—they are influenced by the urban form and the location of a building. In order to capture these indirect induced impacts, buildings can be evaluated at different locations throughout a metropolitan region; thereby, quantifying the influence of location on these attributes. Thus, capturing indirect induced impacts requires selecting and evaluating individual buildings at various locations within an urban system.

Building level analysis based on the location of the building has the advantage of having the building as the unit of reference. This allows for calculations based on both building size (i.e., square meters) and living space demand (i.e., m^2/person). Using the building as the reference unit, the direct interactions of the individual building with the urban environment can be captured through transportation of the building users: direct induced impacts. Mobility is a fundamental requirement for access, interaction, and participation in the various functions of society. Thus, transportation serves as a critical metric for the interconnection of the individual building and the surrounding urban environment. The methodology will focus on residential buildings, which are the home for the building users. Consequently, the building residents' interactions with the urban environment can be captured through transportation impacts. These impacts are termed direct induced impacts. This allows a comparison on the same reference unit—the residential building. Here the metric of comparison will be per person in order to compare results between the building and transportation. The research methodology therefore quantifies the embodied and operational impacts of transportation as a proxy for direct induced impacts.

As summarized in Chapter 2: *Problem statement*, life-cycle assessment is the predominant environmental analysis methodology for scientific research of the building sector. Therefore, the research will also extend upon the life-cycle assessment methodology to address the research scope and prove or disprove the research hypothesis. A total of four impact categories will be analyzed: building embodied impacts (B_E), building operational impacts (B_O), transportation embodied impacts (T_E), and transportation operational impacts (T_O). Traditional life-cycle assessment research currently covers only the categories of building embodied impacts and building operational impacts. The results for the four impact categories will be tied back to the building for each location evaluated. The schematic methodology to capture and evaluate induced impacts in the built environment is shown in figure 3.1.

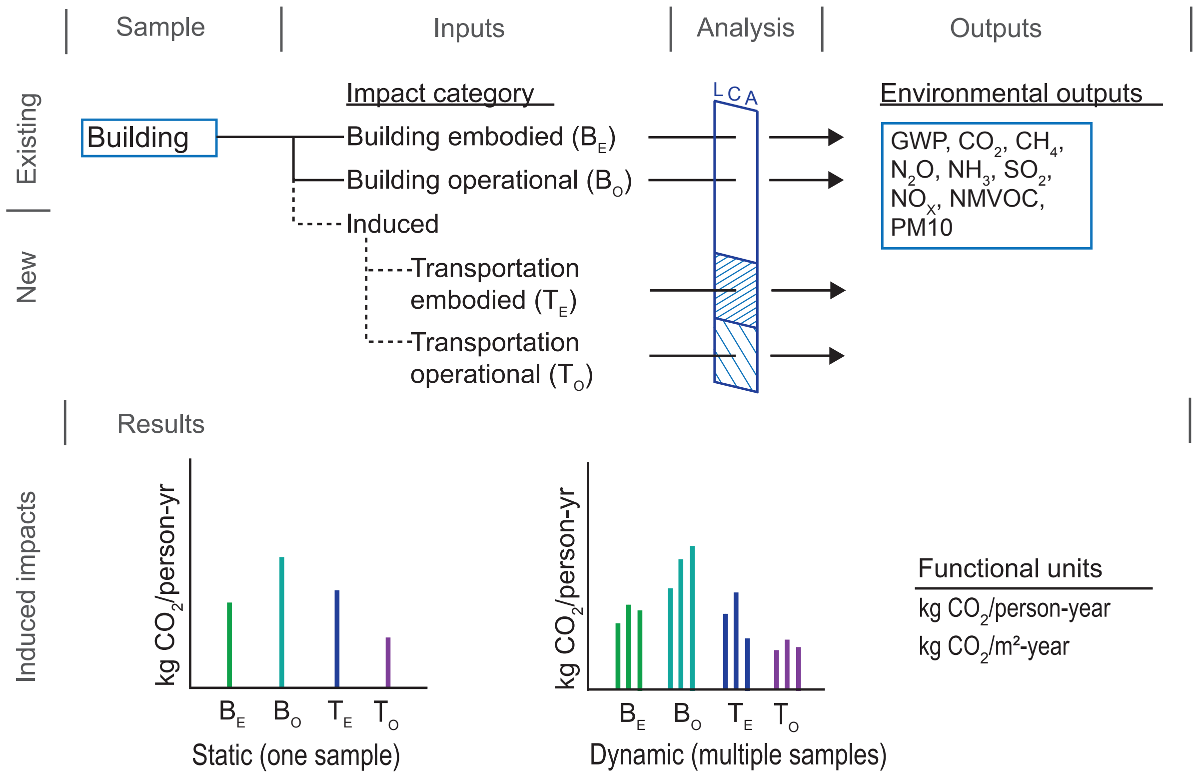

Figure 3.1: Overview of the expanded research methodology to capture induced impacts resulting from the interactions of a building and its surrounding urban context.

3.3 Case study

3.3.1 Urban region of Munich

In order to test the validity of the expanded methodology, and to illustrate the magnitude of induced impacts, a case study for evaluation is required. The *urban region of Munich* is taken as case study. The term *urban region of Munich* is used in the thesis, but needs to be differentiated from other existing institutional terms for the general region. This region (i.e., the *urban region of Munich*) includes the Capital City of Munich and nine surrounding districts (Germ. Landkreise). These districts in their original German names are Bad Tölz-Wolfratshausen, Dachau, Ebersberg, Erding, Freising, Fürstenfeldbruck, Miesbach, München, and Starnberg. To distinguish the Capital City of Munich (Germ. Landeshauptstadt München) from the district of Munich (Germ. München Landkreis), the city will be referred to as *Munich* or *City of Munich* and the district as *München LK*. See figure 3.2 on the following page for an illustration of the *urban region of Munich*. The study will also look in detail at the City of Munich. Thus, the 25 neighborhoods in Munich are shown in figure 3.3 on the next page. The neighborhoods of the City of Munich and the surrounding districts are shown together in figure 3.4 on page 24.

Figure 3.2: The *urban region of Munich* including the Capital City of Munich (labeled Munich) and the nine surrounding districts .

The *urban region of Munich* needs to be differentiated from four other regional definitions. First, the official *Planning Region of Munich* (Planning Region 14) includes the capital city Munich and the districts of Dachau, Ebersberg, Erding, Freising, Fürstenfeldbruck, Landsberg am Lech, München, and Starnberg. This is the formal planning region per the state of Bavaria. Second, the *European Metropolitan Region of Munich (EMM)* is composed of numerous cities and districts in the Munich region in an incorporated association. Rather than a strict geographical boundary, the EMM is defined by the association; thus, the EMM can grow or decline based on membership in the organization. Third, another regional term is the *Munich Transportation and Tariff Association area of operation* (Germ. MVV-Verbundraum). This area overs the cities and districts where the transportation authority operates, and includes the City of Munich, Dachau, Ebersberg, Erding, Freising, Fürstenfeldbruck, Landsberg am Lech, München, and Starnberg. The districts of Bad Tölz-Wolfratshausen, Landsberg am Lech, and Miesbach are only partially covered [131] by the transportation authority area. Finally, the term *Munich Metropolitan Region* is also used, but this is not a fixed term with defined geographical boundaries.

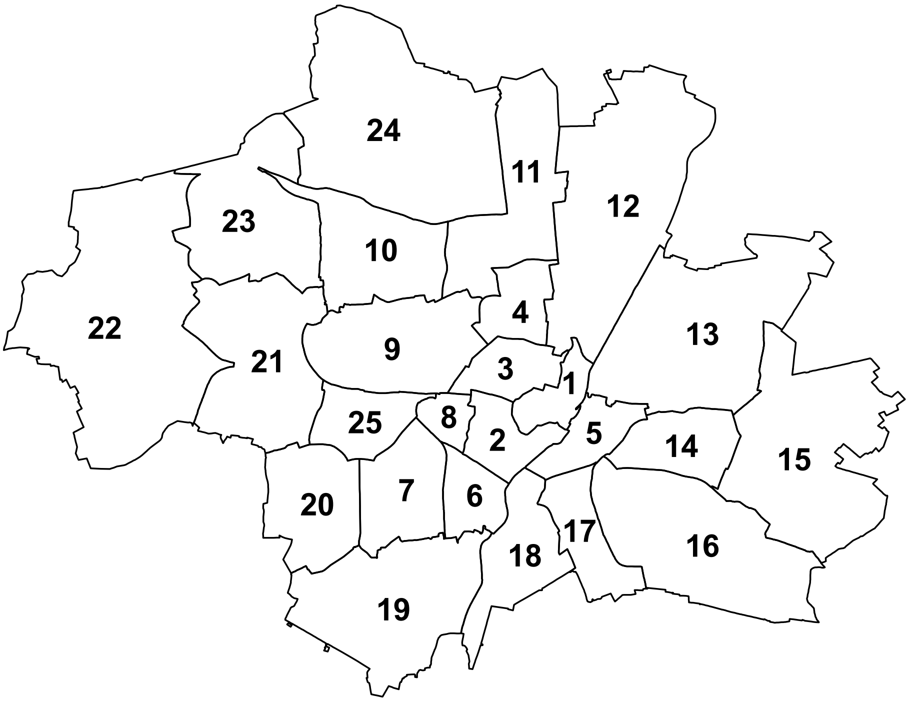

Figure 3.3: Neighborhoods in the City of Munich:
Altstadt-Lehel (1), Ludwigsvorstadt-Isarvorstadt (2), Maxvorstadt (3), Schwabing-West (4), Au-Haidhausen (5), Sendling (6), Sendling-Westpark (7), Schwanthalerhöhe (8), Neuhausen-Nymphenburg (9), Moosach (10), Milbertshofen-Am Hart (11), Schwabing-Freimann (12), Bogenhausen (13), Berg am Laim (14), Trudering (15), Ramersdorf-Perlach (16), Obergiesing (17), Untergiesing-Harlaching (18), Thalkirchen-Solln (19), Hadern (20), Pasing-Obermenzing (21), Aubing-Lochhausen-Langwied (22), Allach-Untermenzing (23), Feldmoching-Hasenbergl (24), and Laim (25).

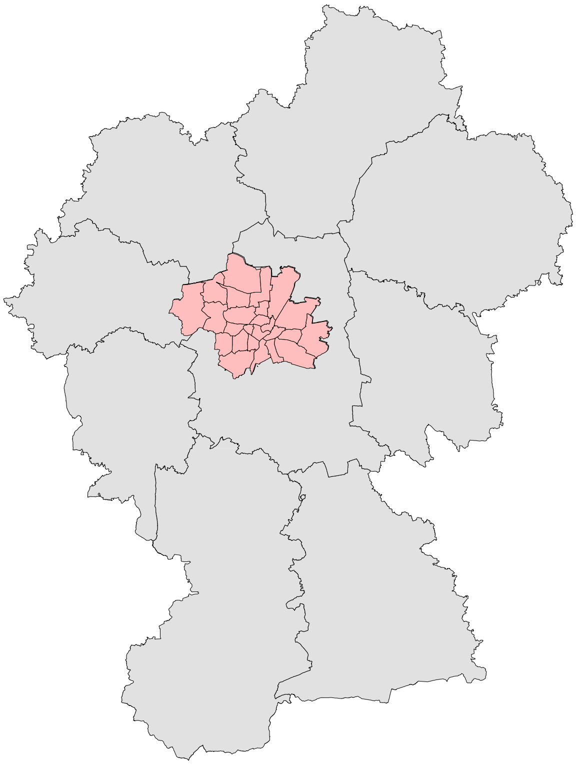

Figure 3.4: The *urban region of Munich* including the neighborhoods of the City of Munich and the surrounding districts.

The *urban region of Munich* is used for the case study due to several crucial factors. First, the region has an extensive and diverse transportation network composed of public and private transportation systems. The Munich public transportation system consists of buses, trams, the subway, and suburban trains. In addition, the city of Munich has a large non-motorized (e.g., walking, bicycling) infrastructure system. The private transportation network in Munich is well developed with numerous grades of roads and is well connected with the surrounding area via highways. The analysis of a region with a less diverse transportation network (either for private or private transportation) would not provide the same level of insight for the transportation embodied and operational impact categories.

Second, the region offers a diverse built environment with strong variations between locations. The high density city center is composed largely of five story buildings. However, as one moves away from the city center to the city periphery, the building size and density decrease. Outside of the city periphery, there are small towns and villages, but the urban/suburban sprawl typical of North American cities is absent. This clear delineation of the urban environment is optimal for studying the impacts of different residential locations. Three building locations will therefore be analyzed: the city center, the periphery of the city, and outside the city in a surrounding district.

Third and final, detailed transportation survey information is required to analyze transportation use within the metropolitan region. Extensive and detailed transportation data is available for the entire region covering the city and the surrounding districts. Thus, in-depth analysis of transportation use for the region is possible.

3.3.2 Household locations

As discussed in section 3.2, indirect induced impacts can be captured by varying the location of a building within an urban context. For the thesis, three locations are examined in depth: the city center, the city periphery, and the district locations (i.e., outside the capital city of Munich). In general terms, the three locations can be classified as follows. The city center represents the high density core of the City of Munich. The periphery location is the area outside the main core of the city and also the denser locations outside the City of Munich itself. The districts location represents the rural areas outside the City of Munich and its suburbs. The generalized locations are shown graphically in figure 3.5 on the next page. Specific values used to determine the building embodied (B_E), building operational (B_O), transportation embodied (T_E), and transportation operational (T_O) impacts for each location are discussed in each subsequent chapter. All assumptions about specific locations are provided therein.

The three locations—city center, periphery, and districts—influence all the impact categories. The location within the urban context determines the “typical” residential building construction, which is presented in Chapter 4: *Building embodied impacts*. The type of building in turn influences the operational energy demand (see Chapter 5: *Building operational impacts*). The house types are a multi-family house, a row house, and a single family house (locations: city center, periphery, and district). Transportation embodied impacts are location

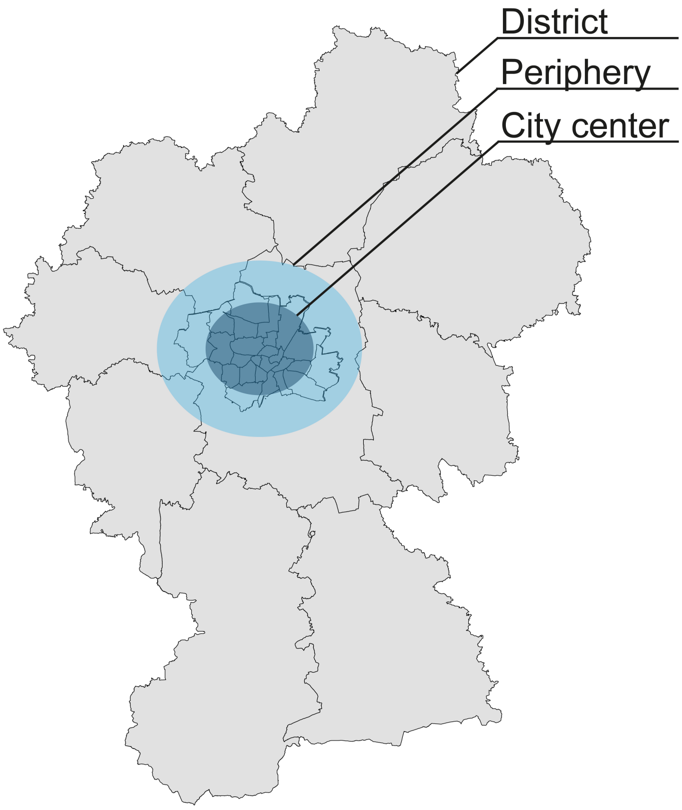

Figure 3.5: Case study household locations in the *urban region of Munich*.

sensitive due to infrastructure and vehicle supplies (both public and private) (see Chapter 6: *Transportation embodied impacts*). Finally, transportation operational impacts are strongly influenced by location and geographical travel data is used to calculate the impacts in Chapter 7: *Transportation operational impacts*.

In order to understand the sensitivity of the building type on the results, a sensitivity analysis will examine the influence on changing the location of the same building type at all three locations. This will illustrate the importance of building type on the overall impacts after accounting for direct induced impacts captured within transportation embodied (T_E) and transportation operational (T_O) impacts.

3.4 Life-cycle assessment

Having determined a methodology to capture induced impacts (both direct and indirect) and a case study region, an environmental analysis methodology is needed. While there are several environmental analysis methods for the built environment (see Chapter 2: *Problem statement*), life-cycle assessment is the proven methodology for scientific research of environmental impacts of buildings [1, 64].

Life-cycle assessment is a method to determine the environment impacts of products or services as outlined by the International Organization for Standardization. It covers the entire lifespan of a process or product from material extraction through production and manufacturing to the end-of-life [103]. Life-cycle assessment principles and framework are outlined by ISO 14040 [103] and the requirements and guidelines are given in ISO 14044 [104]. The four phases of a life-cycle assessment are 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation of the results (see figure 3.6 on the following page) ([103, 104]). In comparison to a life-cycle assessment, a life-cycle inventory study has only three phases: 1) goal and scope definition, 2) inventory analysis, and 3) interpretation. There are several types of life-cycle assessments each having advantages and disadvantages, which will be discussed.

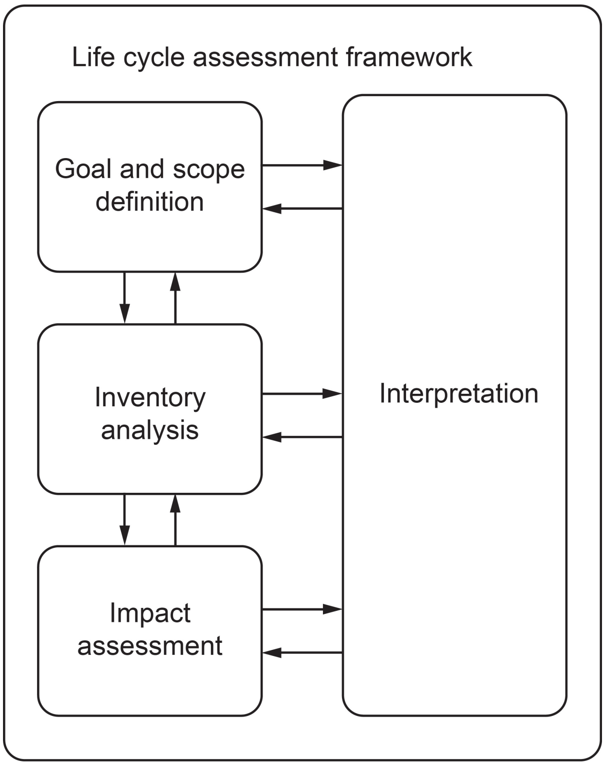

Figure 3.6: Life-cycle assessment framework per ISO 14040 [103].

3.4.1 Process-based LCA—theoretical background

The two most common LCA methods are process-based LCA and economic input-output LCA (EIO-LCA). Process-based LCA focuses on the entire network of individual processes involved in a product or service. The advantage of a process-based LCA is that detailed studies can be conducted for unique products or specifically identified process-cycles. The disadvantage is the innumerable processes for even simple products, which necessitates defining a system boundary for the LCA, which omits some impacts. This results in a truncation error as only those processes within the boundary are evaluated. An alternative LCA methodology is an economic input-output LCA [106].

3.4.2 Economic input-output LCA—theoretical background

Input-output economics, pioneered by Wassily Leontief [132], represents an entire economy as a matrix of interdependent sectors [132]. Input-output tables, provided by statistical offices of federal governments, represent the national economy in a fixed number of sectors, and illustrate the economic relationship between each sector. The input-output table can be coupled with environmental factors to relate economic changes to environmental impacts of the economy in question [106, 133].

In an EIO-LCA, economic data relating the sectors of an economy are combined with environmental impacts to give final LCA results. The benefits of an EIO-LCA are the improved processing time, reduced cost to perform the LCA, the absence of a system boundary, and the inclusion of indirect (e.g., secondary) effects. The disadvantages of the EIO-LCA are 1) use of aggregate data—the level of detail is limited to the number, and detail, of sectors in the entire economy (e.g., the 2002 U.S. input-output table has 428 sectors compared to the 2008 German input-output table with 73 sectors) [134, 135], 2) the necessity of using monetary units, and 3) the omission of the use phase and end-of-life phase [136]. The age of the data is a potential drawback for all types of life-cycle assessments. In order to maximize the advantage of each method and minimize the disadvantages, a hybrid LCA—a combination of a process-based LCA and an EIO-LCA—can be used.

3.4.3 Hybrid LCA—theoretical background

Hybrid life-cycle assessments seek to use the best aspects of process-based LCA and EIO-LCA, while minimizing their individual weaknesses. The main alternatives for hybrid LCA are either to use process-based LCA data for an EIO-LCA or EIO-LCA data for a process-based LCA [106]. The integration of EIO-LCA data into process-based LCA—a tiered hybrid—offers the benefits of maintaining the input-output matrix coefficients and using the process based model for greater detail [106], [137]. The integration of process-based LCA into EIO-LCA allows for disaggregating the input-output data and requires modifying the input-output matrix.

3.4.4 Life-cycle environmental output formulas

The quantification of the impact phases—embodied, operational, transportation, and infrastructure—is done using a life-cycle assessment. Life-cycle assessment is a well-established methodology for the quantification of environmental impacts [103], [104], and has been extensively used for evaluation of embodied and operational impacts in the built environment [106, 138]. The research methodology uses the process-based life-cycle assessment approach. This methodology is selected to enable the use of two extensive life-cycle databases: *Ecoinvent* [139] and *Ökobau.dat* [140]. Both of these databases are process-based. A hybrid life-cycle is not used due to an absence of cost data for all impact categories. Without cost data, these items are not able to be evaluated, as the input for evaluation is financial costs. However, material quantities, the basis for the process-based analysis, are readily available for all categories. The process-based LCA model captures environmental outputs from the four impact categories: building embodied impacts, building operation impacts, transportation embodied impacts, and transportation operation impacts.

Data for the research are for Central Europe, and focused on southern Germany when location specific data is available. Detailed information regarding data sources is provided in the sections for each impact phase. The research evaluates the life-cycle results (i.e., the environmental impacts) from the four impact phases as outlined in the following equations, as updated and modified from other sources [1].

Total environmental impacts, E_{Tot}

The total environmental impacts (E_{Tot}) are the summation of the building embodied impacts (B_E), the building operational impacts (B_O), the transportation embodied impacts (T_E), and the transportation operational impacts (T_O). See equation (3.1).

$$E_{Tot} = B_E + B_O + T_E + T_O \tag{3.1}$$

Building embodied environmental impacts, B_E

The building embodied impacts result from the initial construction of the building (B_{Ei}), the recurring impacts from on-going maintenance or renovation of an existing building (B_{Er}), and the end-of-life processes (B_{EOL}). See equation (3.2).

$$B_E = B_{Ei} + B_{Er} + B_{EOL} \tag{3.2}$$

Initial building embodied impacts (B_{Ei}) are the summation of the impacts from the material production (B_{mi}), the transportation of the materials from the producer to the building site (B_{ti}), and the construction and erection process (B_c). Material production is the product of the environmental output for the material (m_i) with the material quantity (M_i). Transportation environmental outputs are the product of the environmental output for given transportation characteristics (tr_i) (e.g., mode, distance, speed, carrying capacity) with the material quantity. See equation (3.3) and equation (3.4).

$$B_{Ei} = B_{mi} + B_{ti} + B_c \tag{3.3}$$

$$B_{Ei} = \sum(m_i M_i) + \sum(tr_i M_i) + B_c \tag{3.4}$$

Recurring building embodied impacts (B_{Er}) result from normal maintenance and/or the renovation of an existing building. This variable accounts for variations in the component lifespan (L_{mi}) over the lifespan of the building (L_b). See equation (3.5).

$$B_{Er} = \sum\left(m_i M_i \left[\left(\frac{L_b}{L_{mi}}\right) - 1\right]\right) \tag{3.5}$$

Building end-of life impacts (B_{EOL}) are the summation of the impacts from the demolition process (B_d), transportation to disposal (B_t), and the disposal/recycling process (B_r). Transportation to disposal is the product of the transportation characteristics (tr_i) with the waste material quantity (M_d). See equation (3.6) and equation (3.7) on the next page.

$$B_{EOL} = B_d + B_t + B_r \tag{3.6}$$

$$B_{EOL} = B_d + \sum(tr_i M_d) + B_r \tag{3.7}$$

Building operational environmental impacts, B_O

Environmental impacts from operational use of the building (B_O) are from the annual operational use (B_{OA}) (i.e., domestic hot water, HVAC, and electricity) over the lifespan of the building (L_b). See equation (3.8).

$$B_O = B_{OA} \times L_b \tag{3.8}$$

Transportation embodied environmental impacts, T_E

Equations to calculate embodied transportation impacts (T_E) are identical to those for the building embodied impacts, except that the items of interest are vehicles (T_V) and infrastructure (e.g., roads) (T_I). Embodied impacts for vehicles (T_V) are the initial outputs for the new vehicle (T_{Vi}) and recurring outputs for maintenance of the vehicle (T_{Vr}). Where T_c represents the outputs from the construction process for vehicles and/or infrastructure, accordingly. See equation (3.9), equation (3.10), equation (3.11), and equation (3.12).

$$T_E = T_V + T_I \tag{3.9}$$

$$T_V = T_{Vi} + T_{Vr} \tag{3.10}$$

$$T_{Vi} = \sum(m_i M_i) + \sum(tr_i M_i) + T_c \tag{3.11}$$

$$T_{Vr} = \sum \left(m_i M_i \left[\left(\frac{L_b}{L_{mi}} \right) - 1 \right] \right) \tag{3.12}$$

Infrastructure embodied impacts (T_I) are the summation of the initial impacts for the infrastructure (e.g., roads, tunnels, tracks) (T_{Ii}) and the recurring impacts for maintenance (T_{Ir}). See equation (3.13), equation (3.14), and equation (3.15).

$$T_I = T_{Ii} + T_{Ir} \tag{3.13}$$

$$T_{Ii} = \sum(m_i M_i) + \sum(tr_i M_i) + T_c \tag{3.14}$$

$$T_{Ir} = \sum \left(m_i M_i \left[\left(\frac{L_b}{L_{mi}} \right) - 1 \right] \right) \tag{3.15}$$

Transportation operational environmental impacts, T_O

Transportation operational impacts (T_O) represent the impacts for the operational phase of transportation for the users of the building. The operational impacts are the product of the transportation impacts based on given transportation characteristics (tr_i) as noted before and the distance of travel (D_i). See equation (3.16).

$$T_O = \sum (tr_i D_i) \tag{3.16}$$

Utilization of the life-cycle assessment formulas requires relevant data. The selection of data and datasets for each of the four impact categories (i.e., building embodied, building operational, transport embodied, and transportation operational) is presented in each subsequent chapter, accordingly. This allows a more extensive review and discussion of assumptions, datasets, and associated decisions made.

3.5 Conclusion

Current research on environmental impacts from the built environment focuses on the individual building or on the entire urban system. This treats buildings as isolated objects devoid of an urban context and ignores actual patters of construction—new buildings or renovations within existing cities. Consequently, a new impact category, induced impacts, is required to capture the environmental impacts resulting from the interactions of an individual building and the larger urban context.

Having identified a new impact category, a new methodology is required to capture induced impacts. Therefore, a new methodology is developed to capture, evaluate, and assess induced impacts within the built environment. Indirect induced impacts (e.g., building type, living space demand) can be captured by examining buildings at different locations within an urban region. Thus, three locations within the urban region are chosen: the city center, the city periphery, and the outside districts. Direct induced impacts are captured through transportation related impacts. Direct induced impacts include the embodied impacts of transportation vehicles and infrastructure and the operational impacts during the transportation use phase.

The case study of the *urban region of Munich* is selected for application of the new methodology. The *urban region of Munich* is selected due to its diverse transportation network, strong variations in the built environment, and the availability of detailed transportation user information. The reference unit for the methodology is the residential building in question, which allows for analysis on a per square-meter and per person basis to compare all impact categories. Three building types will be chosen for each of the locations based on statistical and real estate market analysis provided in the subsequent chapter.

Life-cycle assessment is used for the research given its widespread scientific acceptance and to account for all upstream impacts. The expanded life-cycle assessment methodology is innovative in its integrated approach to capture the building embodied, building operational, transportation embodied, and transportation operation impacts within one life-cycle assessment.

Chapter 4

Building embodied impacts

This chapter presents the life-cycle building embodied impacts—the first of the four impact categories as presented in the expanded methodology in Chapter 3: *Methodology*. In order to capture both embodied impacts and indirect induced impacts, three locations are examined: the city center, the city periphery, and the districts. Building typologies and characteristics representing *typical* residential building types at each location are determined using statistical and real estate market analysis. Based on these findings, appropriate case study buildings are selected. In the city center a multi-family house is chosen, in the city periphery a row house is selected, and finally, for the district location a single family house is used as a representative building type. The chapter then presents the life-cycle assessment of the embodied impacts for the selected case study buildings.

While life-cycle assessment of buildings is well researched, the chapter contributes to the research state-of-art in three important ways. First, a new procedure is used to select case study buildings representative of the larger building stock. Traditionally, life-cycle assessments are conducted for random case studies regardless of their appropriateness for the larger building typology of the region. In comparison, this work uses statistical and market analysis to select typical buildings for specific locations within a region. Second, the life-cycle assessment results provide reference values for comparison purposes. The specific findings, based on actual building typologies, can be used for benchmarking embodied impacts of new buildings in the *urban region of Munich*. Finally, the results illustrate the difference in embodied emissions for different residential housing types. While compact urban form is often argued to have better environmental performance, the work provides actual analysis proving this point. The multi-family house has lower impacts than the row house, which in turn has lower impacts than the single family house. Thus, illustrating the gradation of embodied impacts based on building compactness.

4.1 Introduction

Building embodied impacts result from raw material extraction, transport, production, manufacture, assembly, disassembly, and deconstruction. Calculating embodied impacts requires detailed information about the building construction, materials used, material transportation distance, and end-of-life processes. Data for the life-cycle assessment of building embodied impacts are usually taken from realized building projects to provide results for actual buildings [1, 64].

As outlined in Chapter 3: *Methodology*, three building locations are to be examined in order to capture indirect induced impacts. The three locations within the *urban region of Munich* are the city center, the city periphery, and the districts. In accordance with life-cycle assessment literature, actual buildings will be used for the three case studies. Using realized projects is advantageous as it captures actual construction methods, building layouts, and materials used in practice. However, selecting a case study for each location poses the risk that the building may not be representative of typical buildings at that location. Thus, the work will analyze a real building that matches the typical characteristics of the majority of buildings in that physical location. Through statistical and market analysis it is possible to determine characteristics for a typical building at each of the three locations. Based on this information, case study buildings representative of the location can be selected. The analysis for selecting the defining building characteristics is presented next.

4.2 Defining the building case studies

4.2.1 Statistical analysis

The selection of case study residential buildings for the embodied life-cycle assessment requires information on the floor area demand, building types and sizes, and construction materials of buildings within the *urban region of Munich*. In order to find appropriate case studies, statistical information on the building stock, as well as information from the current real estate market is utilized. The research scope is limited to residential buildings. In total three buildings will be evaluated, one for each location within the *urban region of Munich*—city center, city periphery, and districts.

Firstly, the floor area demand of residential buildings in the *urban region of Munich* is determined based on the locations of relevance. In 2011, floor area totaled 51,023,100 m^2, 182,981,000 m^2, and 554,635,000 m^2 for Munich, Oberbayern, and Bavaria, respectively [141]. The floor area (Germ. Wohnfläche) is defined per [141]. On the same date the population was 1,378,200, 4,430,700, and 12,595,900 persons for Munich, Oberbayern, and Bavaria, respectively [142]. Based on these values, the floor area demand for Munich, the districts of interest, Oberbayern, and Bavaria are determined. The German national average floor area per person in December 2011 was 46.6 m^2 [143]. The resulting floor area demand based on locality are presented in table 4.1 on the next page.

Table 4.1: Living space demand per location within the *urban region of Munich* [141, 142]. For the districts, Dachau has the lowest demand (40.0 m^2/person) and Starnberg the highest demand (44.8 m^2/person).

	Floor area demand (m^2/person)
DISTRICTS	
Bad Tölz-Wolfratshausen	42.4
Dachau	40.0
Ebersberg	41.3
Erding	41.8
Freising	40.7
Fürstenfeldbruck	42.5
Miesbach	44.0
München LK	41.7
Starnberg	44.8
Districts Avg.	42.2
Munich	37.0
Oberbayern	41.3
Bavaria	44.0
Germany	46.6

Munich has the lowest floor area demand (37.0 m^2/person), which is significantly lower than the value for Oberbayern (41.3) and Bavaria (44.0), which include Munich as well. The districts have floor areas ranging from 40.0 (Dachau) to 44.8 (Starnberg) m^2/person due to the varying demand of the districts.

Statistical information regarding the proportion of residential buildings and units based on building type and location is also available [141]. The three types of residential dwellings categorized are single family houses (SFH), double family houses (DFH), and multi-family houses (MFH). The average floor area of each building type per unit is also provided based on location. This information is summarized in table 4.2 on the following page. It must be noted that these values include all existing buildings up to the year 2012, and thus the values are not suitable for the analysis of current trends.

The statistical information for building types (table 4.2 on the next page) illustrates a few key points. First, within the districts, single-family houses make up two-thirds of all buildings. Thus, single family homes are of extreme importance due to their ubiquity. Second, in the City of Munich, almost 90% of residential units are within multi-family buildings. Therefore, multi-family buildings are of crucial importance within cities. Finally, the data also show that the average floor area per unit decreases when going from a single family house to a double house to a multi-family house. Data on the number of persons per building type is not available at either the Bavarian or federal level.

Next, the trends in housing construction per building type in Bavaria over the last five years of available data (i.e., 2006 to 2011) is presented in table 4.3 on the following page. The results show an increase of 3.73, 2.35, and 2.56% for single family houses, double family

Table 4.2: Proportion of residential building types at various geographical levels [141]. Residential units in the City of Munich are dominated by multi-family houses (87.5%), while buildings in the districts are largely single family houses (67.6%).

		Buildings (%)	Residential units (%)	Avg. floor area per unit (m^2)
Munich	SFH	47.3	8.6	120.8
	DFH	10.6	3.9	86.8
	MFH	42.1	87.5	62.5
Districts[a]	SFH	67.6	35.1	133.8
	DFH	19.3	20.1	95.3
	MFH	13.1	44.8	70.9
Oberbayern	SFH	64.9	26.5	131.6
	DFH	18.2	14.9	94.8
	MFH	16.9	58.6	66.0
Bavaria	SFH	66.3	33.0	192.2
	DFH	20.7	20.6	93.7
	MFH	13.0	46.4	68.0

[a] Average for Bad Tölz-Wolfratshausen, Dachau, Ebersberg, Erding, Freising, Fürstenfeldbruck, Miesbach, München LK, and Starnberg.

houses, and multi-family houses, respectively. Thus, while all housing types grew around 3% over five years, construction of SFH grew at a higher rate than the other house types. In addition, the average living space per person in Bavaria increased 3.2% between 2006 and 2011, illustrating another important trend in housing construction which must be considered when viewing the data. Again it must be noted that the data includes all existing buildings [141].

Table 4.3: Growth in buildings and residential units per housing type in all of Bavaria (2006-2011) [141]. Single family house construction grew at the highest rate.

	Buildings			Residential	units	
	2006	2011	Change (%)	2006	2011	Change (%)
SFH	1.89E+6	1.96E+6	3.73	-	-	-
DFH	5.97E+5	6.11E+5	2.35	1.19E+6	1.22E+6	2.35
MFH	3.75E+5	3.85E+6	2.65	2.69E+6	2.75E+6	2.70

In addition to information on the number of buildings, statistical data is also available regarding the type of construction within Germany [144]. The most frequent structural construction material for buildings in Germany (over 30%), regardless of housing type, is clay masonry units (see table 4.4 on the next page). Masonry unit construction, regardless of actual block type, dominates all construction at 68.7, 73.7, and 72.5% for single family houses, double family houses, and multi-family houses, respectively. Reinforced concrete construction is used for 18% of multi-family houses and only marginally for the other building types. Wood construction for single family houses is relatively low (under 17%), whereas this construction type is more common in other countries (e.g., United States of America). It should be noted that these construction types focus mainly on the structural system (i.e., walls). Regardless of these systems, similar structural elements (e.g., concrete foundations, concrete floor slabs) may be found in all construction types.

Table 4.4: Main structural material per housing type (all values in %) [144]. Clay masonry units make up the largest share for all building types.

	St.	RC	Clay MU	LSMU	AACMU	LWCMU	Wood	Etc.
SFH	0.01	6.16	32.58	14.43	21.04	3.70	16.39	5.68
DFH	0.00	6.60	37.38	13.40	18.02	4.85	13.20	6.55
MFH	0.00	18.73	32.37	25.27	11.55	3.29	1.76	7.03
All	0.01	7.27	32.93	15.26	20.00	3.76	14.91	5.87

St. – steel, RC – reinforced concrete, MU – masonry unit, LSMU – limestone masonry unit, AACMU – autoclaved aerated concrete masonry unit, LWCMU – light weight concrete masonry unit, Etc. – other.

Consequently, statistical information and trends have been shown for residential building types, floor area, construction rates, and construction materials. The aim of this chapter is to analyze several representative buildings in order to provide information on the embodied impacts of residential buildings. Results for a single building are not sufficient to capture possible differences in building types.

The building type selected for the case studies is the first decision that has to be made. For the city location, a multi-family house is used due to their dominance (88%) of residential units in Munich. For the city periphery location, a row house (RH) is used. While the DFH is always a lower percentage than the SFH or the MFH, this building type is significant within the districts (20% of residential units) and should be analyzed as well. While the statistics are given for a double house, a row house is used instead to represent actual building trends at the city periphery. For outside the city, a single family house is used as single family houses make up the largest percentage (59%) in Oberbayern. These values are from table 4.2 on page 38. The second decision for the case study selection is building construction material. The building construction material for all three buildings is taken as clay masonry units. This is due to the fact that clay masonry units are the most common construction material for all residential buildings (see table 4.4).

4.2.2 Real estate market analysis

The final criterion for selecting the building case studies is building size. General size information per building type is given in table 4.2 on page 38; however, this includes the entire building stock (i.e., new and existing buildings). Therefore, these values are not representative of current building sizes and do not include the trend of increasing house size [141]. Therefore, representative sizes for each building type within the *urban region of Munich* are determined using a statistical analysis of the new housing market. Using the most prevalent online real estate provider [145], a survey was taken for single family homes, row houses, and multi-family homes.

The selection criteria for single family house included Munich and a radius of 50 km. Row houses and multi-family houses (individual apartment units) included Munich and a radius of 5 km. All available houses were collected regardless of size. Then a statistical analysis was run to remove all mild outliers (see Chapter 6: *Transportation embodied impacts*). The revised data set removed all data points above the mild outliers to prevent skewing the data set. The revised dataset was then analyzed again and the average house size was determined (see table 4.5). The average floor area is found to be 156, 138, and 85 m^2 for a single family house, row house, and multi-family house unit, respectively.

Table 4.5: Market survey of building sizes per building type.

Building type	Sample size	Avg. floor area (m^2)
SFH	185	156
RH	68	138
MFH (per unit)	227	85

The living demand for each case study is based upon its geographical location. For the multi-family house in Munich, the living area for Munich (37.0 m^2/person) is used. For the row house, the living demand for Dachau district (40.0 m^2/person), a neighboring community to Munich, is used. This value is used as the row house is located on the city edge, but there is not demand data available at this level. As Dachau district has the lowest demand outside of Munich this value is chosen. For the single family house, the living demand in Starnberg (44.8 m^2/person) is used. Starnberg is chosen as it is has the lowest demand of all districts, thus giving the largest comparison to the City of Munich demand for a sensitivity analysis.

All the characteristics for the case study selection are presented in table 4.6 on the facing page. It should be noted that these are not fixed requirements, but are rather used as guidelines to select buildings meeting the general characteristics of typical buildings. Matching the exact average floor area, for example, is not likely for an actual building, but rather sets an order of magnitude in the selection process. Further, the normalization of the results via the selected living space demand (m^2/person) will provide a common unit for comparative analysis.

It must be noted that the living space demand values as well as the building characteristics are statistical averages. The aim is to provide values for *typical* residential building types representative at three locations based on the statistical averages presented previously. As the life-cycle assessment results for the building embodied impact are on a per square-meter and per person basis, varying the living space demand allows for a sensitivity analysis of the results. This allows for understanding other socio-demographic effects such as household size, which can have a large impacts on the final results (see Chapter 8: *Results and discussion*).

Table 4.6: Summary guidelines for the selection of representative case study buildings based on statistical background information. The value for the multi-family house are given per unit not for the entire building. Case study 1 is located in the districts outside the city of Munich, Case study 2 is located at the city periphery, and Case study 3 is located in the city center.

	Building type	Material	Floor area (m^2)	Demand (m^2/per.)	Persons
Case study 1	SFH	Clay MU	ca. 156	44.8	3
Case study 2	RH	Clay MU	ca. 138	40.0	3
Case study 3	MFH	Clay MU	ca. 85	37.0	2

4.3 Case study buildings

4.3.1 Multi-family house

The selected multi-family house case study is located at 168 Schwanthalerstraße in the Schwanthalerhöhe neighborhood in Munich, Germany. Construction of the building was completed in 2011 and was designed by *Emmermann Architekten und Stadtplaner* (architect) and *Berk und Partner Bauingenieure* (civil engineer). The building has five full stories, two stories of space within the roof, a basement (unheated). There is commercial space for one tenant at the ground floor and ten apartment units above this. The front façade of the building faces south. The east and west walls are directly adjacent to neighboring buildings, and thus have no openings. See figure 4.1 on the next page.

The heat-transfer surface area (*A*) (Germ. wärmeübertragende Umfassungsfläche) is 1138 m^2 calculated per EnEV 2009 [147]. The heated building volume (V_e) (Germ. beheizte Gebäudevolumen) is 3,657 m^3. The building floor area (A_N) (Germ. Gebäudenutzfläche) is given by EnEV 2009 [147] by equation (4.1) and is 1,170 m^2. For the apartment units in the building, this is an average of 97.5 m^2/ unit, which correlates to table 4.6.

$$A_N = 0.32m^{-1} \times V_e \tag{4.1}$$

The surface-area-to-volume ratio (A/V_e) (Germ. Oberfläche-zu-Volumen-Verhältnis) is 0.31. The total window and door area (A_W) is 285.3 m^2, and the total exterior wall area (A_{AW}) is 927.6 m^2. The window and door percentage is 23.5%.

The construction of the building is as follows. The foundation of the building is a 60 cm thick high-strength concrete foundation (C30/37). The basement walls (20 cm thick, C25/30), stairwell and elevator core walls (20 cm thick, C20/25), and all floor slabs (20 cm thick, C25/30) are reinforced concrete elements. Structural walls at the ground floor and the first level are 20

Figure 4.1: Southern façade of the multi-family house case study in the Schwanthalerhöhe neighborhood in Munich [146].

cm thick reinforced concrete walls (C20/25). Starting at the second floor all structural walls are constructed with 17.5 cm thick structural clay masonry units.

The south façade has 10 mm of stucco on 10 cm of rigid foam insulation attached to the exterior of the structural walls. The north façade has a similar construction, but has 14 cm of insulation. The east and west exterior structural walls are separated from the adjacent buildings with a 40 mm building separation board. The interior face of the structural walls is covered in 7 cm of stucco. The typical floor construction is either parquet or tiles (ca. 10 mm), a cast plaster floor (60 mm), sound insulation (25 mm), and heat insulation (20 mm) on top of the structural slab. The roof construction consists of wood joists and supports concrete roof tiles, insulation, and oriented strand board.

4.3.2 Row house

The row house used for the study consists of four individual row houses each directly next to each other (i.e., two middle houses and two edge houses). They were designed by the architectural firm *Birgit Dreier* in accordance with the EnEV 2009 standard. The floor plan of each building is 5.71 m in width and 10.49 m in length. Each row house has a floor area of 156 m^2, which is slightly larger than the statistical average (table 4.6 on page 41).

The entrances of the houses face north, and the long axis of each unit runs north-south. Each house has a basement, ground floor, first floor, and roof floor. The basement is unheated, and the roof floor has a short setback on the north side creating a terrace. The basement walls and foundation are constructed from concrete. The exterior walls (i.e., all north and south walls, and one wall of the edge houses) are constructed from clay masonry units (36.5 cm wide). The internal walls separating the houses are constructed from clay masonry units (17.5 cm wide). Floor slabs are constructed from reinforced concrete, and the roof structure is constructed from roof tiles supported by wood joists. As the construction, and more importantly the energy use, differs between a middle (i.e., interior) and an edge (i.e., exterior) row house, both variants are evaluated. The plan and section for the row houses are presented in figure 4.2 and figure 4.3 on the following page.

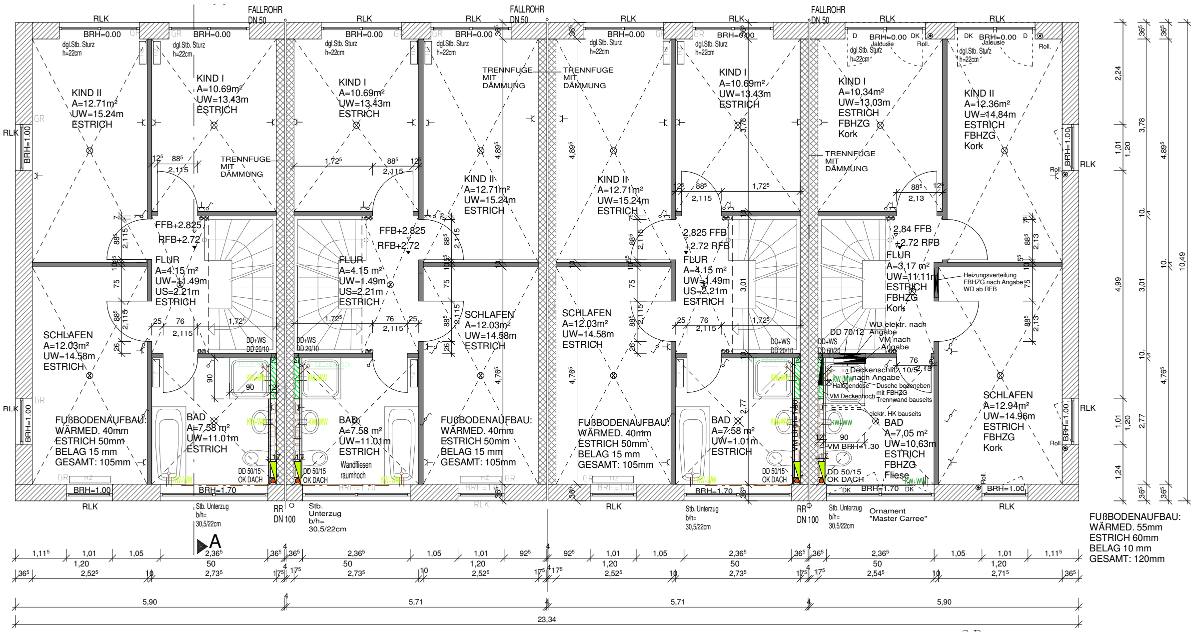

Figure 4.2: Row house building plan - first floor. There are two “edge” and two “middle” row houses [148].

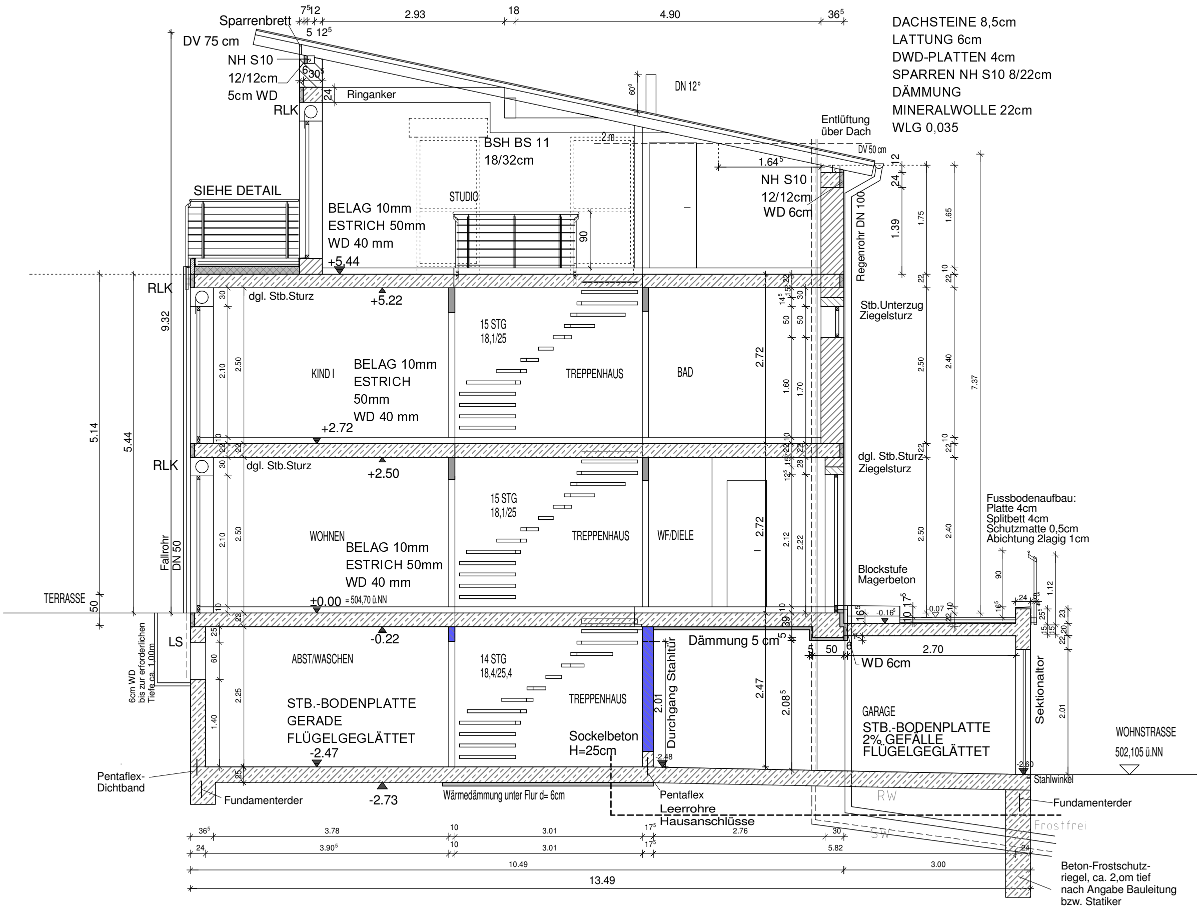

Figure 4.3: Row house building section. The north façade has a setback at the roof level creating a terrace [148].

4.3.3 Single family house

The single family house is modeled based on half of a double house. The statistical information for single family houses are based on actual single family houses, and not halves of double houses. However, the characteristics of the double house half match the criteria for the typical single family house well and therefore it is used for the case study. Only one half of the building is analyzed and the shared wall between the double houses is replaced with an exterior wall to represent the actual conditions of a detached single family house. The house was designed by *Bauplan*[2] (architectural firm). The building has a floor area of 123 m^2, which is lower than the statistical average for single family houses (Table 4.6 on page 41). The house has a basement, ground floor, and first floor. The basement walls and foundation are constructed with reinforced concrete similar to the floor slabs. The walls above grade are clay masonry units, and the roof is made from concrete tiles supported by wood joists. The plan for the single family house and a section are presented in figure 4.4 on the following page and figure 4.5 on page 47. Summary information for the three case studies is presented in table 4.7.

Table 4.7: Summary of case study buildings.

	Building type	Material	Floor area (m^2)	Demand (m^2/per.)	Persons
Case study 1	SFH	Clay MU	123	44.8	3
Case study 2	RH	Clay MU	156	40.0	4
Case study 3	MFH	Clay MU	1170	37.0	32

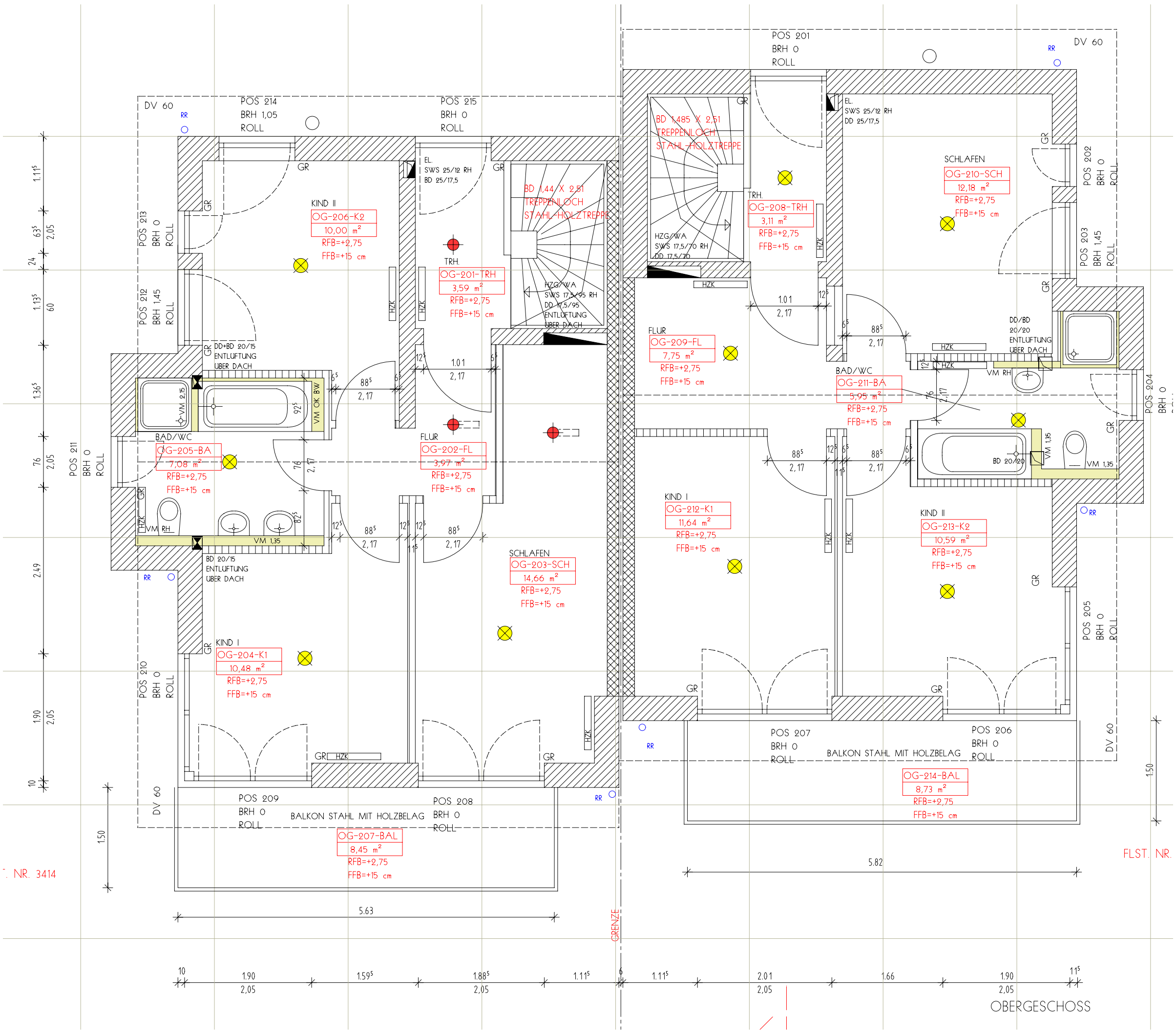

Figure 4.4: Single family house building plan—first floor. The half section on the left is used for the analysis [149].

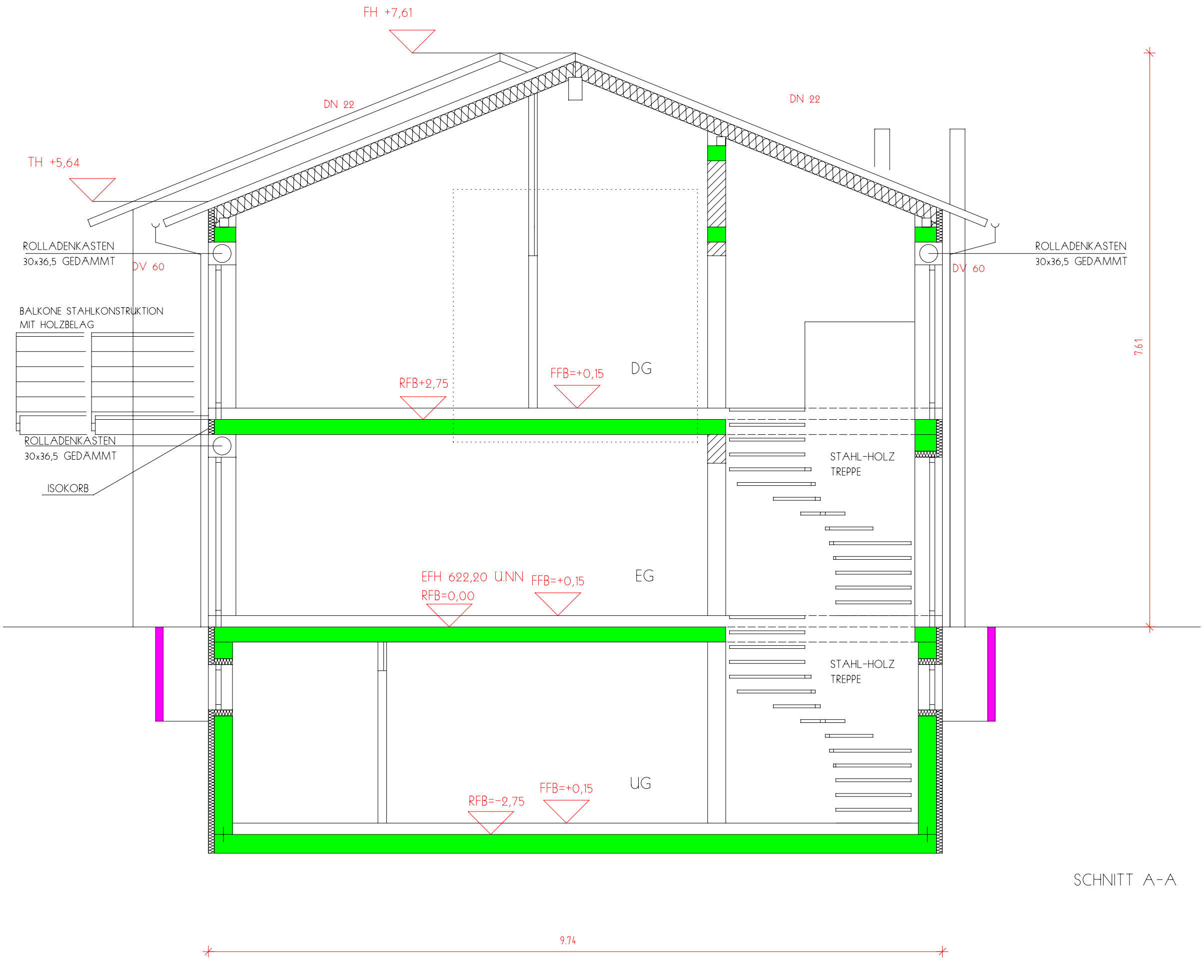

Figure 4.5: Single family house building section showing the unheated basement, ground floor, and first floor [149].

4.4 Building embodied life-cycle assessment

In order to perform the life-cycle assessment of the case study buildings, all the requirements of ISO 14040 and 14044 must be addressed. In accordance with ISO 14040, the goal of an LCA must define the intended application, reasoning, intended audience, and whether results are comparative [103]. The scope of the LCA must include the studied product system and its functions, functional unit, system boundary, allocation procedures, impact assessment categories and methodology, data requirements, assumptions, limitations, data quality requirements, critical review (if done), and report required for the analysis [103].

The intended application of the life-cycle assessment is for scientific research. The reason for carrying out the study is to compare the environmental impacts from different building types within the *urban region of Munich*. The intended audience is the international scientific community; engineers, architects, and planners; and policy makers. The results are intended to be used for comparison, and will be disclosed to the public.

The system for the LCA is residential buildings: a multi-family house, a double family house, and a single family house. The product function is living quarters for residents. The functional unit is environmental impact per house, and environmental impact per living area (m^2), and environmental impacts per resident. The general system boundary is shown in figure 4.6 on the next page. As shown in the figure, maintenance of the building and the construction and demolition processes are not included in the system boundary due to a lack of information available for these processes. The detailed system boundary is from the life-cycle database used [139, 150]. The allocation is per the *Ecoinvent* data set methodology [150]. Impact assessment categories include cumulative energy demand (CED) and global-warming potential (GWP) using the CML 2001 method [150].

The required data for the LCA are construction materials for each building, travel distances from the production site to the building site, and life-cycle inventory data for each material. Transportation refers to the transportation of the material from the production plant to the construction site. Three different transportation distances are used: local (50 km), regional (75 km), and long distance (100 km). This is a more detailed analysis than is typically conducted, where transportation distances are usually taken as 50 km for all materials [5].

The determination of transportation distance was done though an online survey of production locations within the *urban region of Munich*. Local transportation is used for common materials available within the surrounding 50 km and includes heavy materials (e.g., concrete, aggregate), which are transportation price sensitive (i.e., they are not economical to transport long distances). Regional transport includes more specialized materials/products (e.g., roof tiles, windows), which are still available within 75 km. Long distance transportation is used for specialty materials only available at distances over 75 km. Transportation is considered from the production plant to the construction site. The end-of-life transportation is already included within the end-of-life datasets. For end-of-life processes, all inert materials are considered to be sent to final disposal, whereas biomass materials are sent to municipal incineration. This is important for the life-cycle calculation of accumulated carbon within biomass products.

It is possible that certain building materials for a house in the *urban region of Munich* have very long transportation distances to the production plant (e.g., wood originally from Brazil). Transportation from the excavation site to the production plant is, however, already included in the life-cycle data sets based on average distances for materials used in Central Europe. Thus, only transportation from the production site to the construction site is additionally required.

All other assumptions and limitations, as so far as there are any, will be presented in detail for each case study. Data quality will be met by using actual constructed buildings within the region of the study and their associated material information, in addition to using established LCA databases (i.e., *Ecoinvent* and *Ökobau.dat*) [139, 140]. An external critical review is not undertaken; however, the validity of the results will be compared with appropriate scientific literature. The final results are presented in this text.

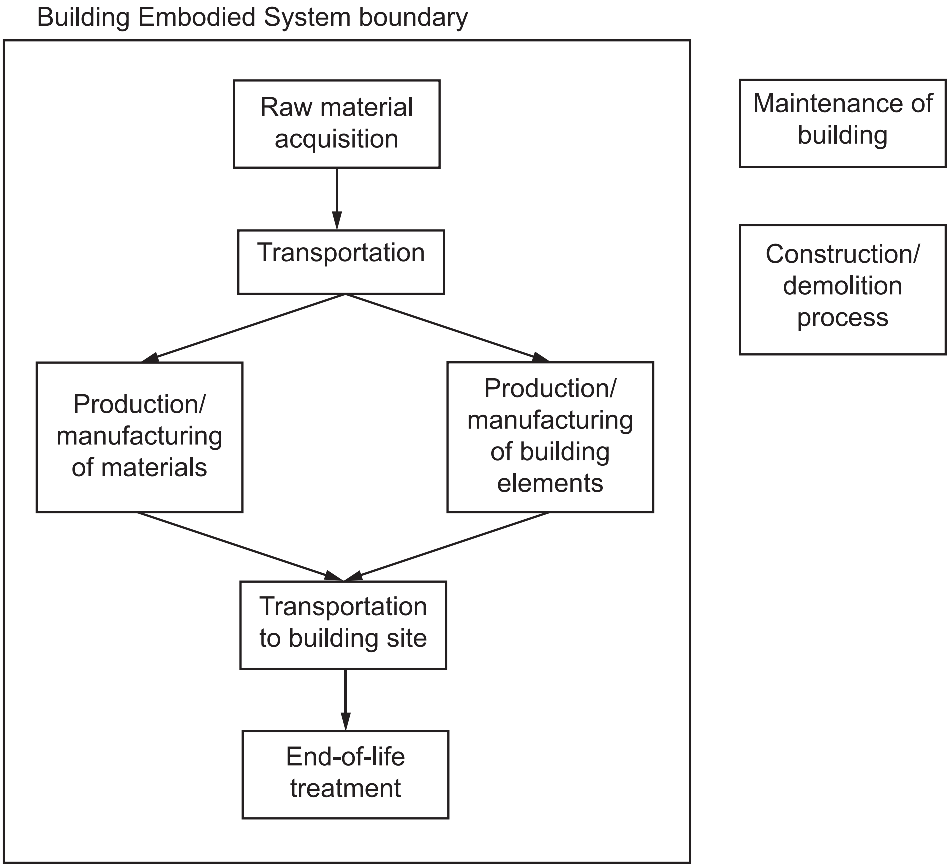

Figure 4.6: System boundary for building case studies. Modified from [103].

Data for the life-cycle inventory are from the *Ecoinvent* database version 2.2 [139] and the *Ökobau.dat* 2013 version [140]. The *Ecoinvent* database is one of the largest databases with extensive building material and process datasets. The *Ökobau.dat* data set from the German federal government provides additional useful datasets focusing mainly on construction [140]. Both these databases have been thoroughly reviewed to ensure their accuracy [150, 151].

4.4.1 LCA analysis software

In order to work with the over 4,000 datasets [150] in the *Ecoinvent* database, a software program is required to sort and identify the processes, extract the outputs of interest, and summarize the results for the user. The software program, written in *Python*, enables the reading and processing of the *Ecoinvent* database and returns the analysis results as shown in figure 4.7. The entire program has around 750 lines of code.

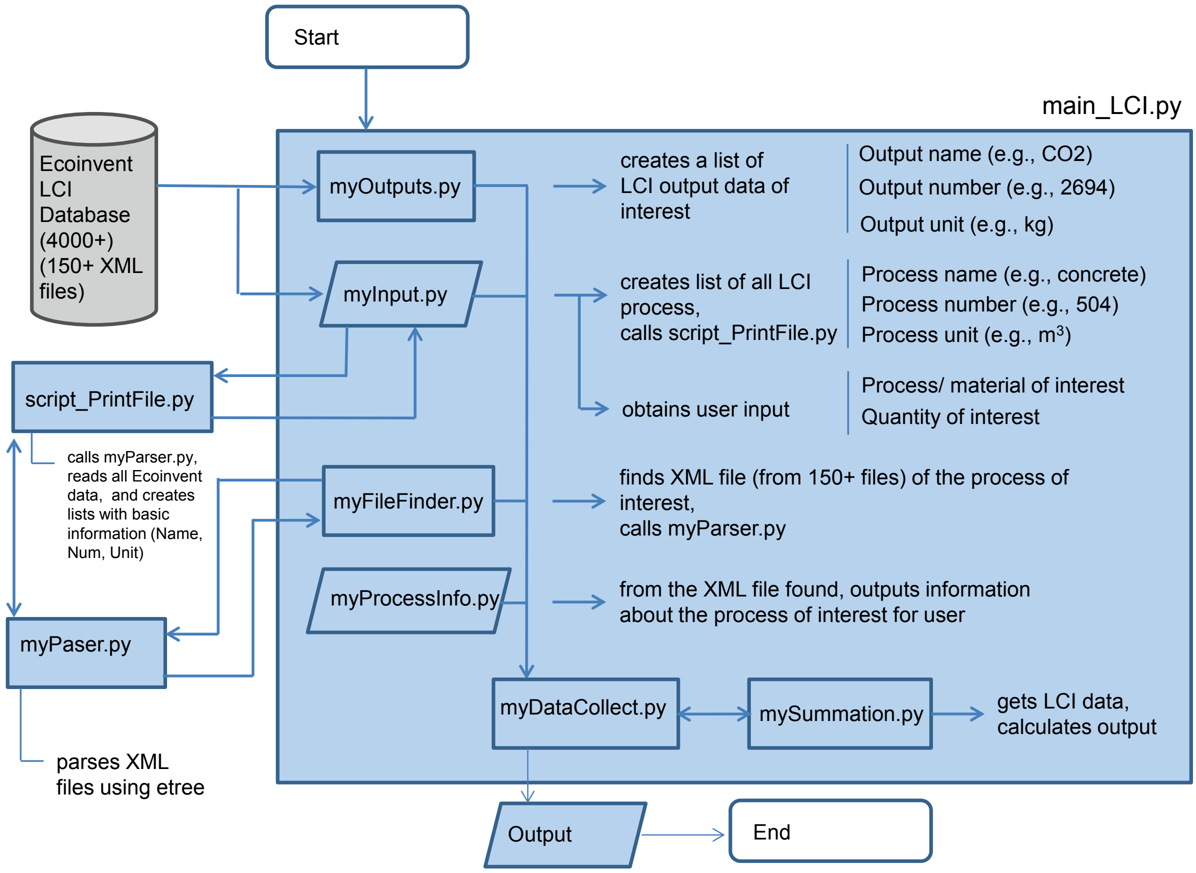

Figure 4.7: Software architecture to conduct the life-cycle inventory analysis, written in *Python*.

4.5 Building embodied results

4.5.1 Multi-family house results

For the multi-family house, 17 different construction materials are evaluated, which cover all major structural and architectural elements of the building. The material quantity calculations reveal that concrete makes up 84% (1.70E+6 kg) of the building material mass (see figure 4.8 on the next page and figure 4.9 on page 52). The dominance of concrete is due to the extensive use of concrete in the building: foundation, all floor slabs, elevator and stair core, walls up to the second floor, and selected walls above the second floor. The material “Concrete, normal” differs from “Concrete” in that “Concrete, normal” contains no superplasticizers.

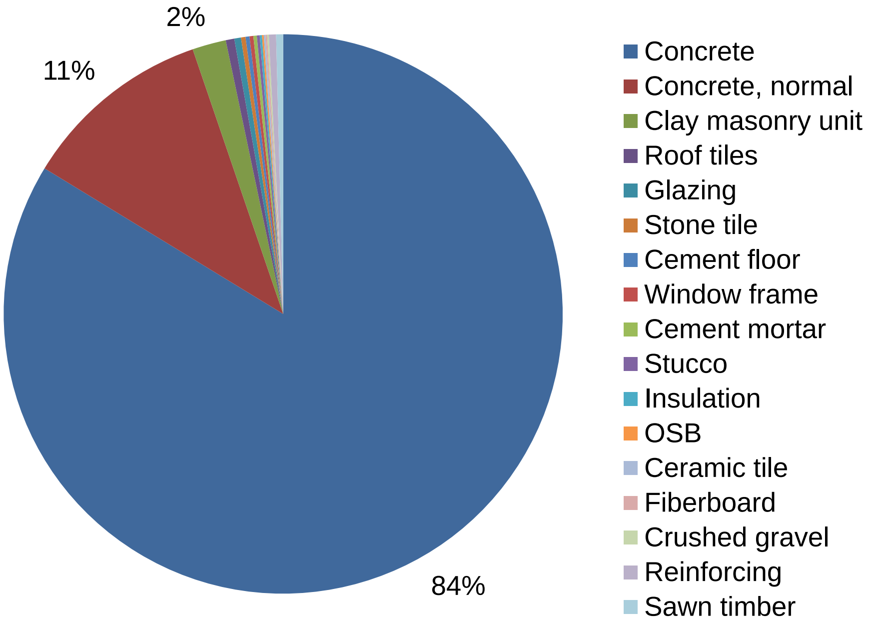

Figure 4.8: Multi-family house—material percentages by weight, illustrating the dominance of concrete in relation to all other building materials.

The relationship between material weight and material emissions (CO_2-Eq.) is shown in figure 4.10 on page 53. These results reveal that concrete has the highest percentage of CO_2-Eq. emissions, but this percentage is lower (76%) than its material percent (84%). Conversely, window frames which make up a very small percentage of total material (0.22%) have a strong influence on emissions (3%). Thus this illustrates that the specific environmental performance of each material must be reviewed in detail in addition to material amounts. The cumulative results for the multi-family house are presented in table 4.8 on the following page and table 4.9 on page 53. These values are given for the entire house (Total) and then per square-meter and per person as per table 4.7 on page 45. The percentage of the impacts from the materials, transportation from the plant to site, and the disposal are also included (Table 4.9 on page 53). For all calculations in the work, renewable energy sources are biomass, solar, water, and wind. Non-renewable energy sources are fossil fuels, nuclear, and primary forests.

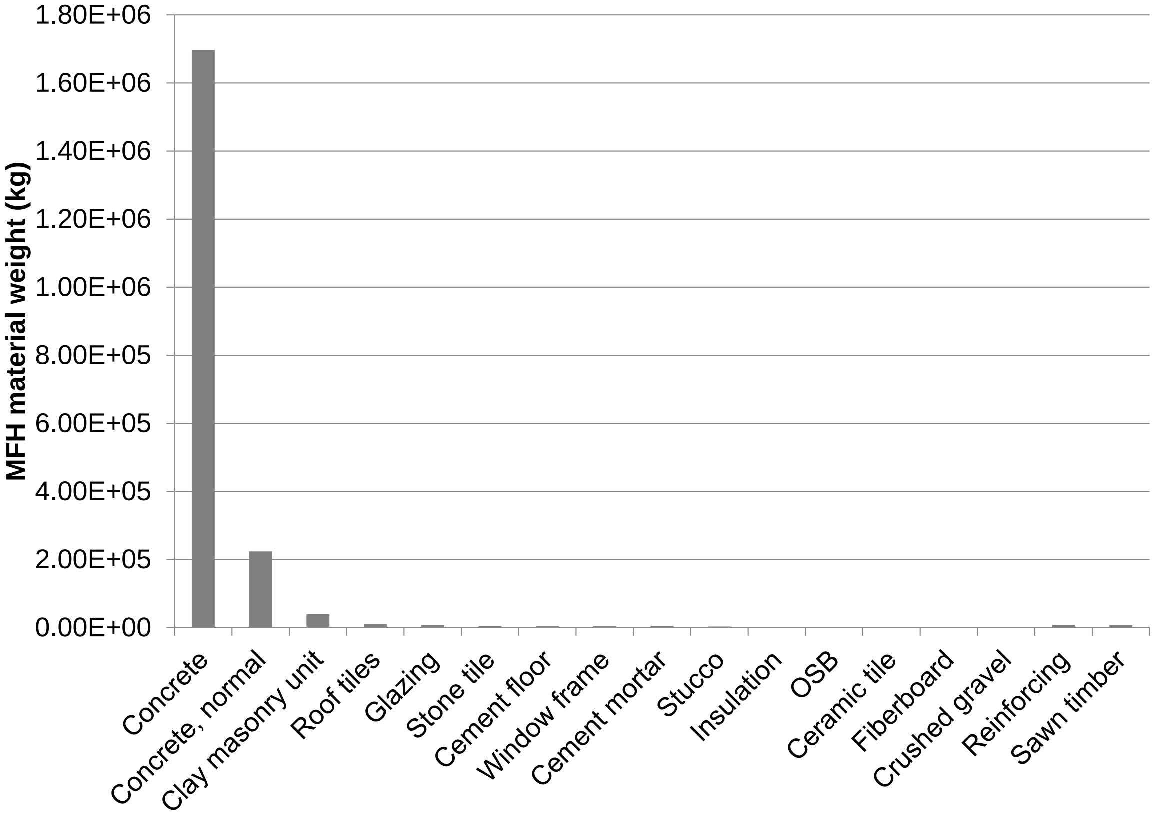

Figure 4.9: Multi-family house—material weights in kg.

Table 4.8: Embodied results for the multi-family house 1 of 2. Total impacts per square-meter, total impacts per person, and total impacts are presented.

Impact category	Total (/m^2)	Total (/person)	Total
Renewable energy (MJ)	4.01E+02	1.48E+04	4.69E+05
Non-renewable energy (MJ)	2.76E+03	1.02E+05	3.23E+06
GWP (kg CO_2-Eq.)	3.14E+02	1.16E+04	3.67E+05
ODP (kg CFC 11-Eq.)	1.97E-05	7.28E-04	2.30E-02
AP (kg SO_2-Eq.)	8.64E-01	3.20E+01	1.01E+03
EP (kg Phosphate-Eq.)	1.19E+00	4.39E+01	1.39E+03
POCP (kg Ethylene-Eq.)	3.70E-02	1.37E+00	4.33E+01

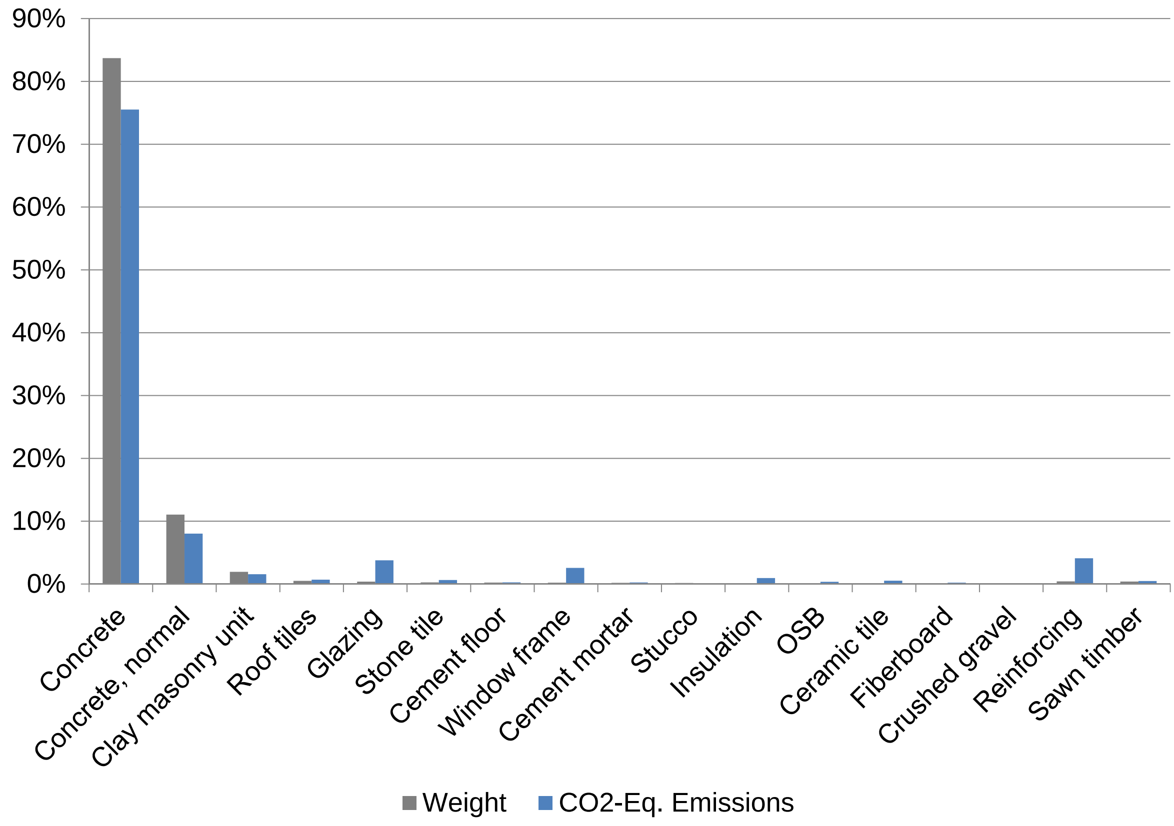

Figure 4.10: Multi-family house—material percentages and CO_2 emission percentages.

Table 4.9: Embodied results for the multi-family house 2 of 2. Total impacts are presented and broken down into percentages by material, transportation from the production site, and disposal.

Impact category	Total	Material (%)	Transport (%)	Disposal (%)
Renewable energy (MJ)	4.69E+05	96.9%	1.9%	1.2%
Non-renewable energy (MJ)	3.23E+06	65.2%	13.9%	20.8%
GWP (kg CO_2-Eq.)	3.67E+05	83.6%	7.2%	9.2%
ODP (kg CFC 11-Eq.)	2.30E-02	58.4%	15.9%	25.7%
AP (kg SO_2-Eq.)	1.01E+03	65.6%	13.7%	20.7%
EP (kg Phosphate-Eq.)	1.39E+03	54.7%	18.0%	27.3%
POCP (kg Ethylene-Eq.)	4.33E+01	74.7%	10.1%	15.2%

4.5.2 Row house results

For the row house, a house with three external walls (i.e., an edge house) and a house with two external walls (i.e., a house between others, the middle house) are evaluated. The following results refer to the middle house unless otherwise noted. The structural and architectural components are classified in 19 different materials. Similar to the multi-family house, concrete dominates (67%) the materials by weight; however, this percentage is smaller than the multi-family house (see figure 4.11 and figure 4.12 on the next page).

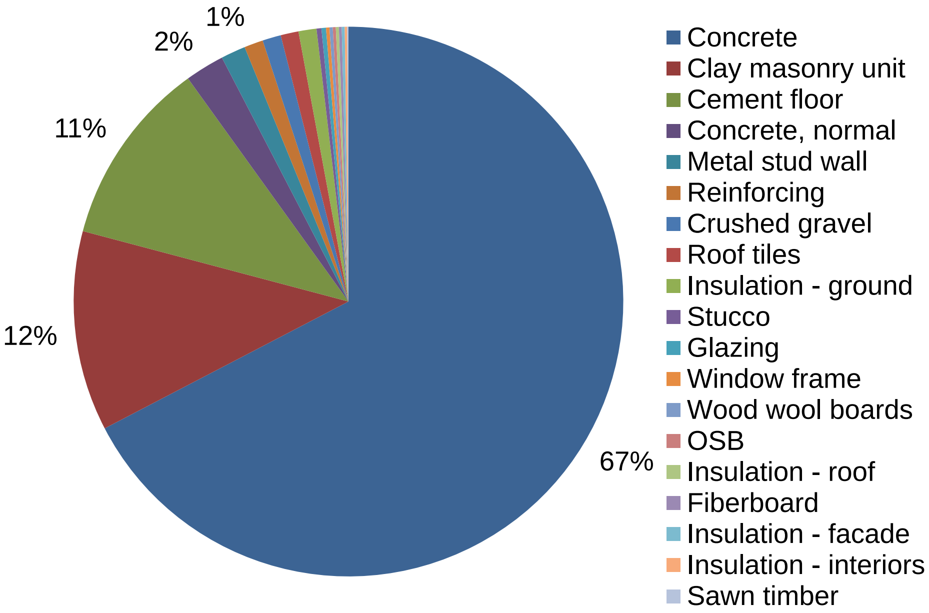

Figure 4.11: Row house (middle)—material percentages by weight. Similar to the multi-family house, concrete is the dominate material by weight.

Results are also presented for the comparison of material weight and material emissions as percentages (see figure 4.16 on page 59). The figure shows that concrete dominates the percentage of materials and also CO_2-Eq. emissions, but to a lesser extent (67% of material weight and 50% of emissions). Steel reinforcing is seen to have a relatively large emission percentage (9%) for its material proportion (1%). This is due to the high energy demands to produce steel [139].

The complete results for the entire house, and the normalized results, are presented in table 4.10 on the next page and table 4.11 on page 56. These values are for a middle house, but an edge house is also calculated. The edge row house has a slightly higher global warming potential (4.1%) and total energy demand (6.3%).

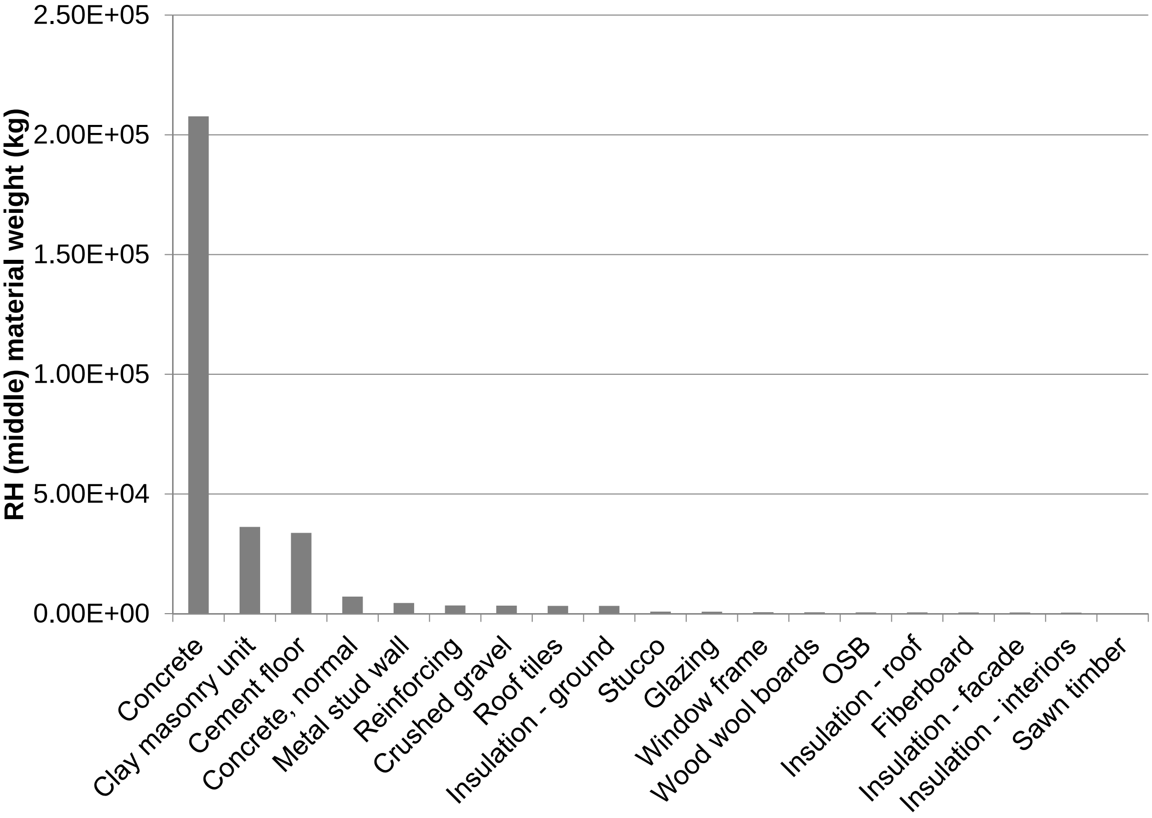

Figure 4.12: Row house (middle)—distribution of material weights.

Table 4.10: Embodied results for the row house (middle) 1 of 2. Total impacts per square-meter, total impacts per person, and absolute impacts are shown.

Impact category	Total (/m^2)	Total (/person)	Total
Renewable energy (MJ)	7.27E+02	2.91E+04	1.13E+05
Non-renewable energy (MJ)	4.41E+03	1.77E+05	6.89E+05
GWP (kg CO$_2$-Eq.)	4.26E+02	1.70E+04	6.64E+04
ODP (kg CFC 11-Eq.)	4.44E-05	1.78E-03	6.93E-03
AP (kg SO$_2$-Eq.)	1.22E+00	4.89E+01	1.91E+02
EP (kg Phosphate-Eq.)	1.36E+00	5.45E+01	2.13E+02
POCP (kg Ethylene-Eq.)	7.12E-02	2.85E+00	1.11E+01

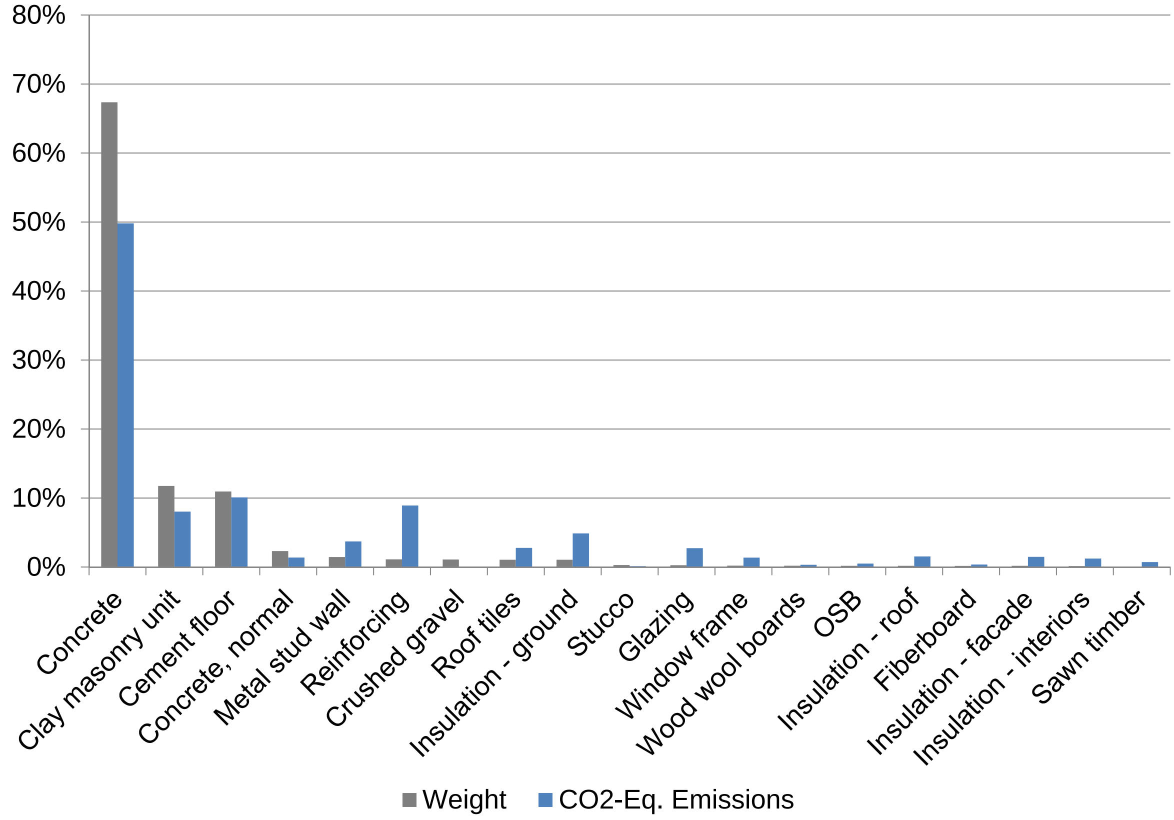

Figure 4.13: Row house (middle)—material percentages and CO_2 emission percentages. Although concrete is the largest material by weight, its emissions are proportionally less.

Table 4.11: Embodied results for the row house (middle) 2 of 2. Total impacts are presented and broken down into percentages by material, transportation from the production site, and disposal.

Impact category	Total	Material (%)	Transport (%)	Disposal (%)
Renewable energy (MJ)	1.13E+05	98.1%	1.3%	0.7%
Non-renewable energy (MJ)	6.89E+05	74.7%	10.8%	14.6%
GWP (kg CO_2-Eq.)	6.64E+04	86.0%	6.6%	7.4%
ODP (kg CFC 11-Eq.)	6.93E-03	78.6%	8.7%	12.7%
AP (kg SO_2-Eq.)	1.91E+02	71.5%	12.0%	16.5%
EP (kg Phosphate-Eq.)	2.13E+02	53.7%	19.3%	26.9%
POCP (kg Ethylene-Eq.)	1.11E+01	84.7%	6.5%	8.8%

4.5.3 Single family house results

The life-cycle assessment for the single family home evaluates 20 different materials. Similar to the multi-family house and row house, material weights are dominated by concrete (see figure 4.14 and figure 4.15 on the following page). The relationship between material weight and material emissions are shown in figure 4.16 on page 59 with similar findings as per the other two case studies. Cumulative results are summarized in table 4.12 and table 4.13 on the next page.

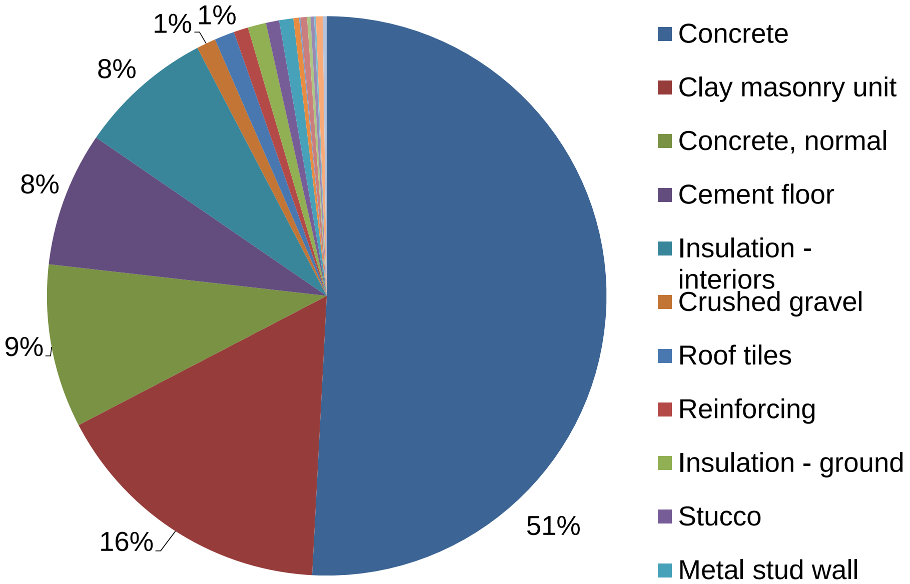

Figure 4.14: Single family house—material percentages by weight. Concrete makes up the majority of materials by weight, but is much less than the percentages for the multi-family house and row house.

Table 4.12: Embodied results for the single family house 1 of 2. Total impacts per square-meter, total impacts per person, and total impacts are presented.

Impact category	Total (/m^2)	Total (/person)	Total
Renewable energy (MJ)	1.04E+03	4.67E+04	1.28E+05
Non-renewable energy (MJ)	5.61E+03	2.51E+05	6.90E+05
GWP (kg CO_2-Eq.)	5.19E+02	2.32E+04	6.38E+04
ODP (kg CFC 11-Eq.)	5.82E-05	2.61E-03	7.16E-03
AP (kg SO_2-Eq.)	1.55E+00	6.93E+01	1.90E+02
EP (kg Phosphate-Eq.)	1.65E+00	7.40E+01	2.03E+02
POCP (kg Ethylene-Eq.)	8.85E-02	3.97E+00	1.09E+01

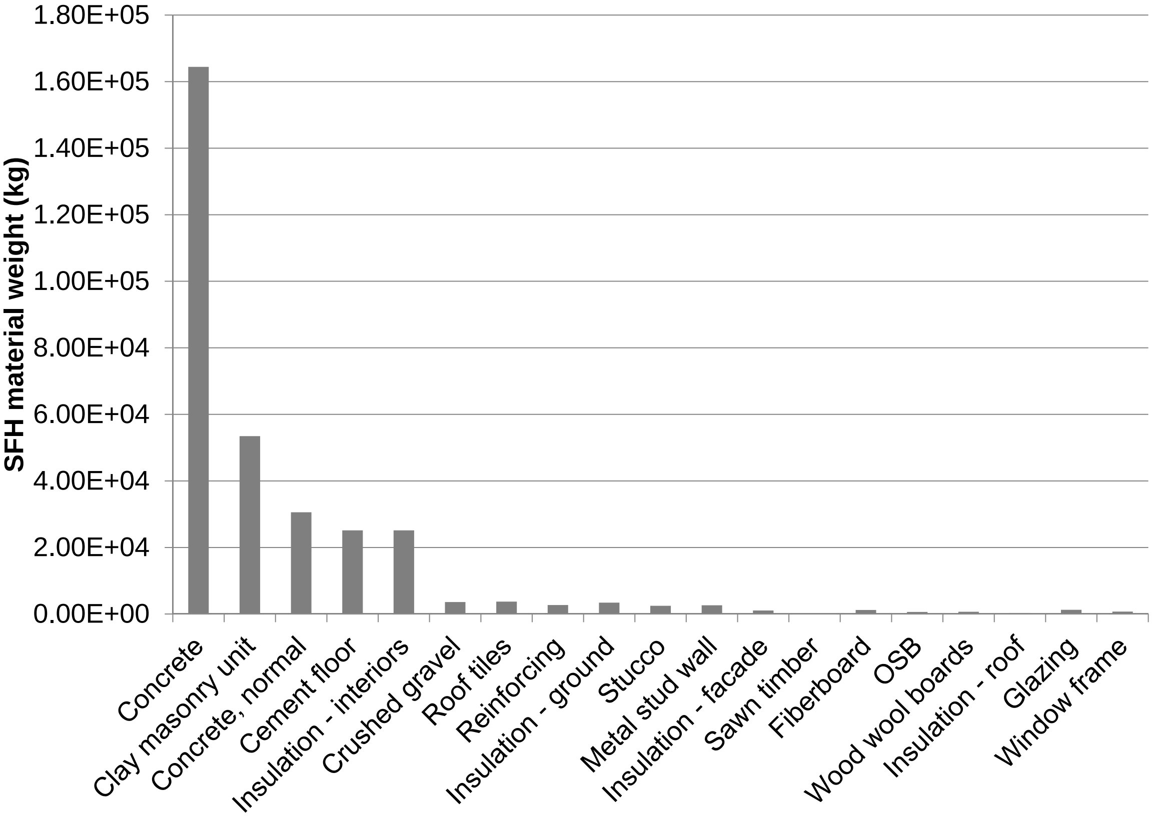

Figure 4.15: Single family house—material weights.

Table 4.13: Embodied results for the single family house 2 of 2. Total impacts are presented and broken down into percentages by material, transportation from the production site, and disposal.

Impact category	Total	Material (%)	Transport (%)	Disposal (%)
Renewable energy (MJ)	1.28E+05	98.3%	1.2%	0.6%
Non-renewable energy (MJ)	6.90E+05	75.2%	11.0%	13.8%
GWP (kg CO_2-Eq.)	6.38E+04	85.5%	7.0%	7.5%
ODP (kg CFC 11-Eq.)	7.16E-03	79.7%	8.6%	11.7%
AP (kg SO_2-Eq.)	1.90E+02	72.2%	12.3%	15.6%
EP (kg Phosphate-Eq.)	2.03E+02	52.7%	20.7%	26.5%
POCP (kg Ethylene-Eq.)	1.09E+01	84.7%	6.8%	8.5%

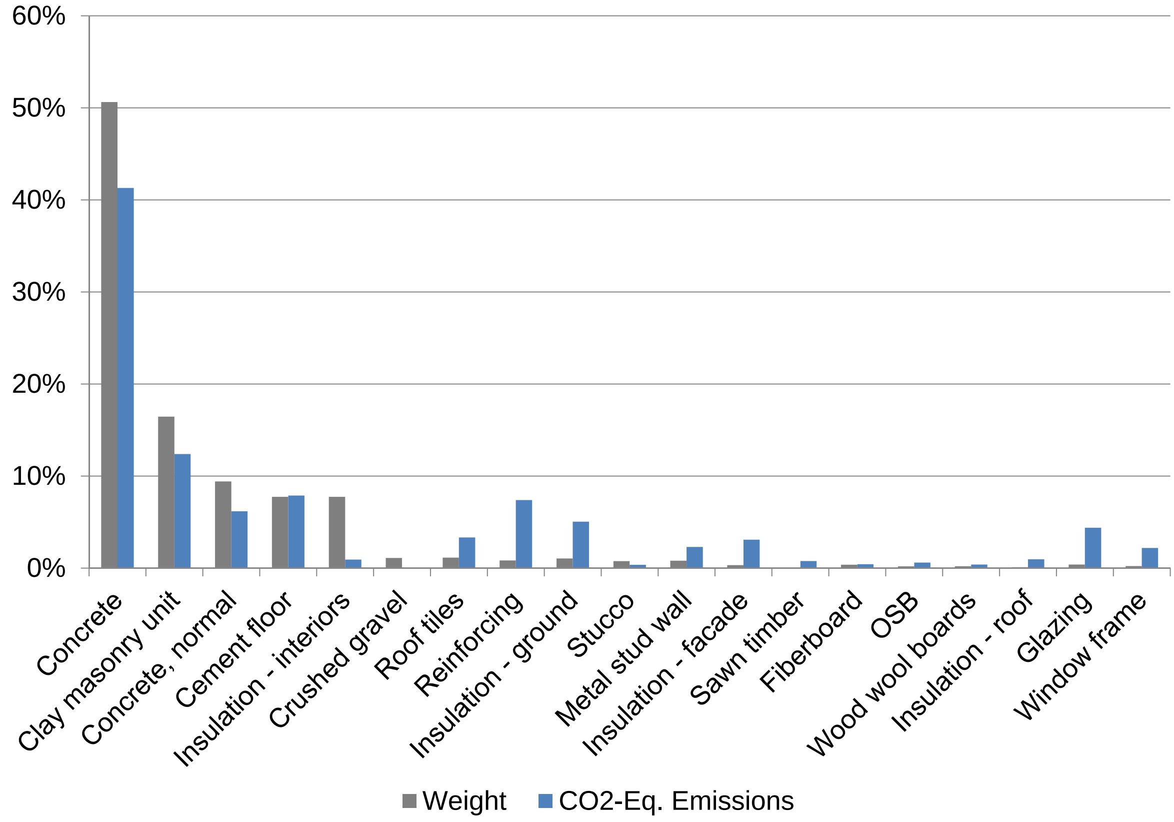

Figure 4.16: Single family house—material percentages and CO_2 emission percentages.

4.6 Discussion

The findings of the life-cycle assessment for the three case study buildings are compared to the scientific literature to verify their validity. The GWP emissions per floor area for the three buildings are juxtaposed with values from the literature [5, 59, 152] in figure 4.17. The average emissions are 408 kg/m^2 for the three case studies, which falls within the range of results from the literature. Concentrating on the case study findings, the multi-family house clearly has the lowest emissions per area followed by the row house (+39%) and then the single family house (+66% using the MFH as the reference). Thus, although the multi-family house has the largest net emissions (Table 4.8 on page 52, table 4.10 on page 55, and table 4.12 on page 57), once these results are normalized it has the smallest emissions.

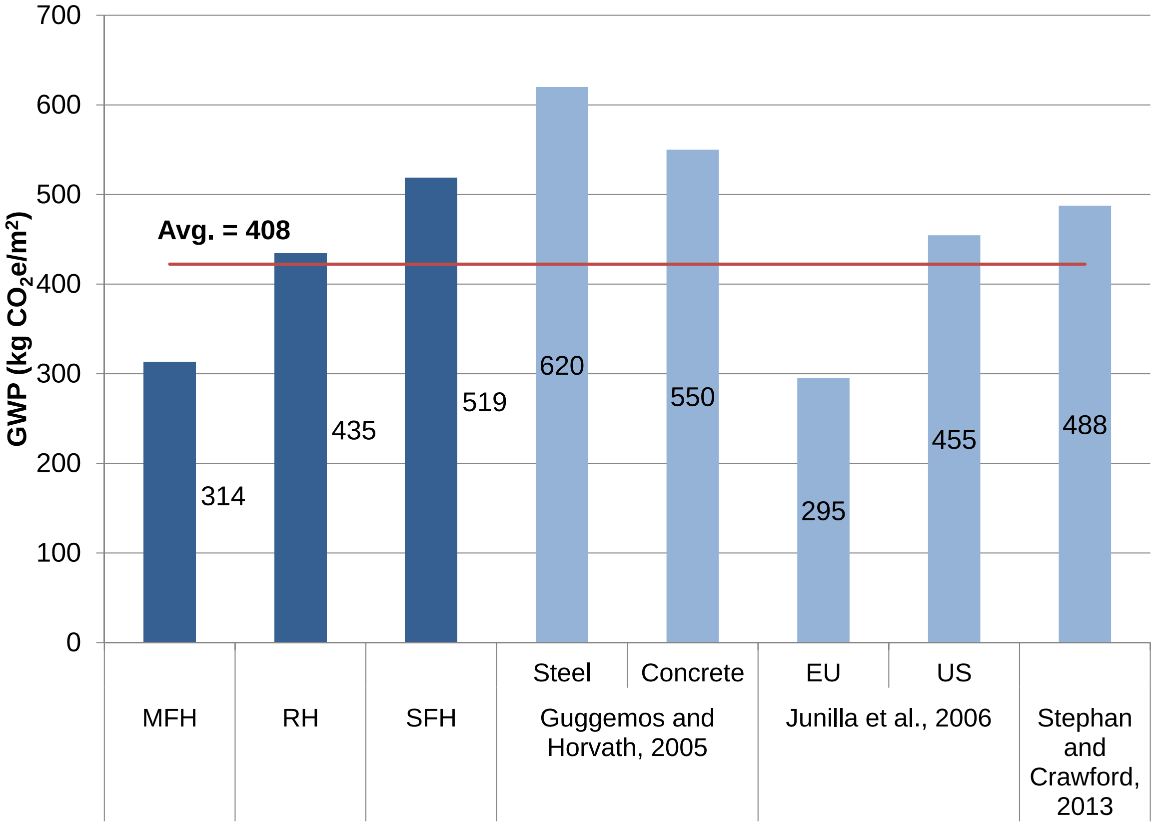

Figure 4.17: LCA GWP results for three case studies compared to the research literature. The average values of the multi-family house, row house, and single family house fall within the range of values seen in the literature.

The case study results are also presented based on the occupancy of the houses (table 4.6 on page 41). Figure 4.18 on the next page shows the CO$_2$-Eq. emissions per person for the multi-family house, row house - A (middle), row house - B (edge), and single family house. The total value is broken up into materials, transportation, and disposal, which are clearly dominated by material emissions. Comparing the case studies to the multi-family house (reference), row house - A, row house - B, and the single family house have 47, 53, and 100%

higher emissions (figure 4.18).

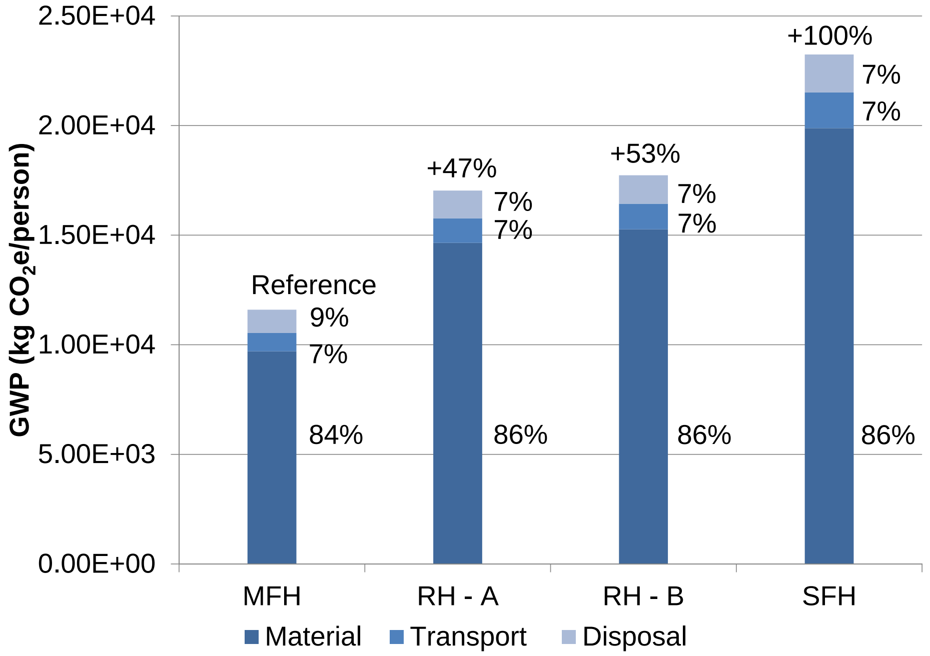

Figure 4.18: Comparison of GWP results between case studies. The results show that the MFH has the lowest embodied GWP emissions and the SFH has the highest embodied GWP emissions.

In addition to CO_2 emissions, the energy required for material production, transportation, and disposal per person are presented in figure 4.19 on the next page. The pattern of the results for energy is similar to the GWP emissions. Row house - A, row house - B, and the single family house are 58, 68, and 155% higher compared to the reference multi-family house. Energy demand is more sensitive to changes than GWP emissions.

The results show that materials dominate both embodied GWP emissions and energy. For GWP, transport emissions are 7% for all building types, and end-of-life emissions range from 7–9%. For energy, transportation makes up a slightly larger portion of total energy (9–12%). Disposal energy is also larger for GWP (i.e., 12-18%).

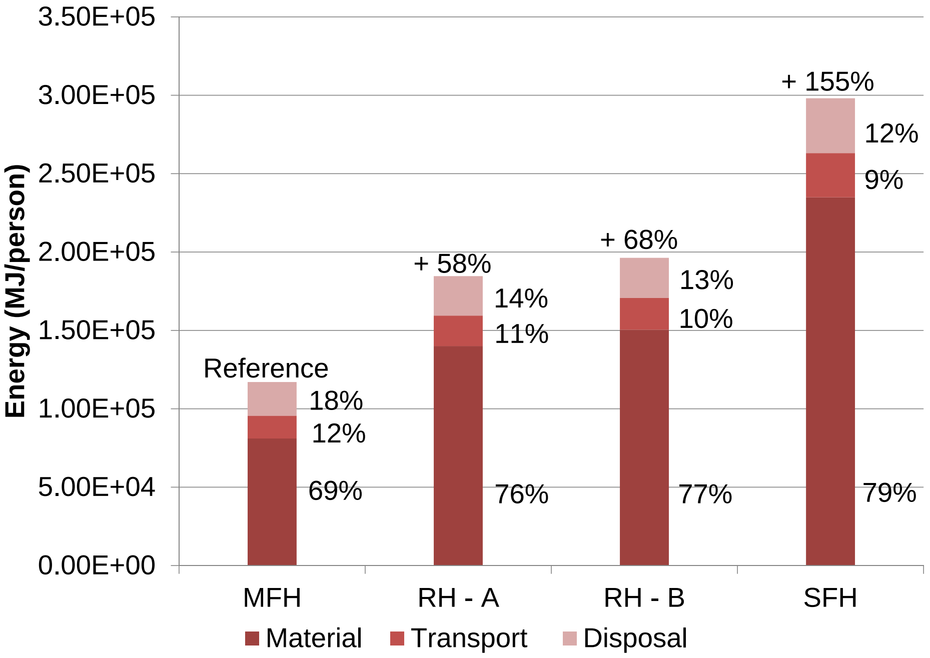

Figure 4.19: Embodied energy for the multi-family house, middle row house, edge row house, and the single family house. Similar to the GWP results, the MFH has the lowest embodied energy.

4.7 Conclusion

The life-cycle assessment of embodied impacts from buildings is a well-established research area. The work adds to the research state-of-the-art with three contributions. The first contribution is that instead of conducting a life-cycle assessment for random buildings as is often done, the chapter presents a new procedure to determine typical buildings representative of an urban region. This new method combines statistical analysis with actual market data to give defining characteristics for three buildings in the region. The characteristics of importance are found to be residential living space demand, building type (and future growth in building types), construction materials (i.e., the building structural system), building size (i.e., the floor area), and residents per building.

Using this new procedure, the characteristics of typical residential buildings are determined. The criteria for the buildings are then matched with recently constructed buildings in the *urban region of Munich*. The city center location is represented by a multi-family house, the periphery by a row house, and the district location by a single family house. The three residential case study buildings are then evaluated using life-cycle assessment. A process-based life-cycle assessment is used for the analysis utilizing data from the *Ecoinvent* and *Ökobau.dat* databases. The life-cycle system boundary accounts for raw material acquisition, transportation to the production site, production and manufacturing, transportation to the building site, and end-of-life treatment. Materials analyzed are from the construction plans and bill-of-quantities for the case studies and include both architectural and structural materials.

The second contribution of the work is the analysis showing that higher living space demand housing types have lower embodied environmental impacts. The findings show that environmental impacts are the lowest for the multi-family house followed by the row house and then the single family house. The row house has 39% higher emissions compared to the multi-family house, and the single family house has 66% higher emissions compared to the multi-family house. The results are found to be in line with existing scientific research. The findings also show that concrete dominates the building materials for all three case studies. For the multi-family house, concrete makes up 76% of total CO_2 emissions. Concrete makes up 50% and 41% of total CO_2 emissions for the row house and the single family house, respectively. While concrete has the highest percentage of CO_2 emissions, this percentage is lower than its material weight percentage.

In addition to assessing the impacts from typical embodied aspects (i.e., material acquisition, transportation, production, transport to site, and end-of-life), the analysis also captures indirect induced impacts. As outlined in Chapter 3: *Methodology*, analyzing buildings typologies across an urban region captures indirect induced impacts. These include factors including building type, building form, living space demand, construction materials, structural systems, shared building walls with neighboring buildings, and area of heat transfer.

Finally, the work contributes to the state-of-the-art by providing reference LCA results for three representative building types in the *urban region of Munich*. The specific results are also of interest as they provide reference values for embodied impacts. Designers can compare the embodied impacts to these reference values to determine the relative performance of their building. The results from the building embodied impacts will be combined with the remaining impact categories—building operational impacts, transportation embodied impacts, and transportation operational impacts.

Chapter 5

Building operational impacts

This chapter determines the building operational impacts for the three case study buildings. Operation impacts are the focus of considerable attention and often overshadow embodied impacts due to their assumed dominance over the lifespan of a building. The chapter first reviews the state-of-the-art in energy standards, which concentrate on operational impacts. The heating demand for each case study building is calculated using the German standards and simulation software. Hot water and electricity use are subsequently determined, and the associated environmental impacts are calculated based on life-cycle assessment data.

The research adds to the state-of-the-art by investigating the interplay between operational impacts and embodied impacts. A renovation scenario is modeled and the revised operational impacts are calculated. In addition, the required embodied impacts for the renovation are determined. A comparison of the embodied and operational impacts is done to determine the payback period—the amount of time for the operational impacts to equal the additional embodied impacts. Finally, the results for the operational impacts are evaluated in detail.

5.1 Introduction

Current environmental assessment of buildings focuses heavily on operational impacts (see Chapter 2: *Problem statement*). The dominance of operational impacts compared to embodied impacts (i.e., 85% versus 15%) [1, 64] is responsible for the concentration on the operational phase in both research and real world applications. Despite the extensive research already done on operational impacts, it is important to include these impacts for the integrated analysis of the new research methodology.

Building operational impacts result from heating, hot water, electricity, ventilation, and cooling. Based on the building operational energy codes for Germany, simulation software programs can determine these operational demands for given building characteristics and climate zones. Future building renovations to further reduce the building operational impacts must also be examined. In addition, the impact of the renovation on the building embodied impacts (i.e., through the new material demands) is currently missing from building operational impact analysis. The interplay between building operational and embodied impacts is crucial for an integrated and holistic analysis of impacts.

5.2 German energy regulations

5.2.1 EnEV 2007

In Germany the Energieeinsparverordnung (EnEV; English - Energy Saving Ordinance) sets requirements for operational energy demand in buildings [147, 153]. The EnEV 2007 standard gives prescriptive requirements for yearly primary energy demand for new residential buildings [153]. Per EnEV 2007, the maximum yearly primary energy demand (Q''_P in kWh/(m^{2}yr)) for new residential buildings is given by equation (5.1) [153]. The transmission heat loss (H'_T in W/(m^{2}K) is given by equation (5.2) [153]. These requirements are for new residential buildings, where the hot water is not predominately heated using electricity.

$$Q''_P = 50.94 + 75.29 \times \frac{A}{V_e} + \frac{2600}{(100 + A_N)} \tag{5.1}$$

$$H'_T = 0.3 + \frac{0.15}{(A/V_e)} \tag{5.2}$$

The reference variables required to calculate the operational energy demand per EnEV are

A, heat transfer surface area (Germ. wärmeübertragende Umfassungsfläche) [153];

V_e, heated building volume (Germ. beheizte Gebäudevolumnen), the volume of the enclosed heat transfer surface area [153];

A_N, building floor space (Germ. Gebäudenutzfläche), the energy reference floor area [153], defined as

$$A_N = 0.32\, m^{-1} \times V_e; \tag{5.3}$$

A/V_e, surface-area-to-volume ratio (Germ. A/V Vehältnis);

A_W, total window and door area (Germ. Fläche der Fenster und Türe);

A_{AW}, area of exterior walls (Germ. Fläche der Außenwände);

f, portion of window area (Germ. Fensterflächenanteil), defined as

$$f = \frac{A_W}{(A_W + A_{AW})} \tag{5.4}$$

Based on these reference values it is possible to calculate the maximum yearly primary energy demand and the transmission heat loss. The yearly primary energy demand (Q_P) represents the summation of the yearly heating demand and the hot water demand multiplied by the energy efficiency ratio (equation (5.5) on the facing page).

Q_P, yearly primary energy demand, (Germ. Jahres-Primärenergiebedarf), defined as

$$Q_P = (Q_h + Q_W) \times e_P \tag{5.5}$$

e_P, energy efficiency ratio, primary energy related (Germ. Anlagenaufwandszahl, primärenergiebezogen) is determined by the Q_h and A_N per Figure C.5.1.1 in Appendix 1 [154].

Yearly hot water demand (Q_W) is limited in EnEV to 12.5 kWh/(m^{2}yr) [153]. Thus having the primary energy demand and the hot water demand, only the energy efficiency ratio is needed to calculate the heating demand. Heating demand is determined using the following equations;

Q_h, yearly heating demand (Germ. Jahres-Heizwärmebedarf) [153]:

$$Q_h = 66 \times (H_T + H_V) - 0.95 \times (Q_S + Q_i) \tag{5.6}$$

H_T, specific transmission heat loss based on the heat transfer surface area (Germ. Spezifischer Transmissionswärmeverlust) [153]):

$$H_T = H'_T \times A \tag{5.7}$$

H_V, specific ventilation heat loss without a tightness test (Germ. Spezifischer Lüftungswärmeverlust) [153]:

$$H_V = 0.19 \times V_e \tag{5.8}$$

Q_S, solar gain (Germ. Solare Gewinne) [153]:

$$Q_S = \sum (I_S)_{j,HP} \times \sum 0.567 \times g_i \times A_i \tag{5.9}$$

where I_S, H_P, represents the solar irradiance, and j the orientation. I_S for south to south-west irradiance is 270 kWh/(m^{2}yr), for north-west to north-east irradiance is 100 kWh/(m^{2}yr), for all other orientations irradiance is 155 kWh/(m^{2}yr) [153].

Q_i, internal heat gain (Germ. Interne Gewinne) [153]:

$$Q_i = 22 \times A_N \tag{5.10}$$

5.2.2 EnEV 2009, EnEV 2014 and KfW standards

In comparison to the prescriptive values in EnEV 2007, the updated EnEV 2009 sets maximum primary energy demand based on the results of a simulated reference building with specified characteristics (i.e., U-values, air tightness of the envelope, heating system, hot water system, and ventilation system) [147].

EnEV 2009 revised the maximum heat transfer coefficients (i.e., U-values) for individual building parts. U-values from EnEV 2007 where updated in EnEV 2009 as follows (units of

W/(m^{2}K)): outer walls – 0.45 to 0.24 (-47%), windows and glazed doors – 1.70 to 1.30 (-24%), roofs – 0.30 to 0.24 (-20%), flat roofs – 0.25 to 0.20 (-20%), and walls/slabs against earth – 0.50 to 0.30 (-40%) [147]. From these five main building components, the net U-value decreased by 28.75% from EnEV 2007 to EnEV 2009. However, this assumes that each building component represents an equal portion of the building in question. A more accurate calculation of the change in heating demand between the standards must take into account the proportion of each building component with regards to the building in question.

As of May 2014, EnEV 2014 is the energy standard in effect throughout Germany [**EnEV2014**]. EnEV 2014 specifies enhanced requirements for new buildings, but does not change any requirements from EnEV 2009 for existing buildings. The most important changes in EnEV 2014 are as follows: 1) average reduction of 25% in yearly primary energy demand, 2) average increase of 20% in heat transfer coefficient, and 3) adaptation of the nearly zero energy building standard for all new buildings starting in 2021. The research in the thesis is based on EnEV 2009 as this was the standard in place during the start of the project.

While the EnEV ordinance is legally binding for new residential buildings in Germany, additional voluntary standards are given for lower primary energy demand than EnEV. The KfW (Kreditanstalt für Wiederaufbau; English: Credit Institution for Reconstruction) has the Effizienzhaus (English: Efficient House) standard 85, 70, 55, and 40, which limits the primary energy demand to 85, 70, 55, and 40% the value from the EnEV 2009 standard, respectively [155]. In addition to the EnEV ordinance and the KfW voluntary standards, there are numerous other voluntary standards. The operational energy calculations for the research will focus on the EnEV ordinance as this provides a wide range of primary energy values for new residential buildings in Germany.

In addition to the current energy standards, future operational energy requirements are also of importance when examining the impacts over the life-cycle of the building. As such, future changes to the energy standards are accounted for via a renovation scenario and is described in detail subsequently.

5.3 Characteristics of the building case studies

The research determines the operational energy demand for the case study buildings. The first building type is the multi-family house (MFH) in the city center of Munich. The second building type is the row house (RH) in the city periphery. Two row houses configurations are examined: a row house between other row homes (i.e., with only two exterior walls) (RH - A) and a row house on the exterior of the homes with three exterior walls (RH - B). The third and final building type is a single family house (SFH) located outside Munich. Basic characteristics of each case study required for operational energy calculations are presented in table 5.1 on the next page. More extensive information about the case study buildings are summarized in Chapter 4: *Building embodied impacts*.

Table 5.1: Case study building characteristics for operational calculations. MFH: multi-family house, RH - A: middle row house, RH - B: interior row house, SFH - single family house.

	MFH	RH - A	RH - B	SFH
Heated area (m^2)	1170	156	156	123
Heated volume (m^3)	3657	488	488	385
Stories	5	3	3	2
Roof area (m^2)	268	51	51	69
Exterior wall area (m^2)	327	55	120	113
Building footprint (m^2)	211	60	60	64
Southern window area (m^2)	116	23	23	16
East and West window area (m^2)	0	0	8	27
North window area (m^2)	139	6	6	7

5.4 Heating and hot water calculations

5.4.1 Heating calculations

The heating demand values were calculated using advanced simulation software [156]. The software uses a stochastic model to simulate the current and future energy demand of buildings based on the life-span of building components and energy regulations [157]. The methodology utilizes the life-span of building components to model the building envelope [157]. The initial model calculated the thermal heat demand for the regional building stock [157], and this methodology was expanded for a building stock of 3.5 million buildings [158].

In order to compare the operational impacts based on the building type, several design criteria are held constant for each building. First, all buildings have 2012 as the first year of operation and meet the EnEV 2009 standard. Second, the buildings do not have solar collectors, air conditioning, or ventilation systems. The g-value (solar heat gain coefficient) is taken as 0.60 per the requirements for the reference building in EnEV 2009 [147].

For the building heating systems, the same unit is used for all buildings despite a variation in floor space to maintain consistency and as the energy conversion efficiency would be similar in the end for other units. The system used is a central building heating unit containing a water heater and a heating unit with an energy conversion efficiency ratio (Germ. Wirkungsgrad) of 0.7968 powered with natural gas.

5.4.2 Future energy renovation

In order to examine the building over a longer time frame, future energy renovations are considered. The current renovation rate is 0.8% per year, and the federal renovation program has set a goal of 2% per year [159]. A technical study of energy renovations in Bavaria reviewed the impact of a “moderate renovation rate” of 5% per year and an “aggressive renovation rate” of 10% per year [159]. Assuming a renovation rate between the federal goal and the moderate rate, a rate of 3% per year is used. Thus the buildings would be renovated in 33 years (i.e., in 2045). Renovations are considered for the roof, exterior walls, and windows through decreased U-values for these elements. Renovation of the ground slab is not considered at this is unlikely for an existing building. Thus the buildings are evaluated with initial U-values from EnEV 2009 and then reevaluated with revised U-values based on estimated future U-value requirements [159]. The initial and final U-values used for the calculations are presented in table 5.2.

Table 5.2: Initial and renovation U-values for the operational life-cycle analysis. Units of W/(m^2K).

	Initial [147]	Renovation [159]
Roof	0.24	0.12
Exterior walls	0.24	0.15
Ground floor	0.5	0.20
Windows	1.3	0.80

5.4.3 Heating simulation results

Nemeth and Lindauer calculated the operational energy for the three case study buildings [156]. Information regarding the methodology and background for the calculation program is described briefly above and in detail in several reports [157, 158, 160]. The simulation model was run for the multi-family house (table 5.3 on the next page), row house (A) (table 5.4 on the facing page), row house (B) (table 5.5 on the next page), and the single family house (table 5.6 on page 72). The calculations were run for an initial year (2012) and then for three renovation scenarios: exterior wall renovation, roof renovation, and window renovation. Each renovation results in a higher thermal performance of the element in question. The detailed results of the simulations are presented in table 5.3 on the next page, table 5.4 on the facing page, table 5.5 on the next page, and table 5.6 on page 72.

Table 5.3: Results for the MFH [156, 158]. Units are (kWh/yr) unless otherwise noted, specific (spec.) values are (kWh/m^{2}yr).

	2012	Wall renov.	Roof renov.	Window renov.
Heated area (m^2)	1,170	1,170	1,170	1,170
Spec. heating demand	22.3	20.6	18.8	11.6
Heating demand	26,045	24,102	21,979	13,534
Primary energy demand	34,380	31,814	29,012	17,865
Final energy demand	31,255	28,922	26,375	16,241
CO_2 heating (kg/yr)	7,626	7,057	6,435	3,963
Spec. hot water demand	12.5	12.5	12.5	12.5
Primary energy water	19,305	19,305	19,305	19,305
End energy water	17,550	17,550	17,550	1,7550
CO_2 Water (kg/yr)	4,282	4,282	4,282	4,282

Table 5.4: Results for the RH - A (middle) [156, 158]. Units are (kWh/yr) unless otherwise noted, specific (spec.) values are (kWh/m^{2}yr).

	2012	Wall renov.	Roof renov.	Window renov.
Heated area (m^2)	156	156	156	156
Spec. heating demand	24.8	22.7	20.1	13.8
Heating demand	3,864	3,539	3,134	2,155
Primary energy demand	5,913	5,416	4,797	3,297
Final energy demand	5,376	4,924	4,360	2,998
CO_2 heating (kg/yr)	1,312	1,201	1,064	731
Spec. hot water demand	12.5	12.5	12.5	12.5
Primary energy water	2,984	2,984	2,984	2,984
End energy water	2,713	2,713	2,713	2,713
CO_2 Water (kg/yr)	662	662	662	662

Table 5.5: Results for the RH - B (edge) [156, 158]. Units are (kWh/yr) unless otherwise noted, specific (spec.) values are (kWh/m^{2}yr).

	2012	Wall renov.	Roof renov.	Window renov.
Heated area (m^2)	156	156	156	156
Spec. heating demand	34.8	30.2	27.6	19.6
Heating demand	5,429	4,717	4,312	3,065
Primary energy demand	8,309	7,218	6,599	4,691
Final energy demand	7,553	6,562	5,999	4,265
CO_2 heating (kg/yr)	1,843	1,601	1,464	1,041
Spec. hot water demand	12.5	12.5	12.5	12.5
Primary energy water	2,984	2,984	2,984	2,984
End energy water	2,713	2,713	2,713	2,713
CO_2 Water (kg/yr)	662	662	662	662

Table 5.6: Results for the SFH [156, 158]. Units are (kWh/yr) unless otherwise noted, specific (spec.) values are (kWh/m^{2}yr).

	2012	Wall renov.	Roof renov.	Window renov.
Heated area (m^2)	123	123	123	123
Spec. heating demand	52.9	47.4	43.0	29.5
Heating demand	6,509	5,836	5,285	3,625
Primary energy demand	9,823	8,807	7,975	5,876
Final energy demand	8,930	8,006	7,250	4,973
CO_2 heating (kg/yr)	2,179	1,953	1,769	1,213
Spec. hot water demand	12.5	12.5	12.5	12.5
Primary energy water	2,320	2,320	2,320	2,320
End energy water	2,109	2,109	2,109	2,109
CO_2 Water (kg/yr)	515	515	515	515

5.4.4 Hot water demand

In comparison to the simulation tool used to determine heating demand, hot water demand is based on the prescriptive values from EnEV 2009 [147]). According to EnEV 2009 heating demand is to be taken as 12.5 kWh/m^{2}yr. The building renovation only affects the heating demand and hot water demand is held constant throughout the building lifespan as per [159]. The hot water demand values are summarized in table 5.3 on page 71, table 5.4 on page 71, table 5.5 on page 71, and table 5.6.

5.5 Electricity

In addition to heating and hot water, the operational phase of a building includes electricity. Detailed electricity consumption per household size in Germany is available in the research literature [161]. Based on this report, cooking and lighting requires 314 kWh/person-year for all households with at least 2 persons [161]. Electricity for refrigerators, freezers, dishwashers, washers, TVs, DVDs, and computers for households with at least 2 persons require 565 kWh/person-year [161]. Thus, average electricity demand is 819 kWh/person-year. From this 31% is from cooking and electricity and 69% is from appliances and electronics.

Having determined electricity, heating, and hot water demand all operational requirements for the building are known. The results for heating and hot water are given in kg CO_2 and MJ [156], but the electricity demand must be converted into these units using life-cycle data information. The life-cycle assessment process “electricity mix, Germany” from *Ecoinvent* is used to convert kWh into environmental impacts [139]. This dataset is based on the typical electricity mix in Germany.

5.6 Building operational and embodied impacts

5.6.1 Influence of building renovations on embodied impacts

While the renovation of a building reduces the operational impacts, it results in additional embodied impacts. These additional impacts must be accounted for if the assessment is to illustrate the integrated interactions between the impact categories. As outlined above, the building renovation focuses on improving the thermal performance of the buildings through improved U-values (table 5.2 on page 70). This improvement in the U-values requires that the old insulation is removed and disposed of and new insulation is installed. This in turn also involves the transportation of the new insulation to the building site and its end-of-life disposal.

Based on the original U-values, U_0, the new insulation material required to achieve the renovated U-values, U_1, must be calculated. The U-value for the building component (i.e., wall, roof) is determined by equation (5.11) and equation (5.12). Where $R_{insulation}$ is the thermal resistance of the insulation, R_{SI} is the resistance of the internal surface, R_{SO} is the resistance of the outside surface, R_A is the resistance of air cavities, R_1 is the resistance of material 1, R_2 is the resistance of material 2, and so on for all materials in the element. Using these equations, the thickness of new insulation is calculated for the renovation of the exterior walls and roof for each building. All windows are entirely replaced for the renovation scenario. These embodied impacts are also taken into account.

$$U_1 = \frac{1}{\frac{1}{U_0} + \frac{1}{R_{insulation}}} \tag{5.11}$$

$$U = \frac{1}{R_{SI} + R_{SO} + R_A + R_1 + R_2 + ...} \tag{5.12}$$

After determining the material demands for the renovations, a life-cycle assessment, as outlined in Chapter 6: *Transportation embodied impacts*, is done. The influence of the renovation on embodied impacts are shown in figure 5.1 on the following page and figure 5.2 on page 75. The initial construction scenario (I) accounts for all impacts for the original construction as per Chapter 6. The renovation scenario (R) represents all the embodied impacts for the building including the renovation (i.e., the initial building construction and the end-of-life disposal are included).

The results for embodied CO_2 emissions illustrate that the renovation makes up 7–14% of all emissions. The multi-family house has the smallest increase in embodied CO_2 emissions (7.2%), while the edge row house (RH-B) has the largest increase (13.8%). The relative percentage of CO_2 emissions from materials, transport, and disposal remains largely unaffected between the initial and renovation scenarios as expected. For embodied energy, there is a larger increase between the initial and renovation scenario: 15–20%. Similar to the CO_2 emissions, the multi-family house has the smallest increase in embodied energy (15.1%), while the edge row house has the largest increase (20.2%).

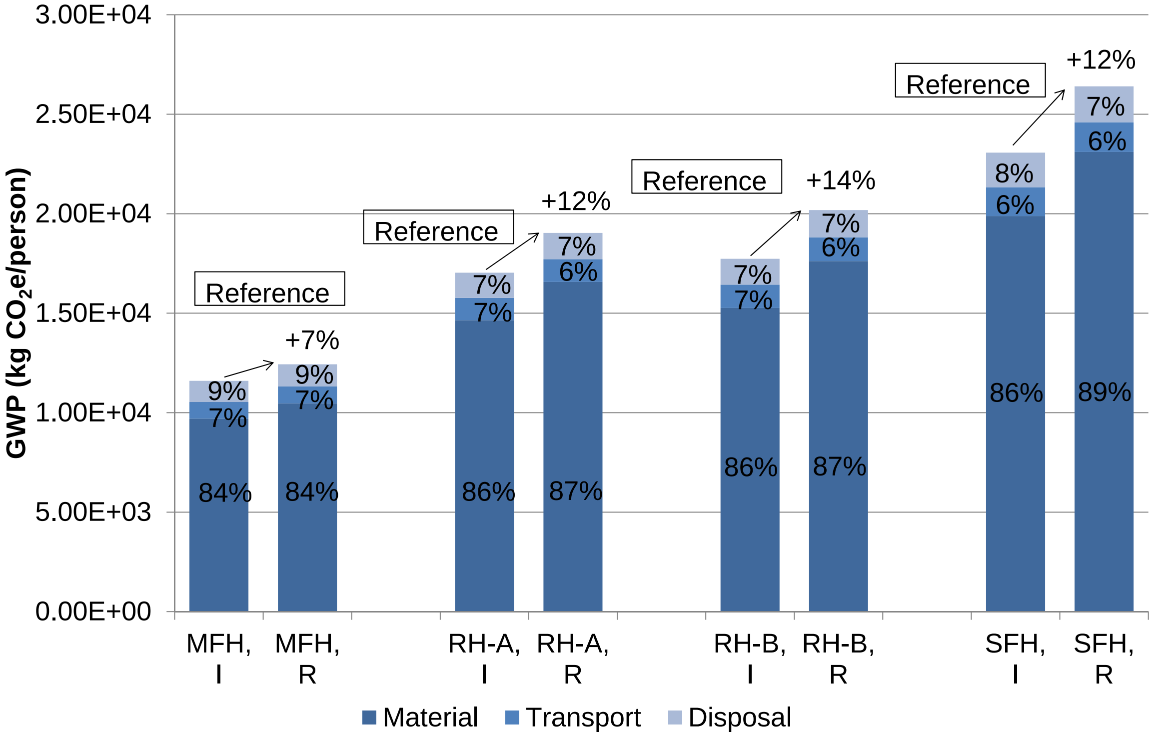

Figure 5.1: The influence of building renovation on total embodied CO_2 emissions comparing the initial construction (I) and the renovation (R) for the three housing types.

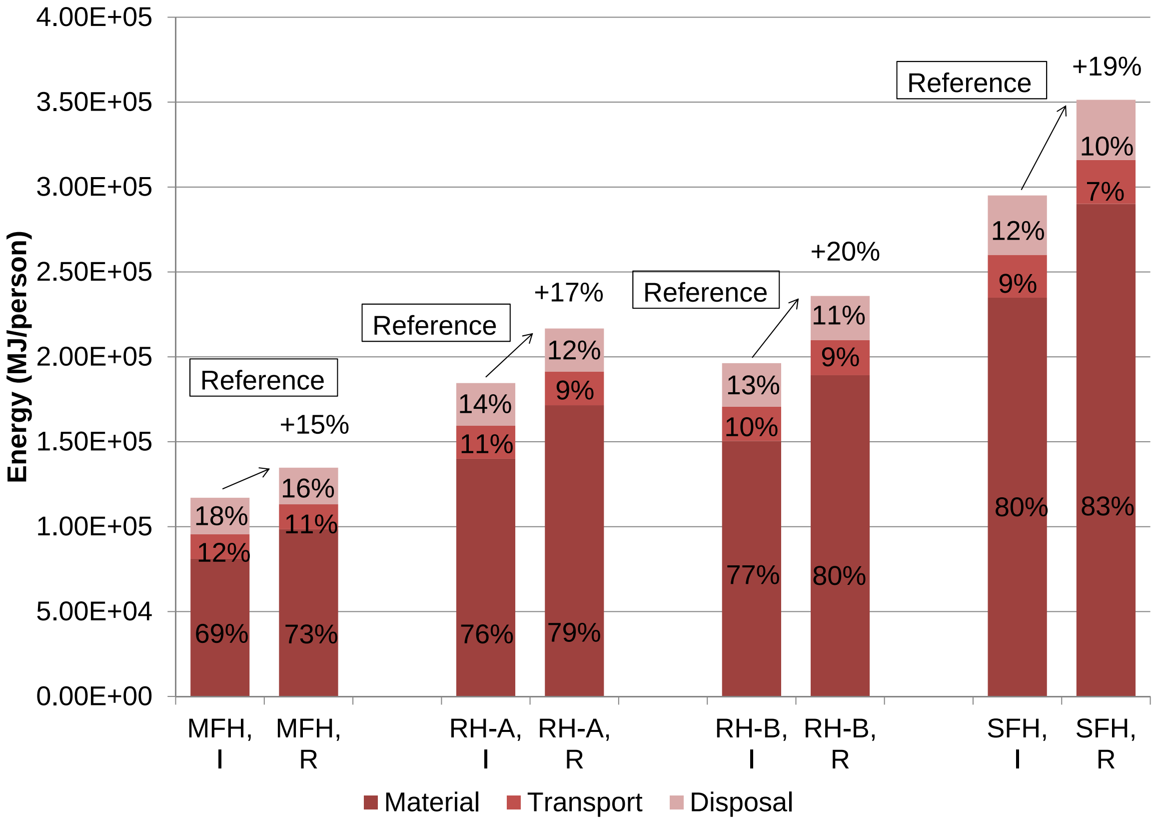

Figure 5.2: The influence of building renovation on total embodied energy comparing the initial construction (I) and the renovation (R) for the three housing types.

5.6.2 Payback period

The research calculates the interrelation between building embodied impacts and building operational impacts. Another critical figure relating embodied and operational impacts is the payback time—the number of years of operation required for operational impacts to match the embodied impacts. Payback assessment is useful in determining the relative importance of embodied and operational impacts. In addition, the time frame for renovation paybacks must be considered.

The results shows that the initial payback period for operational CO_2 emissions ranges from 13 to 16 years for the initial construction (figure 5.3). This initial phase refers to the original building embodied impacts and operational performance prior to the renovation. The initial energy paybacks are even lower and range from 8 to 11 years. The renovation embodied impacts (i.e., only the impacts from the renovation process itself) are compared against the new (and lower) operational impacts. The payback time for renovation embodied impacts for CO_2 emissions and energy range from 1 to 3 years. For both the initial and renovation scenarios, the multi-family house has the shortest payback period and the single family house has the longest period.

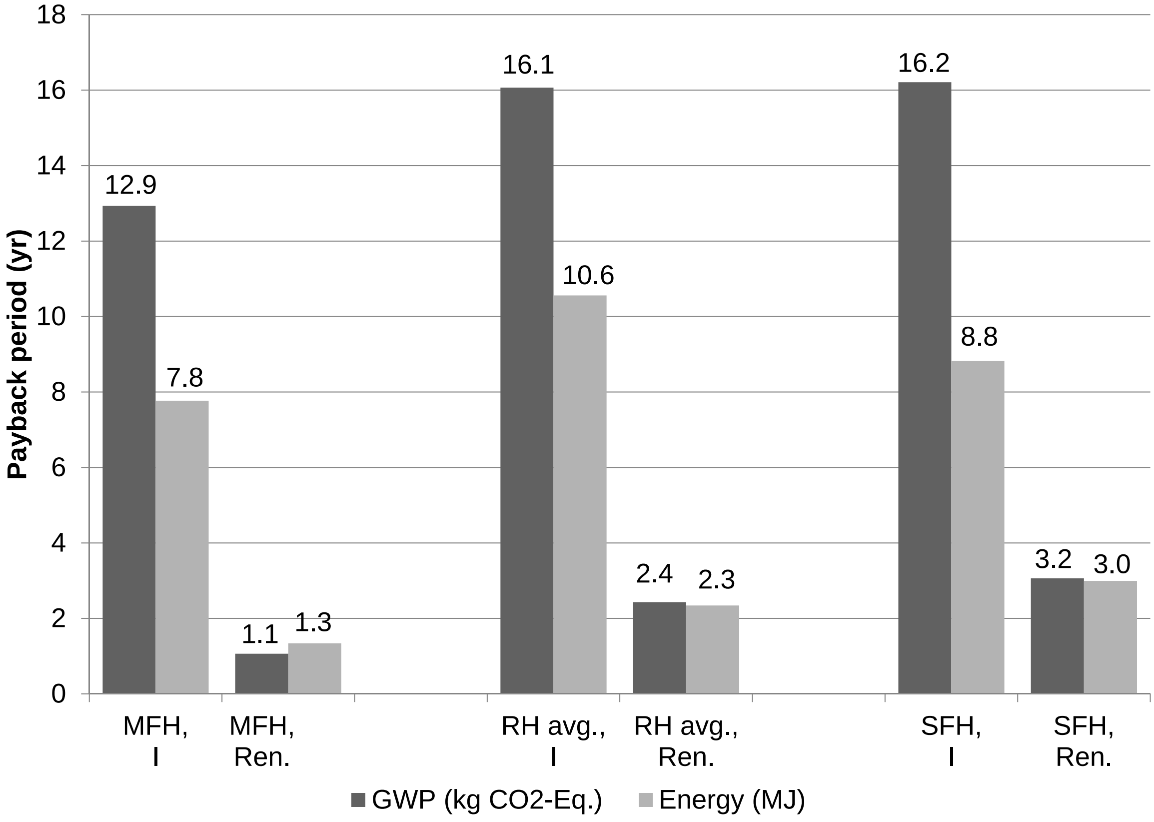

Figure 5.3: Payback period for the initial construction (I) and the renovation (R) for the three housing types.

5.7 Results and discussion

The environmental impacts for heating, hot water, and electricity are presented in figure 5.4 on the next page and figure 5.5 on page 79. Figure 5.4 on the next page illustrates the CO_2 emissions for each housing type for both the initial scenario and the renovation scenario. See section 5.4.2 on page 69 for details of the renovation including when the renovation is to take place. Only the heating demand is affected by the renovation—hot water and electricity remain constant. In addition, the total reductions in operational CO_2 emissions due to the renovation for each building type is presented.

The operational CO_2 emissions are the lowest for the multi-family house. The middle row house (A) has lower emissions than the edge row house (B). This is expected as there are only two exterior walls for the middle house, and thus less transmission area for heat loss. The single family home has the highest operational emissions. The largest potential savings from renovation is for the single family house (23%), whereas the multi-family house only has a savings potential of 13%.

Electricity makes up the largest share of emissions for the multi-family house and both row houses. Heating makes up the largest proportion (51%) of emissions for the single family house before renovations. Only after renovating does electricity once again make up the largest share (48%) of emission for the single family house. The results clearly indicate that heating demand is directly related to building type, size, and construction, as well the influence of neighboring building walls.

Results for operational energy demand are similar to CO_2 emissions (figure 5.5 on page 79). Once again energy demand is the lowest for the multi-family house followed by the row house and then the single family house. Electricity dominates operational energy demand for the multi-family house (59%) and increases in importance following the renovation (67%) due to the reduced heating demand. The proportion of energy demand from electricity decreases in the row house and is the smallest (in percent) for the single family house. Again, heating in the single family house prior to renovation is the largest share of total energy demand (51%).

The results also illustrate the interrelation between building embodied and building operational impacts. The future scenario of renovating the building for improved operational performance requires the investment of additional embodied impacts. The work shows that embodied CO_2 emissions for the renovation increase the net emissions 7–12%, and energy by 15–20% (figure 5.1 on page 74 and figure 5.2 on page 75). While these seem like significant values, review of the payback period (i.e., the number of years it takes operational impacts to equal embodied impacts) reveals a short payback period. The initial embodied CO_2 emissions have a 13–16 year payback and embodied energy has a payback of 8–11 years (figure 5.3 on page 76). Given the 60 year time lifespan of the building, these payback periods are relatively short. Also, the additional embodied impacts from renovation have a short payback period of 1–3 years. These values are calculated using the lower operational impact level after the renovation. The interplay of embodied and operational impacts is nonetheless an important

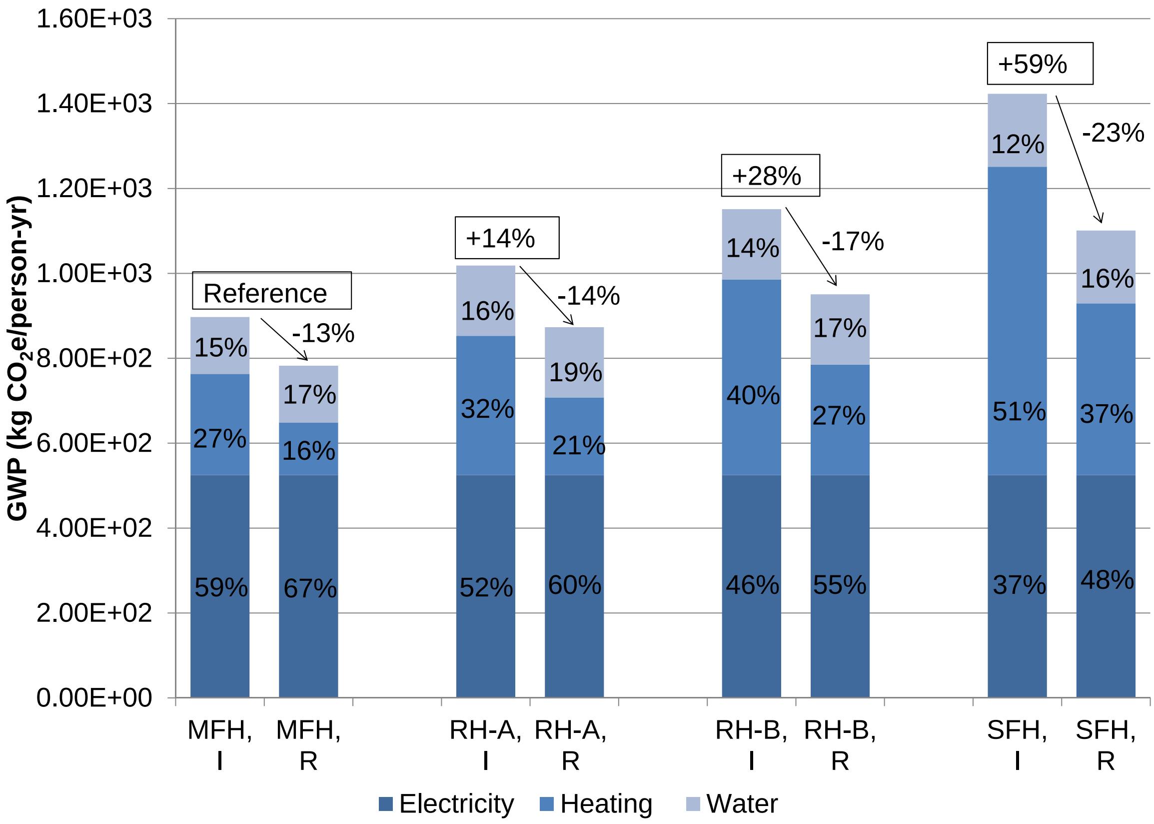

Figure 5.4: Total building operational emissions results for the multi-family house (MFH), middle row house (RH-A), edge row house (RH-B), and single family house (SFH). The initial scenario (I) and the renovation scenario (R) are shown.

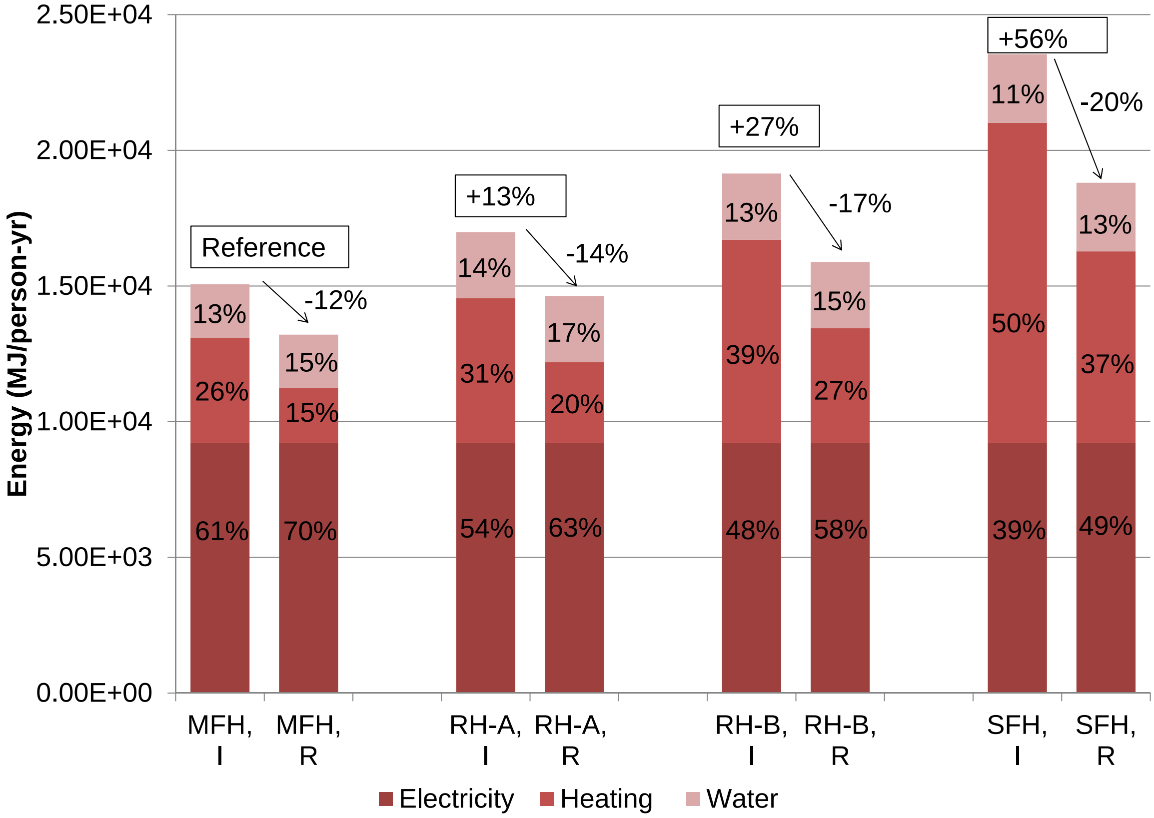

Figure 5.5: Total building operational energy results for the multi-family house (MFH), middle row house (RH-A), edge row house (RH-B), and single family house (SFH). The initial scenario (I) and the renovation scenario (R) are shown.

topic, and holistic analysis must account for these often overlooked interactions.

5.8 Conclusion

Environmental analysis of buildings focuses significant attention on operational impacts. While increasing attention is paid to building embodied impacts, operational impacts remain the main topic of concern as illustrated by Germany energy guidelines. In order to quantify the significance of induced impacts and to ensure an integrated approach to environmental assessment of the built environment, the operational impacts for the three case study buildings are determined. The building operational phase covers heating, hot water, and electricity use. Using the latest German energy codes and simulation software, the heating demand for each building is calculated. Hot water and electricity use are determined for the buildings based on the research literature. Given the long lifespan of buildings, an energy renovation is realistic for all the case studies. As such, the operational impacts are calculated for a future renovation scenario.

The results show that per person operational emissions and energy are lowest for the multi-family house followed by the row house and then the single family house. The middle row house (with a building on either side) has lower heating demand than the edge row house (with three external walls) due to the increased area of transmission losses. Based on the results, minimizing emissions and energy in multi-family houses should focus on electricity. Attention can be focused on reducing electricity demand (i.e., appliances with low electricity demand) and reducing the emissions per unit of electricity in the electricity mix. Heating demand remains the largest area of impact for single family houses, which is logical due to their low volume-to-area-ratio. The results for row houses are seen to be highly dependent on the number of exterior walls, which significantly affects heating demand. Minimizing operational impacts for both the edge row house and the single family house can be achieved through increasing the thermal performance of the houses. The results of the operational analysis are presented on a per person-year basis to allow for a comparison with the embodied impacts of the buildings and other impacts categories.

In addition, the work determined the change in operational impacts after renovating the buildings. The renovation reduces operational CO_2 emissions and energy significantly as expected. However, the associated increase in embodied impacts for the renovation must be considered as well. The research calculates the increase in embodied CO_2 emissions and energy are up to 19% the original embodied values. Thus, the building renovation must account for these negative results as well to provide an integrated analysis of the renovation. Finally, the operational impact payback time for the original building embodied impacts and also for the renovation are calculated. The initial payback period is shown to be a maximum of 16 years, and the renovation payback ranges for 1 to 3 years. Therefore, while the holistic analysis of the interplay between operational and embodied impacts must be accounted for, it is shown to have a relatively short payback period. The results of the building operational impacts will be carried over for the analysis of the remaining impact categories: transportation embodied impacts and transportation operational impacts.

Chapter 6

Transportation embodied impacts

The embodied impacts for transportation are analyzed in this chapter. First, transportation vehicles for both private transportation (i.e., automobiles) and public transportation (i.e., bus, tram, subway, and suburban train) are calculated. The road network in the City of Munich is quantified for total material demands reviewing the entire life-cycle of road infrastructure. These material demands are then converted into environmental impacts. Then the road infrastructure for the surrounding districts is determined. Next, the infrastructure demands for the public transportation infrastructure for the tram, subway, and suburban train networks are determined. This analysis covers stations (both above and below ground) and the line infrastructure (e.g., tracks, tunnels,) between stations. Finally, the chapter summarizes and compares all embodied transportation impacts for the *urban region of Munich*.

While scientific research is starting to investigate the importance of transportation embodied impacts, there are only a few studies on this subject to date. The work in this chapter contributes to the literature by providing an in-depth analysis of the infrastructure and vehicle embodied impacts for the *urban region of Munich*, which has yet to be determined. The results are an important supplement to current data on transportation operational impacts, which dominate transportation environmental analysis. Utilizing the results from both the operational and embodied analysis enables a holistic review of transportation environmental impacts.

6.1 Introduction

The work thus far has analyzed and quantified building embodied impacts and building operational impacts. By varying the location of the buildings within the urban environment, the indirect induced impacts are captured. The inclusion of transportation impacts allows for the assessment of the building residents with the surrounding urban environment. The quantification of transportation impacts represents the direct induced impacts in the built environment.

Traditional assessment of transportation impacts focuses on operational impacts (i.e., the use-phase of transportation). However, the importance of transportation vehicles and infrastructure on overall impacts has been previously shown and must therefore, be included [35].

Accordingly, this chapter analyzes transportation embodied impacts, which account for embodied impacts of transportation vehicles and transportation infrastructure. Both private and public transportation systems are analyzed for the particular case of the *urban region of Munich*. The first analysis is for the embodied impacts from transportation vehicles.

6.2 Vehicle embodied impacts

Comprehensive life-cycle assessment of transportation embodied impacts requires analysis of not only transport infrastructure, but also the vehicles used on these systems. Transportation vehicles include public transportation vehicles, automobiles, motorcycles or mopeds, non-motorized vehicles (e.g., bicycles, skates, skateboards). Other non-motorized modes utilize the human body as the vehicle (e.g., walking, running).

Impacts from non-motorized vehicles, including the human body as a vehicle and bikes for bicycling, are assumed to be zero. In reality these non-motorized vehicles do have embodied impacts (e.g., walking shoes, the bicycle and its parts). However, the assumption is predicated upon the fact that these impacts are minor compared to motorized vehicles as determined by simple back-of-the-envelope calculations. In the City of Munich, public transportation vehicles include buses, trams, subway trains, and suburban trains. The work analyzes the embodied impacts from private automobiles and public transportation vehicles. The life-cycle assessment for the vehicles is examined in detail in the following sections.

6.2.1 Automobiles

Detailed life-cycle data for emissions of passenger automobiles is available in the literature. Helms et al. conducted an extensive life-cycle based assessment of numerous vehicles [162]. The work gives the emissions for small, mid-size, and large automobiles (table 6.1 on the next page). The automobiles listed as UMBReLA (an acronym for Umweltbewertung der Elektromobilität; English: Environmental evaluation of electric mobility) are not specific automobiles, but rather represent *typical* cars for each specific weight class and engine fuel type. These representative vehicles were then evaluated for their life-cycle impacts and compared to other LCAs done for specific automobiles on the market [162]. The average emissions are 5.0, 5.9, and 8.2 t CO_2-Eq./vehicle for small, mid-size, and large vehicles, respectively [162]. This results in an average of 6.4 t CO_2-Eq./vehicle for an average life-span of 12 years [162], which yields an average of 529 kg CO_2-Eq./year for each vehicle. Average energy demand for a vehicle is 9.14 GJ/vehicle-year.

There are an average of 462 and 583 personal automobiles per 1,000 residents in Munich and the surrounding region, respectively [131]. As a reference there are 502 personal automobiles per 1,000 residents in Germany on average [131]. Thus for the average automobile ownership rates, the average embodied greenhouse gas emissions are 244 and 309 kg CO_2-eq./person-year for Munich and the surrounding region, respectively. For energy de-

Table 6.1: Life-cycle emissions for automobiles per size [162].

Category	Type	Emissions ($t CO_2$-Eq./vehicle)	Energy demand (GJ /vehicle)
Car, small	UMBReLA, Otto	4.9	85
	UMBReLA, Diesel	5.0	85
Car, mid-size	UMBReLA, Otto	5.8	105
	UMBReLA, Diesel	5.9	108
	VW Golf 1.4 TDI	6.1	
	VW Golf 1.4, TSI	6.7	
	Mercedes A150	5	
Car, large	UMBReLA, Otto	8.1	135
	UMBReLA, Diesel	8.2	140
	E-Klasse CDI	8.3	

mand, this results in 4.22 and 5.33 GJ/person-year in Munich and the surroundings, respectively. However, to be able to compare the embodied impacts for public and private vehicles the occupancy rate and passenger-kilometers must be accounted for. For automobiles the average occupancy rate is taken as 1.5 persons/vehicle regardless of location [163]. Using this occupancy rate, for an automobile the embodied greenhouse gas emissions are 353 kg CO_2-eq./person-year and energy demand is 6.09 GJ/person-year.

The environmental impacts of automobiles per passenger-kilometer are also determined. The total number of automobiles in the *urban region of Munich* are 1.33 million vehicles per automobile ownership rates [131] and population values [142]. Having the average environmental impacts for small, medium, and large size automobiles, the impacts for the entire automobile fleet is then found. The passenger-kilometers for automobile drivers and passengers together in 2012 was 25.0 billion Pkm [131]. The emissions for the entire fleet are then divided by the total Pkm for automobiles to obtain the results on a per Pkm basis.

6.2.2 Public transportation vehicles

While there has been significant research on the environmental impacts of public transportation within the City of Munich [37], these studies focus solely on operational (i.e., use-phase) impacts. To date there is no information on the embodied impacts of public transportation vehicles nor infrastructure [37, 131, 164–166]. A report examining “urban infrastructure” in the City of Munich also does not review embodied emissions for vehicles nor transportation infrastructure (e.g., roads, tracks, tunnels) [167]. This section of the work fills this information gap by determining the embodied emissions of public transportation vehicles in the *urban region of Munich*.

Public transportation in Munich consists of the bus, tram, subway (Germ. U-Bahn), and suburban train (Germ. S-Bahn) networks. In Munich there are four tram types in service (Typ S, Typ R3, Typ R2, and Typ P), three types of subway trains (Typ C, Typ B, and Typ

A), and one vehicle for suburban trains (ET 423) table 6.2 [164, 165]. For the tram vehicles, Typ R2 makes up the greatest share and for subway trains, Typ A dominates the vehicle stock with 194 vehicles. Additional information regarding the capacity (the sum of seating and standing places), maximum vehicle speed, and vehicle weight for public transportation vehicles in Munich are presented in table 6.2 [164, 165]. For comparison and to determine the environmental calculations, the urban metro train from Oslo, Norway (i.e., the Green Line) is also presented in table 6.2 [168].

Table 6.2: Public transportation vehicles in Munich (MVV Vehicles) and the reference urban train from Oslo (Green Line) [164, 165, 168]. (Where S. Train denotes suburban trains.)

	Quantity	Capacity (passenger)	Max. speed (km/h)	Weight empty (t)
Bus (Avg.)	418	32	36	13.7
Tram Typ S	14	221	60	40.0
Tram Typ R3	20	218	60	40.8
Tram Typ R2	68	157	60	31.0
Tram Typ P	5	315	70	39.5
Subway Typ C	18	912	80	164.0
Subway Typ B	63	290	80	57.1
Subway Typ A	194	290	80	53.2
S. Train ET 423	238	544	140	105.0
Green Line (*Ref.*)	1	678	80	92.1

In order to calculate the environmental impacts of the vehicles, detailed material information for the vehicles is required. Specific information for the material content of Munich public transportation vehicles (MVV-vehicles) is not available. However, a detailed life-cycle assessment with material quantities was carried out by Struck et al. for an urban metro train in Oslo, Norway [168], which closely resembles the public transport rail vehicles in Munich. Material quantities for this metro train (i.e., the Green Line) are given for the production, maintenance, and end-of-life recycle stages (table 6.3 on the next page). As the Green Line is similar to the vehicles in Munich, the detailed material quantities are scaled by weight to estimate the material requirements of the MVV-vehicles (equation (6.1)). From these calculations, the total material requirements for each tram (4 types total), each subway train (3 types total), and the suburban train (1 type) within the Munich public transportation system are calculated.

$$Material_{MVVVehicle} = Material_{Green\ Line} \times \frac{MVV\ vehicle\ weight}{Green\ Line\ weight} \tag{6.1}$$

Having determined the material quantities for the MVV-vehicles, a life-cycle assessment is conducted and the environmental impacts for each vehicle type (8 in total) are obtained. Data is from the *Ecoinvent* database and is supplemented with *Ökobau.dat* database where specific materials are absent from the *Ecoinvent* database [139, 140]. The life-cycle assessment accounts for material recycling in accordance with the Green Line. In addition to recycling, the wood material is disposed via municipal incineration due to importance of the end-of-life

Table 6.3: Life-cycle materials (kg) for metro train (Green Line) [168].

	Initial	Maintenance	Recycled
Aluminum	28,416	119	-27,848
Ceramic	121		
Chemicals	1,105		
Copper	2,389		-2,341
Elastomer	4,848	30,834	
Electronics	5,247	971	
Glass fiber reinforced plastic	1,840		
Minerals	75		
Steel, high alloy	24,282	75,261	-23,796
Steel, low alloy	20,365	1,517	-19,958
Thermoplastic	1,758		
Wood	1,681		
Oil		10,470	
Glass			-637

phase for wood products; other elements are not analyzed at their end-of-life. The results of the analysis yield the environmental impacts for each public transportation vehicle type in the Munich region (8 vehicles total) (table 6.4). The direct vehicle comparison (table 6.4) shows that the life-cycle assessment calculations are of the same order of magnitude for the Munich vehicles and the Green Line, giving confidence in the results.

Table 6.4: Life-cycle assessment for public transportation vehicles, fleet average per vehicle. [168]

Impact category	Bus	Tram	Subway	S. Train	Green Line
Renewable energy (MJ)	2.36E+05	6.07E+05	1.27E+06	1.81E+06	-
Non-renewable energy (MJ)	2.23E+06	5.76E+06	1.21E+07	1.71E+07	-
GWP (kg CO_2-Eq.)	1.18E+05	3.05E+05	6.39E+05	9.07E+05	1.36E+06
ODP (kg CFC 11-Eq.)	1.52E-02	3.91E-02	8.20E-02	1.16E-01	1.52E-01
AP (kg SO_2-Eq.)	6.17E+02	1.59E+03	3.34E+03	4.73E+03	8.14E+03
EP (kg Phosphate-Eq.)	3.86E+02	9.94E+02	2.09E+03	2.96E+03	6.68E+03
POCP (kg Ethylene-Eq.)	3.68E+01	9.49E+01	1.99E+02	2.83E+02	8.45E+02

In order to normalize the vehicle embodied impacts per passenger, vehicle occupancy rates are required (see equation (6.2)). Personal conversations with the transportation authority revealed that occupancy rates for Munich and the surrounding areas are not available [169]. Further, occupancy rates are not openly published in the literature [37, 131, 164–166]. Therefore, average German occupancy rates of 21% for the tram and the subway, 29.8 % for suburban trains [163], and 21% for buses [163, 170] are utilized.

$$Vehicle\ emissions/\ passenger = \frac{vehicle\ emissions}{(vehicle\ capacity \times occupancy\ rate)} \tag{6.2}$$

For the bus, tram, and subway fleets there are different vehicle types, which are varying in passenger capacities and in the number of vehicles in use (table 6.2 on page 86). In order to calculate the emissions/ passenger for the fleet, it is necessary to account for these variations. The average fleet emissions are calculated per equation (6.3). The life-span of the public transportation vehicles is taken as 30 years based on the lifespan of the Green Line in Oslo—vehicle lifespans in the *Munich transportation authority area of operation* are not available [168]. The results of the life-cycle assessment for the vehicles (bus, tram, subway, and suburban train) are presented for average vehicles (table 6.4 on page 87) on the basis of vehicle impacts per person-year (table 6.5).

$$Fleet\ emiss./\ passenger = \sum_{i=1}^{n}(vehicle_i\ emiss./\ passenger) \times \left(\frac{vehilcle_i\ capacity}{fleet\ capacity}\right) \tag{6.3}$$

Table 6.5: Life-cycle assessment for public transportation vehicles, fleet average per passenger-year.

Impact category	Bus	Tram	Subway	S. Train
Renewable energy (MJ)	1.82E+02	5.11E+02	5.07E+02	3.72E+02
Non-renewable energy (MJ)	1.73E+03	4.84E+03	4.81E+03	3.53E+03
GWP (kg CO_2-Eq.)	9.15E+01	2.56E+02	2.54E+02	1.87E+02
ODP (kg CFC 11-Eq.)	1.17E-05	3.29E-05	3.26E-05	2.39E-05
AP (kg SO_2-Eq.)	4.78E-01	1.34E+00	1.33E+00	9.73E-01
EP (kg Phosphate-Eq.)	2.99E-01	8.36E-01	8.30E-01	6.09E-01
POCP (kg Ethylene-Eq.)	2.85E-02	7.98E-02	7.92E-02	5.81E-02

A further analysis is done to examine the embodied impacts per passenger-kilometer traveled (Pkm) as this is a common metric for evaluating mobility impacts. The impacts for the entire public transportation fleet system (i.e., all buses, trams, subway trains, and suburban train) are calculated per year (30 year life-span). Total passenger-kilometers per mode in 2001 were 4.30% (for the tram), 24.70% (for the subway), 59.90% (for suburban trains), 7.90% (for city buses), and 3.20 % (for regional buses) [166, 171]. Based on the percentage of passenger-kilometers per mode and total passenger-kilometers for public transportation (6,712 Mio. Pkm) [166], the Pkm per mode are determined. The environmental impacts for each vehicle stock per Pkm-year are shown in table 6.8 on page 90 and figure 6.2 on page 91.

6.2.3 Vehicle embodied results and discussion

The embodied emissions for transportation vehicles per person-year are presented in table 6.6 on the facing page and figure 6.1 on the next page. As mentioned early, the embodied impacts for walking and bicycling are assumed to be zero. The results are given for each vehicle type per person-year, where person represents the number of people in the vehicle based on the occupancy rates. This accounts for the lifespan of the vehicle including the production and maintenance of vehicles and the end-of-life processes.

Table 6.6: Summary of the embodied impacts for transportation vehicles (per passenger-yr).

Vehicle	GWP (kg CO_2-Eq./person-yr)	Energy (MJ/person-yr)
Foot/ bicycle	0	0
Automobile	3.53E+02	6.09E+03
Bus	9.15E+01	1.91E+03
Tram	2.56E+02	5.35E+03
Subway	2.54E+02	5.32E+03
S. Train	1.87E+02	3.90E+03

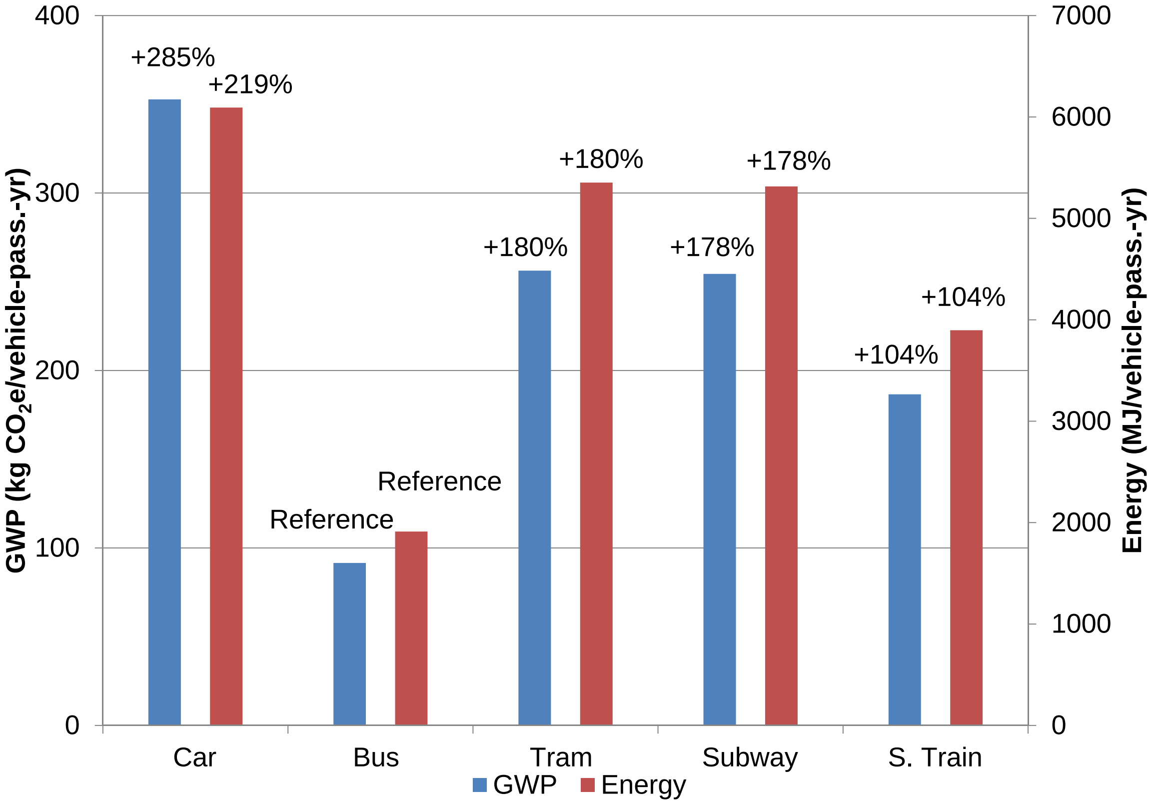

Figure 6.1: Embodied CO_2 emissions (GWP) and energy for vehicle types (per person-year).

The embodied emission results per person-year do not vary significantly between the automobile and subway trains and suburban trains. This is despite the substantial life-span difference (12 year for an automobile and 30 years for the public transit vehicles). The high results for public transportation vehicles are due to the low occupancy rate (21% and 29.8%) compared to that of the automobile (37.5%) and the high material volume for public transport vehicles. The GWP and energy are slightly lower for the public transportation vehicles: the suburban train has the lowest impact. This is due to the higher occupancy rate of the suburban train (29.8%) compared to the other transportation modes (21%). Thus, the results illustrate that increasing occupancy rates has a significant impact on net impacts.

The vehicle embodied impacts are also examined per passenger-kilometer to account for the distance traveled by each mode (table 6.8 and figure 6.2 on the next page). Again the modes of walking and cycling are assumed to have zero environmental impacts. The Pkm for each mode, the GWP for the entire vehicle fleet, and the energy demand for the entire fleet are presented in table 6.7 [166].

Table 6.7: Summary of the Pkm per mode and total impacts for the entire fleet [131, 166, 171].

Vehicle	Pkm/year	GWP (kg CO_2-Eq./year)	Energy (MJ)
Foot/ bicycle	-	0	0
Automobile	2.50E+10	7.06E+08	1.22E+10
Bus	5.30E+08	1.65E+06	3.44E+07
Tram	2.89E+08	4.11E+05	8.58E+06
Subway	1.66E+09	2.20E+06	4.60E+07
S. Train	4.02E+09	7.20E+06	1.50E+08

The vehicle fleet embodied impacts per passenger-kilometer are then calculated. The calculations show that public transportation vehicles have drastically smaller GWP and energy impacts compared to the automobile (table 6.8 and figure 6.2 on the facing page). Thus despite the large Pkm for automobiles, their higher embodied impacts result being the mode with the highest impact. Impacts per Pkm for public transportation modes vary, but are the same order of magnitude for all public transportation modes. The comparison of vehicle embodied impacts per Pkm over the life-cycle of each vehicle shows that public transportation vehicles have much lower impacts compared to personal automobiles. These transportation vehicle embodied impacts will be added to operational travel impacts as well as infrastructure for both automobiles and roads to provide a more detailed investigation of the total impacts.

Table 6.8: Summary of the embodied impacts for transportation vehicle fleets (per Pkm).

Vehicle	GWP (kg CO_2-Eq./Pkm)	Energy (MJ/Pkm)
Foot/ bicycle	0	0
Automobile	2.82E-02	4.88E-01
Bus	3.11E-03	6.49E-02
Tram	1.42E-03	2.97E-02
Subway	1.33E-03	2.77E-02
S. Train	1.79E-03	3.74E-02

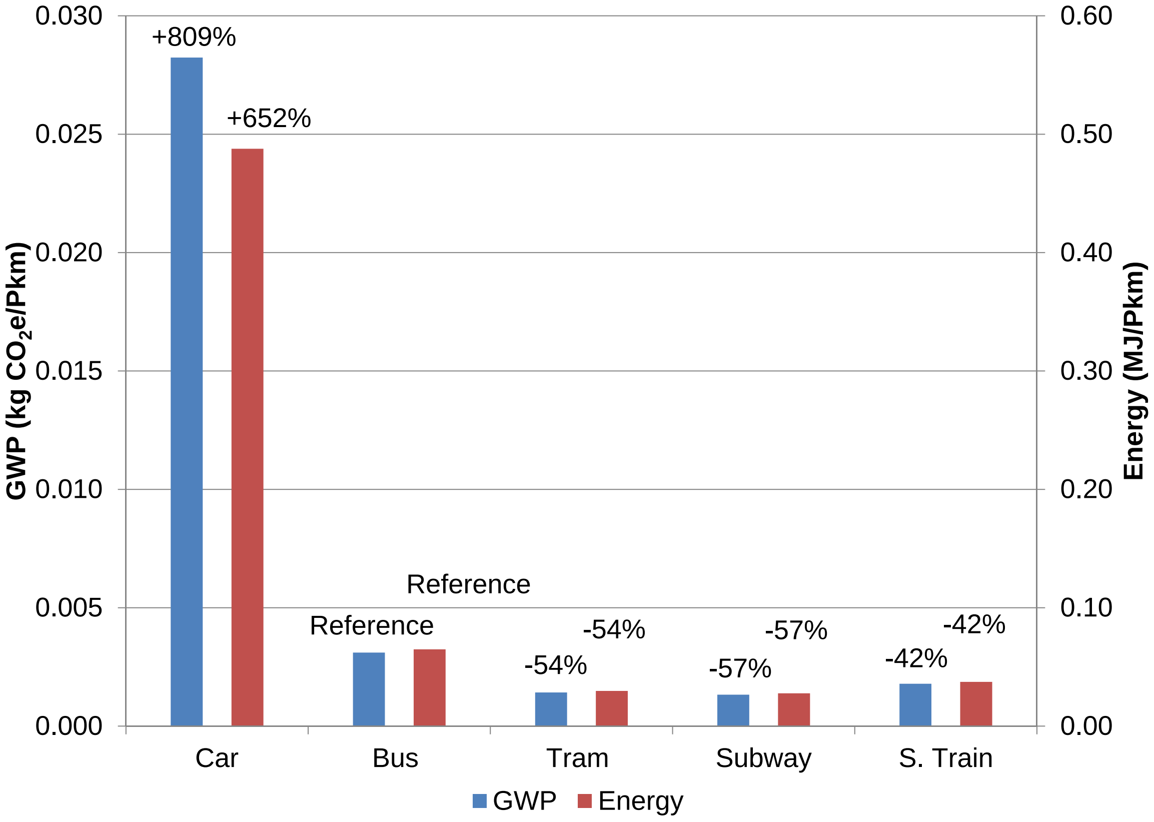

Figure 6.2: Embodied GWP and energy for vehicles (per Pkm).

6.3 Road infrastructure

Transportation infrastructure plays an important role in the built environment. In addition to the environmental outputs of transportation infrastructure, land-use requirements for transportation vary drastically between modes. The innovative *time-area concept* accounts for transportation area requirements considering both safe travel speeds and the occupancy rate of vehicles [172]. The time-area concept reveals that automobiles have the highest land area requirements, which is predominately from all day parking requirements [173]. Further, an automobile at full capacity still requires more time-area than a partially filled bus [173]. Schiller et al. argue that while transportation environmental decisions focus on reduction consumption, attention must also be paid to efficient use of urban space [173, 174]. Based on the importance of area demands for transportation modes, and especially automobile based transportation, the impacts from transportation infrastructure must be quantified.

A life-cycle assessment for roads is utilized to determine the environmental impacts for automobile infrastructure. Detailed road infrastructure information for the city of Munich is used to determine the total impacts for all roads in Munich. The results of this detailed analysis are then used to find the impacts for the surrounding districts. The findings for road infrastructure are combined with the other impact categories to obtain a holistic analysis including transportation infrastructure.

6.3.1 Analysis

In the City of Munich there are seven types of road construction, which differ, based on the material used, thickness of material, and combination of material layers (i.e., the overall road construction). The type of road construction used is determined by the traffic flow of the road in question—given in automobiles per 24 hour time frame. The road classes as prescribed by the Munich Building Department are SV (heavy traffic), BK-I (road class I), BK-II, BK-III, BK-IV, BK-V, and BK-VI (see figure 6.3 on the next page) [175]. Road classes BK-V and BK-VI are only for service roads (non-residential roads), and are not typical in Munich.

To determine the environmental impacts from each road class, the quantity of each class is required. The Baureferat gives the entire length (2,380.45 km) for roads in Munich [176]; however, information per road class is not available. As the impacts will vary between road class due to materials used and quantities, it is necessary to determine the quantity for each class. As mentioned previously, the road class is prescribed by the traffic flow. The traffic flow for roads in Munich is given in the Traffic Flow Map (Germ. Verkehrsmengenkarte) [177].

From the Traffic Flow Map and the road class prescriptions, the length of each road class is calculated by hand. The results are shown in table 6.9 on the facing page. From this calculation the roads given in the Traffic Flow Map total only 566 km, whereas there are 2,380 km of roads in Munich; thus only a fraction of all roads are shown on the map. However, more detailed maps are not available. All the high road classes are shown on the Traffic Flow Map; the remaining roads not shown are likely road class III or IV (BK III or IV) or even road class

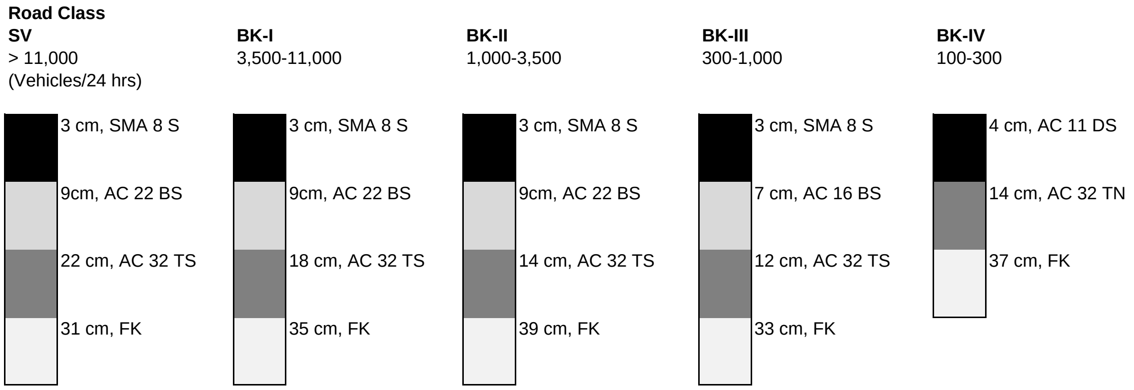

Figure 6.3: Construction (thickness and material) for road classes in Munich based on vehicle traffic [175]. Terms: SMA - mastic asphalt concrete (Germ. Splittmastixaspahlt), BS - binding layer (Germ. Binderschicht), TS - structural layer (Germ. Tragschicht), FK - frost layer (Germ. Frostschutzschicht), AC - Asphalt concrete (Germ. Asphaltbeton) (commonly referred to as asphalt), DS - Top layer (Germ. Deckschicht), and TN - structural layer normal requirements (Germ. TN - Tragschicht normale Beanspruchung).

V or VI. As road class V and VI are only for service roads, it is assumed that that remains roads (1814 km) are of road class III and IV. The assumption is made that half of these are road class III and half are road class IV. Given the absence of more detailed traffic maps and information on road length per class, this assumption is used to obtain more specific road quantity information. The revise road class lengths are shown in table 6.9.

Table 6.9: Road lengths per construction class.

Road class	Length (km)	Percent (%)	Revised length (km)
SV	48	8.5	48
BK-I	94.5	16.7	94.5
BK-II	224	39.6	224
BK-III	192	33.9	1099.5
BK-IV	7.5	1.3	914
BK-V	0	0	0
BK-VI	0	0	0

In addition to road lengths, the width of each road is required. According to Baureferat, roads under control of the city have a total length of 2,179 km and a area of 18,305,759 m^2, which yields an average width of 8.4 m [176]. This value is used in the subsequent calculations. This value is in line with the lane widths given typical road plans in Munich assuming two vehicle lanes and a parking strip (vehicle lane: 3.25 m, parking strip: 2.0 m) [178]. The road width could be expanded to also include infrastructure for bicycles and pedestrians (bike lane: 1.8 m, sidewalk: 2.0 m); however, these infrastructure demands are not currently accounted for in the infrastructure analysis [178].

Having found the road quantities for Munich, the next step is to calculate the environmental impacts using a life-cycle assessment. The goal of the LCA is to determine the environmental outputs from all roads in Munich based on the differentiation per class. The functional unit is environmental output per person-year. This allows us to account for the population density as well as the lifespan of the roads. The life span for each layer of the road varies as follows: top coating (SMA): 15 years, binding layer: 30 years, structural layer: 60 years, frost layer: 60 years [179]. The life-cycle data used for the analysis is from the *Ökobau.dat* database [140]. The *Ecoinvent* database was not used as the only road material given is mastic asphalt, which is no longer used [139]. The datasets used from *Ökobau.dat* are *Splittmastixaspahlt* (cover layer), *Asphaltbinder* (binding layer), *Asphalttragschicht* (structural layer), and *Transportbeton C20/25* (frost layer). As these datasets do not include transportation from the plant to the construction site, transportation is included separately (dataset: *9.3.01 LKW* - an EURO 3, 20-26 t truck). An average transportation distance of 30 km is taken. The system boundary for the LCA is presented in figure 6.4. The construction process is not included within the system boundary as the main impacts occur during the production and transportation processes. The high temperatures to heat the asphalt required for the construction is included within the production phase (i.e., the asphalt is not re-heated at site).

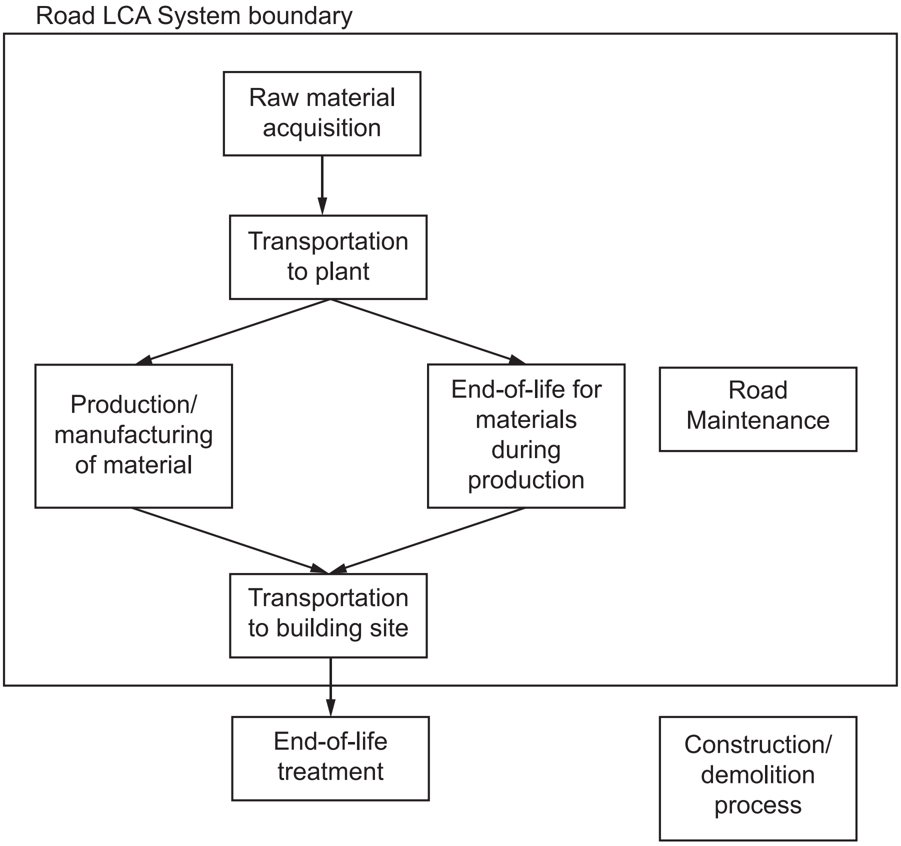

Figure 6.4: System boundary for the life-cycle assessment of road infrastructure.

The results of the life-cycle assessment for a 60 year timespan are presented in table 6.10 on the next page. These values account for all roads in Munich, based on road class, and account for the varying lifespan of each road element. The total mass for the layer SMA, BS, TS, and FK layers are 16.1, 21.1, 18.3, and 44.4%, respectively. These same layers account for 30.4, 38.6, 31.0, and 6.1% of total GWP emissions. This illustrates the low GWP content of the FK layer. The other layers vary only slight in emissions: SMA, BS, and TS have 77.1, 74.9, and 69.0 kg CO_2-Eq./ton of material. For GWP, transportation accounts for 9.5% and materials for 90.5% of emissions.

6.3.2 Road infrastructure results

The results for GWP are shown in figure 6.5 on the following page over a 60 year timespan to illustrate the impact from renewing different road layers over time. The graphic assumes a zero year for all construction, which would not be the case. However, this is useful in illustrating the relative percentages over one 60 year-cycle. Based on this, year 0 accounts for 60.3% (renew all layers: SMA, BS, TS, FK), year 15 for 7.2% (renew SMA layer), year 30 for 25.4% (renew SMA and BS layers), and year 45 for 7.2% (renew SMA layer) of GWP over a 60 year period.

Table 6.10: Total LCA results for all road infrastructure in Munich.

Impact category	Results	Units
Renewable energy	4.50E+08	MJ
Non-renewable energy	4.61E+10	MJ
GWP	9.36E+08	kg CO_2-Eq.
ODP	7.15E-01	kg CFC 11-Eq.
AP	3.14E+06	kg SO_2-Eq.
EP	4.10E+05	kg Phosphate-Eq.
POCP	1.81E+06	kg Ethylene-Eq.
ADPE	1.32E+02	kg Sb-Eq.
ADPF	4.55E+10	MJ

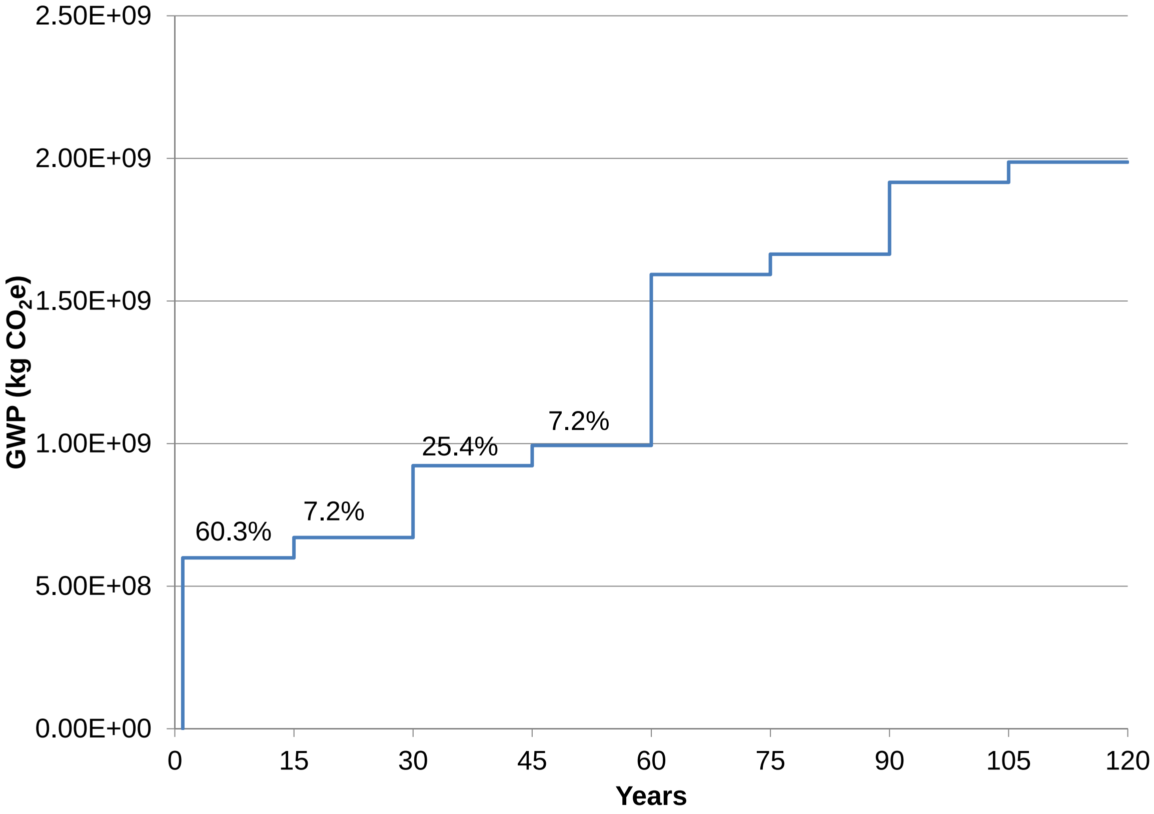

Figure 6.5: Emissions for all Munich road infrastructure over a 120 year lifespan.

6.3.3 District road infrastructure

Having determined the detailed environmental impacts for road infrastructure in the City of Munich, the impacts for the surrounding districts are determined. For the districts road information is available for freeways (Germ. Autobahnen), federal highways (Germ. Bundesstr.), state roads (Germ. Staatstr.), and district roads (Germ. Kreisstr.) (see table 6.11 [180]). However, data for local roads (Germ. Gemeindestr.) are not available [180, 181]. For Munich local roads make up over 90% of all streets, thus illustrating the crucial importance of these roads. Given that the length of local roads is not available [181], a few assessment options are feasible. First, local roads could be omitted, but given their dominance in the City of Munich this would drastically underestimate road impacts. Second, the road infrastructure from Munich could be used as a fixed quantity for all locations. However, the dense road network in the capital city likely does not represent the rural landscape in the outer districts. Third, given the detailed data known for Munich and the available road information for the districts, an estimate of the total roads for the districts can be calculated. For this estimate, the net impacts for Munich are scaled by the fraction of road quantity in the district by the road quantity in Munich. This value is then divided by the population of the district [142] to get impacts per person-year to account for the density differences between districts and Munich. This results in an approximation of the impacts for all roads in the districts (table 6.12 on the following page, table 6.13 on the next page, and table 6.14 on the following page. The resulting impacts will be based on the estimated road quantities in the districts.

Table 6.11: Total roads for all districts (in km) [180] and population per district [142].

Location	Autobahnen	Bundesstr.	Staatstr.	Kreisstr.	Total	Pop.
Munich	56.529	76.102	58.05	3.2	193.0	1.38E+6
Bad Tölz-W.	18.104	133.883	189.86	122.467	454.3	1.22E+5
Dachau	19.3	21.511	133.332	154.5	328.6	1.40E+5
Ebersberg	16.537	38.405	133.811	116.497	305.3	1.31E+5
Erding	18.006	67.447	178.347	255.875	519.7	1.28E+5
Freising	50.553	82.209	129.576	276.3	538.6	1.68E+5
FFB	11.564	53.142	59.096	109.614	233.4	2.07E+5
Miesbach	22.772	118.283	77.654	114.3	333.0	9.60E+4
München	87.571	91.664	148.535	104.585	432.4	3.28E+5
Starnberg	28.412	19.808	166.302	166.302	260.2	1.32E+5

In addition to impacts per person-year, determining the impacts per passenger-km allows for a comparison with the public transportation infrastructure. From the MiD-MUC travel survey, City of Munich residents completed 10.1 billion passenger-kilometers for automobile modes (accounting for both drivers and passengers) in 2008 [131]. This value includes all trips taken by Munich residents, which could be within or outside the boundaries of the city. Residents in the outer districts (i.e., excluding City of Munich residents) traveled 14.9 billion passenger-kilometers for automobile modes. The outer district Pkm value also includes travel by non-

Table 6.12: Part 1 of 3: Results for road infrastructure in Munich and districts (per person-year).

Impact category	Munich	Bad Tölz	Dachau	Ebersberg
Renewable energy (MJ)	5.44E+00	1.44E+02	9.07E+01	9.03E+01
Non-renewable energy (MJ)	5.57E+02	1.47E+04	9.29E+03	9.25E+03
GWP (kg CO_2-Eq.)	1.13E+01	2.99E+02	1.89E+02	1.88E+02
ODP (kg CFC 11-Eq.)	8.65E-09	2.28E-07	1.44E-07	1.43E-07
AP (kg SO_2-Eq.)	3.79E-02	1.00E+00	6.32E-01	6.29E-01
EP (kg Phosphate-Eq.)	4.96E-03	1.31E-01	8.25E-02	8.22E-02
POCP (kg Ethylene-Eq.)	2.18E-02	5.77E-01	3.64E-01	3.62E-01

Table 6.13: Part 2 of 3: Results for road infrastructure in Munich and districts (per person-year).

Impact category	Erding	Freising	FFB	Miesbach
Renewable energy (MJ)	1.57E+02	1.24E+02	4.37E+01	1.34E+02
Non-renewable energy (MJ)	1.61E+04	1.27E+04	4.47E+03	1.37E+04
GWP (kg CO_2-Eq.)	3.26E+02	2.58E+02	9.08E+01	2.79E+02
ODP (kg CFC 11-Eq.)	2.49E-07	1.97E-07	6.94E-08	2.13E-07
AP (kg SO_2-Eq.)	1.09E+00	8.63E-01	3.04E-01	9.35E-01
EP (kg Phosphate-Eq.)	1.43E-01	1.13E-01	3.98E-02	1.22E-01
POCP (kg Ethylene-Eq.)	6.29E-01	4.97E-01	1.75E-01	5.39E-01

Table 6.14: Part 3 of 3: Results for road infrastructure in Munich and districts (per person-year).

Impact category	München LK	Starnberg
Renewable energy (MJ)	5.10E+01	7.65E+01
Non-renewable energy (MJ)	5.22E+03	7.83E+03
GWP (kg CO_2-Eq.)	1.06E+02	1.59E+02
ODP (kg CFC 11-Eq.)	8.10E-08	1.22E-07
AP (kg SO_2-Eq.)	3.55E-01	5.33E-01
EP (kg Phosphate-Eq.)	4.64E-02	6.96E-02
POCP (kg Ethylene-Eq.)	2.05E-01	3.07E-01

Munich residents within the City of Munich. Thus the exact number of passenger-kilometers driven only on the road infrastructure in the City of Munich is not available. The assumption is made that the number of Pkm driven by Munich residents outside of Munich is equal to the number of Pkm driven by non-Munich residents within Munich. Thus the Pkm for Munich residents is used for road infrastructure within Munich. Based on this assumption, the road infrastructure impacts for the City of Munich are presented in table 6.15 on a per passenger-kilometer basis.

Table 6.15: Results for Munich road infrastructure per Pkm.

	GWP (kg CO_2-Eq./Pkm)	Energy (MJ/Pkm)
Roads	1.12E-09	5.59E-8

Using detailed road information for the City of Munich, the total environmental impacts for all roads were found. This information accounts for the lifespan of each section of the road and is determined on a per person basis to allow comparison with other impact categories. These impacts are then extrapolated to the surrounding districts to find the impacts from road infrastructure. Again, net values are normalized through population to account for density differences in distributing the environmental impacts. The findings for road infrastructure will be compared against the other impact categories (i.e., building embodied, transportation operation) to determine the net impacts and the relative importance of each contribution.

6.4 Public transportation infrastructure

A life-cycle assessment of public transportation infrastructure is also conducted. Public transportation infrastructure includes infrastructure for trams, the subway, and suburban trains based on the public transportation services serving the *urban region of Munich*. Local trains are not included in the infrastructure analysis as the focus is on local travel within the region, which is covered by commuter trains. There were a total of 662.773 million passengers and 6,712.035 million passenger-kilometers in 2012 for the entire MVV public transportation system [166]. Total track lengths and train-kilometers per public transportation type are presented in table 6.16. The total passenger-kilometers for 2012 are presented in table 6.17 on the next page based on the percentage of Pkm for public transportation modes.

Table 6.16: Track length and train-kilometers in 2012 per public transportation mode [166].

	Track length (km)	Train-kilometers	(% of total)
Tram	79.0	7.385E+6	19.2
Subway	95.0	10.729E+6	27.9
S. Train	442.0	2.0298E+7	52.8

Table 6.17: Percentage of Pkm per public transportation mode and total passenger-kilometers in 2012 [166]

	Public Transit Pkm (%)	Passenger-kilometers (2012)
Car - Munich	N.A.	1.01E+10
Car - Districts	N.A.	1.49E+10
Regional bus	3.20	2.15E+08
City bus	7.90	5.30E+08
Tram	4.30	2.89E+08
Subway	24.70	1.66E+09
S. Train	59.90	4.02E+09

6.4.1 Tram infrastructure

Trams make up 12.8% of public transportation tracks lengths and 19.2% of train-kilometers. This illustrates their importance within the public transportation network in the City of Munich, to which they are confined (table 6.16 on page 99). Tram construction in Munich is dominated by concrete slab construction (57%) followed by concrete girder (12%), and concrete sleepers (11%) (table 6.18 [182]). Typical construction drawings for realized projects in 2013 were used to determine the material requirements for a unit length of tram track [183].

Table 6.18: Tram track length per construction type [182]

Structural system	Track length (m) - Single track	Percentage (%)
Concrete slab	98,147	57
Wood sleepers	9,379	5
Concrete sleepers	19,521	11
Concrete girder	20,291	12
SFConcrete-H	1,605	1
SFConcrete-B	757	0
INFUNDO	5,500	3
Trail structures	424	0
Precast concrete	13,759	8
Not known	2,783	2
Gravel	216	0
Total	172,381	

The following tram constructions analyzed are concrete slab, wood sleepers, concrete sleepers, and concrete girder. Based on the construction drawings for actualized projects in Munich, the material quantities for each construction type are determined [183]. The concrete slab construction consists of railing, an asphalt cover layer, an asphalt binding layer, an asphalt structural layer, a concrete structural slab, a concrete slab, and a frost protection layer. The wood sleeper construction consists of railing, an asphalt cover layer, wood sleepers, a concrete structural layer, aggregate, and a frost protection layer. The concrete sleeper construction consists of railing, an asphalt cover layer, an asphalt binding layer, an asphalt structural layer, concrete sleepers, a concrete structural layer, and a frost protection layer. Finally, the concrete girder is made of railing, an asphalt cover layer, an asphalt binding layer, an asphalt structural layer, a reinforced concrete girder, and frost protection.

The material quantities are calculated per the construction drawings. The thickness of the frost protection layer is not specified so a value of 40 cm is taken for all sections in accordance with [184]. For the railing, the amount of steel for one track (2 rails) is taken as 98.86 t/track-km per [184]. Life-cycle data comes from the *Ökobau.dat* and the *Ecoinvent* databases. End-of-life phases are only considered for wood to account for carbon storage in the original material. Transportation distances from the plant/factory to the construction site are not considered due to a lack of detailed information on distances.

The center-to-center distance between sleepers is taken as 60 cm and all concrete has 2.5% reinforcing steel [184]. The attachment materials (steel and polyethylene) for the tracks to the structure are also included [184]. The life span of the tram infrastructure, aside from the frost protection layer, is taken as 20 years, which is slightly lower than the 30 year lifespan for suburban train infrastructure [184]. The frost layer has a life span of 60 years [184]. The results of the life-cycle assessment are shown in table 6.19. Analyzing the four constructions covers 85% of tram tracks in Munich. For the remaining 15%, a weighted average is calculated based on the types assessed. The waiting stations for the tram are not evaluated as they are minimal aluminum and glass structures mainly located on the existing sidewalk areas. As the materials for each construction type are very similar, the decisive factor in the LCA is the net thickness of each construction. The thicknesses are as follows: concrete slab (0.685 m), wood sleepers (0.55 m), concrete sleepers (0.55 m), and concrete girder (1.07 m). Accordingly, the thickest construction (concrete girder) has the highest emissions. The wood sleep construction is shown to have the lowest emissions, which is directly comparable to the concrete sleeper construction of the same depth.

Table 6.19: Life-cycle assessment results for different tram constructions.

Construction	Emissions (kg CO_2-Eq./km-yr)	Energy demand (MJ/km-yr)
Concrete slab	4.33E+04	5.60E+05
Wood sleepers	2.70E+04	4.72E+05
Concrete sleepers	4.01E+04	5.31E+05
Concrete girder	5.58E+04	6.96E+05
Remaining constructions	3.73E+04	4.86E+05

The final results for the entire tram infrastructure in Munich are obtained by multiplying the impacts per construction type with the total length of tram track (see table 6.20 on the next page). The environmental impacts from tram infrastructure in Munich can also be calculated on a per person basis. The option here is to use the yearly ridership of trams (only the total ridership for all public transportation is given, 662.773 million passengers). However, to be consistent with analysis of road infrastructure, the net results are divided by the population of Munich. The results are also given per passenger-kilometer.

Table 6.20: Summary of results for tram infrastructure.

Impact category	Total/yr	Total/Pkm	Total/person
Renewable energy (MJ)	4.72E+06	3.66E-03	2.65E-09
Non-renewable energy (MJ)	9.13E+07	7.08E-02	5.13E-08
GWP (kg CO_2-Eq.)	7.35E+06	5.70E-03	4.14E-09
ODP (kg CFC 11-Eq.)	1.56E-01	1.21E-10	8.76E-17
AP (kg SO_2-Eq.)	1.92E+04	1.49E-05	1.08E-11
EP (kg Phosphate-Eq.)	1.02E+04	7.93E-06	5.76E-12
POCP (kg Ethylene-Eq.)	3.05E+03	2.36E-06	1.71E-12

6.4.2 Subway infrastructure

The subway in Munich consists of 7 lines [185] with 95 km of track (double track) [166]. There are 100 subway stations, which accounts for double stations at line crossings [185]. Data for the life-cycle assessment of the subway infrastructure is from Landeshauptstadt München Baureferat U-Bahn-Bau [186]. The Building Department provided construction drawings and bills of materials for the Moosach subway station. This station actually consists of two separate stations: Moosach station on the west and Leipzigerstr. station on the east. The western Moosach station is a connection between the subway and the suburban train, whereas the Leipzigerstr. station is a typical subway station. The Leipzigerstr. station is used as a typical station for the subway network as it is similar in size and construction for typical subway stations. Based on the bill of quantities, the material requirements for Leipzigerstr. station are determined. Reinforcing steel quantities are assumed to be 2.5% of the concrete. The stations have a 100 year life-span with 5% maintenance. Steel fasteners have a lifespan of 15 years. The materials include concrete, reinforcing steel, and concrete fasteners. The subway network is connected with two separate tunnels between stations. These round tunnels are constructed from reinforced concrete and each tunnel has one track. The track is modeled as per the suburban train calculations with concrete sleepers. While there are both concrete and wood sleeps used for subway tracks, concrete sleeps are calculated for all tracks due to their larger environmental impacts to ensure that results are not underestimated.

The lifespan of the tunnel shell is taken as 100 years, the tunnel base (concrete support for the precast track support) and the track support have a lifespan of 60 years, and the ballast has a lifespan of 15 years [184]. Life-cycle data is taken from the *Ecoinvent* and *Ökobau.dat* databases. Material quantities for the subway tunnel are presented in table 6.21 on the facing page. The life-cycle assessment results for the subway track and station are shown in table 6.22 on the next page and table 6.23 on the facing page.

Table 6.21: Materials for subway tunnels per [186].

Element	Construction (kg/km-yr)	Maintenance (kg/km-yr)
Outer shell	1.64E+05	0.00E+00
Inner shell	1.97E+05	9.87E+03
Tunnel base	4.47E+04	2.23E+03
Precast track support	1.56E+05	7.80E+03
Ballast	1.89E+05	0.00E+00

Table 6.22: Summary of subway track infrastructure.

Impact category	Total/yr	Total/Pkm
Renewable energy (MJ)	2.29E+07	1.38E-02
Non-renewable energy (MJ)	5.80E+08	3.50E-01
GWP (kg CO_2-Eq.)	5.81E+07	3.50E-02
ODP (kg CFC 11-Eq.)	1.56E+00	9.43E-10
AP (kg SO_2-Eq.)	1.44E+05	8.67E-05
EP (kg Phosphate-Eq.)	8.42E+04	5.08E-05
POCP (kg Ethylene-Eq.)	1.70E+04	1.02E-05

Table 6.23: Summary of subway station infrastructure.

Impact category	Total/station-yr	Total/yr	Total/Pkm
Renewable energy (MJ)	2.11E+04	2.11E+06	1.27E-03
Non-renewable energy (MJ)	4.55E+05	4.55E+07	2.74E-02
GWP (kg CO_2-Eq.)	5.76E+04	5.76E+06	3.47E-03
ODP (kg CFC 11-Eq.)	8.34E-04	8.34E-02	5.03E-11
AP (kg SO_2-Eq.)	1.19E+02	1.19E+04	7.17E-06
EP (kg Phosphate-Eq.)	5.11E+01	5.11E+03	3.08E-06
POCP (kg Ethylene-Eq.)	1.04E+01	1.04E+03	6.29E-07

6.4.3 Suburban train infrastructure

The suburban train is a local passenger train service connecting Munich with the surrounding districts carrying up to 800,000 passengers on a workday [165]. There are 422 kilometers of tracks, 150 stations, and 244 vehicles [165]. In 2012 the suburban train had 20.3 million train-kilometers [166]. Specific information for the suburban train is not available. While part of the local transportation system, the suburban train is run and operated by the *Deutsche Bahn* and not the Münchner Verkehrsgesellschaft, who run the bus, tram, and subway network.

In comparison to the other transportation infrastructure systems (i.e., roads, tram, subway), detailed life-cycle assessment for suburban train systems in Germany have already been carried out on behalf of the *Deutsche Bahn* [184]. A detailed report by Schied and Mottschall presents the life-cycle assessment for rail infrastructure and rail vehicles in Germany [184]. Due to the extensive level of detail provided and the applicability of the study, this report is used as the primary source of data for suburban train infrastructure analysis. A separate life-cycle assessment is, however, carried out using this primary data. The following paragraphs present the primary data used, the life-cycle datasets, and the resulting LCA environmental impacts.

6.4.4 Suburban train tracks

All track material for the suburban train is from Schied and Mottschall [184]. The elements analyzed are attachments (connecting the rail to the sleeps), rails, sleepers, ballast, and frost protection. Attachments are composed of steel and polyethylene (PE) plastic with a lifespan of 35 years. Rails are of type S54 (the most common 36%) and have a lifespan of 30 years. Concrete sleepers are most common (75%) and have a lifespan of 35 years. The center-to-center distance between sleepers is taken as 60 cm and the sleepers have 2.5% steel reinforcing. A ballast supports the sleepers and has a lifespan of 15 years. Finally, the frost protection layer is 40 cm thick and has a lifespan of 60 years. The material demands per kilometer of track per year for the initial construction and maintenance are presented in table 6.24. [184]

Table 6.24: Materials for above ground suburban train line per [184].

Element	Construction (kg/km-yr)	Maintenance (kg/km-yr)
Attachments - steel	440	0
Attachments - plastic (PE)	120	0
Rails	7,270	50
Sleeper - concrete	25,684	260
Sleeper - reinforcing	670	10
Ballast	473,300	7,100
Frost protection	248,300	0

The life-cycle datasets used for the suburban train tracks are from the *Ökobau.dat* and

Ecoinvent databases. For steel attachments, plastic attachments, rails, concrete sleepers, sleeper reinforcing, ballast, and frost protection the following datasets are used: steel low-alloy (*Ecoinvent*) and milling steel (*Ecoinvent*), steel low-alloy, concrete C30/37, steel reinforcing (*Ecoinvent*), crushed aggregate, and crushed aggregate, respectively. Although covered in the report by Schmied and Mottschall, earthwork is not included to be consistent with the other infrastructure modes [184].

The life-cycle assessment reveals that the attachments, rails, sleepers, ballast, and frost protection are responsible for 15, 56, 8, 14, and 7% of energy demand, respectively. For global warming potential these values are 12, 52, 14, 14, and 8%. These values illustrate the dominance of the rails in the net impacts. The annual total impacts (i.e., construction plus maintenance) for the suburban train track infrastructure are presented in table 6.25. The results are also given per passenger-kilometer based on the 2012 total Pkm for the suburban train (4.02E+9) [166].

Table 6.25: Summary of above ground suburban train line infrastructure.

Impact category	Total/yr	Total/Pkm
Renewable energy (MJ)	8.72E+06	2.17E-03
Non-renewable energy (MJ)	1.42E+08	3.52E-02
GWP (kg CO_2-Eq.)	1.10E+07	2.73E-03
ODP (kg CFC 11-Eq.)	2.86E-01	7.10E-11
AP (kg SO_2-Eq.)	3.84E+04	9.55E-06
EP (kg Phosphate-Eq.)	2.23E+04	5.54E-06
POCP (kg Ethylene-Eq.)	2.06E+03	5.13E-07

In addition to the above ground suburban tracks, there are 15 kilometers of underground suburban train tunnels. These track sections have higher material demands per kilometer due to the tunnel construction. For the tunnels, the same LCA results from the subway are utilized.

6.4.5 Suburban train stations

As there are 150 suburban train stations within the MVV network [165], these must also be included in the infrastructure calculations. Again, Schied and Mottschall carried out a life-cycle assessment for suburban train stations, but at a much reduced level of detail compared to tracks. Only concrete and reinforcing steel were quantified for suburban train stations, which were given a lifespan of 60 years [184].

The authors found a suburban train station with a life span of 60 years required 63,382 kg of concrete and 1,200 kg of steel reinforcing [184]. Maintenance requirements were taken as 5% of original construction materials per Chester and Horvath [187]. Using these values and the same LCA datasets for concrete and reinforcing utilized for the tracks, the impacts are calculated (table 6.26 on the next page). The results show that concrete is responsible for 56% of total energy demand and 81% of global warming potential. Reinforcing steel makes up the remaining percentages. The net emissions are provide for an average station, all stations (150 in total) within the MVV network, and per the Pkm traveled with the network.

Table 6.26: Summary of above ground suburban station infrastructure.

Impact category	Total/station-yr	Total/yr	Total/Pkm
Renewable energy (MJ)	3.34E+03	5.01E+05	1.25E-04
Non-renewable energy (MJ)	6.33E+04	9.50E+06	2.36E-03
GWP (kg CO_2-Eq.)	9.92E+03	1.49E+06	3.70E-04
ODP (kg CFC 11-Eq.)	1.05E-04	1.57E-02	3.90E-12
AP (kg SO_2-Eq.)	1.73E+01	2.59E+03	6.44E-07
EP (kg Phosphate-Eq.)	6.61E+00	9.91E+02	2.46E-07
POCP (kg Ethylene-Eq.)	1.31E+00	1.97E+02	4.90E-08

As noted for the tracks, there are eight underground suburban train stations. These stations require significantly more material and must therefore be accounted for in the total infrastructure demands for the suburban train. The underground suburban train stations are modeled using the subway stations, and these results are added to the total suburban infrastructure impacts.

6.4.6 Public transportation infrastructure results

The life-cycle assessment of the lines/tracks (the area between stations) for all public transportation modes reveals that the subway has the highest impact per kilometer (see figure 6.6 on the facing page). Bus specific infrastructure is already calculated in the road network previously analyzed. The high impact of the subway line is due to the underground lines, which require tunnel construction and hence significant material per kilometer of line. Compared to the tram lines, the subway has 139.7% higher emissions and the suburban train 25.1% lower emissions (see figure 6.6 on the next page). Although the suburban train has 15 kilometers of underground lines, the line infrastructure is found to be lower than that of the tram. This is also expected as the material for the tram line (i.e., asphalt) is more greenhouse gas intensive per m^3 than the main material used for the suburban train lines (i.e., concrete). Also the suburban train has significant material demands for crushed aggregate (ballast), but this material has a low emission profile. In summary, the subway lines have significantly higher emissions than the tram and the suburban train.

Similar to the lines, the subway stations have much higher emissions than the suburban train stations (see figure 6.7 on the facing page). Stations for trams were not evaluated due to their minimal material requirements. Of the 150 suburban train stations, only 8 are underground stations, which require substantial more material than the above ground stations. Underground stations require large of amounts of steel and concrete for the underground structure, support for the structures above, and emergence exists among other elements. The suburban train station is found to have 74% lower emissions compared to the subway station.

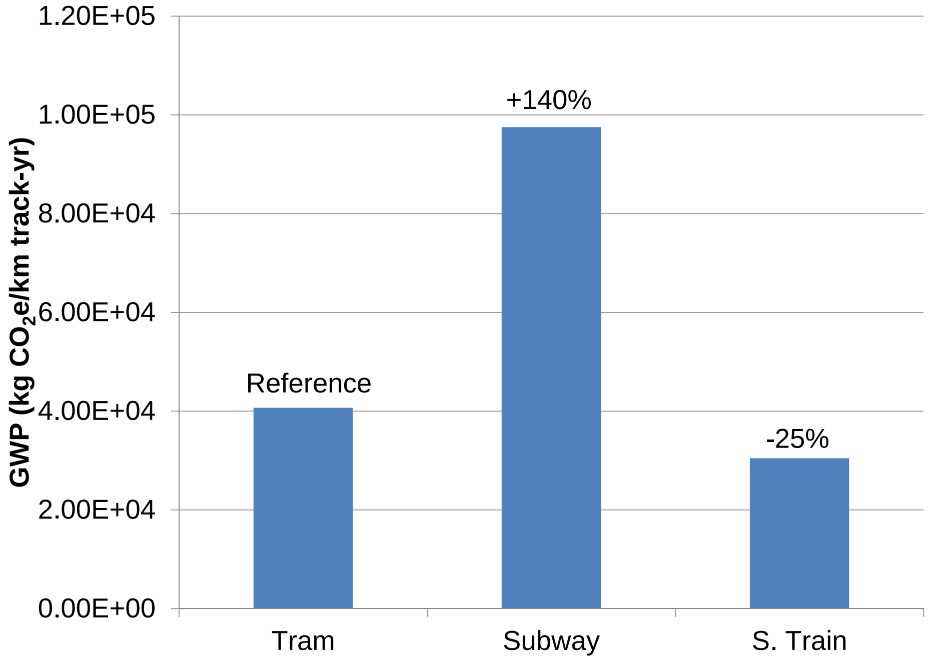

Figure 6.6: Public transportation infrastructure CO_2 emissions for lines.

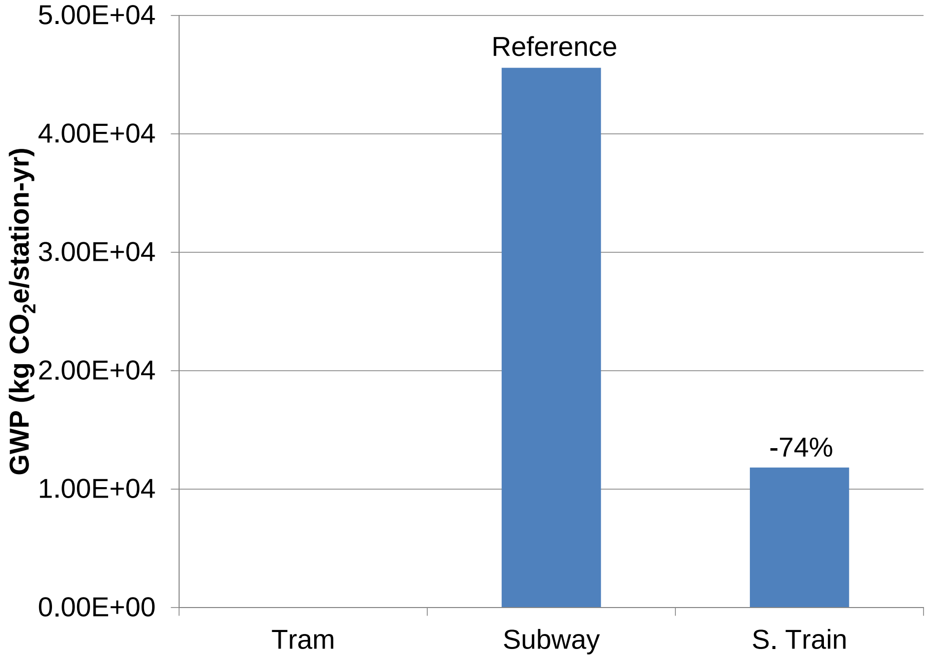

Figure 6.7: Public transportation infrastructure CO_2 emissions for stations.

Combining all stations and lines, the impacts for the entire network are calculated. Figure 6.8 shows the CO_2 emissions for the entire tram, subway, and suburban train systems (i.e., all tracks and all stations are included for each mode). As the line impacts and station impacts for the subway were very high, the high impacts for the subway network are expected. The tram network has the lowest impacts, which is expected due to the absence of stations and the relatively small network line lengths. The suburban train has lower emissions compared to the subway and higher emissions (107.2%) compared to the tram. Interestingly the subway results are higher than the suburban train despite a lower number of stations (subway 100, suburban train 150) and short total line length (subway 190 km, suburban train 442 km). This illustrates the high impacts of underground versus above ground systems on the total environmental performance of the system.

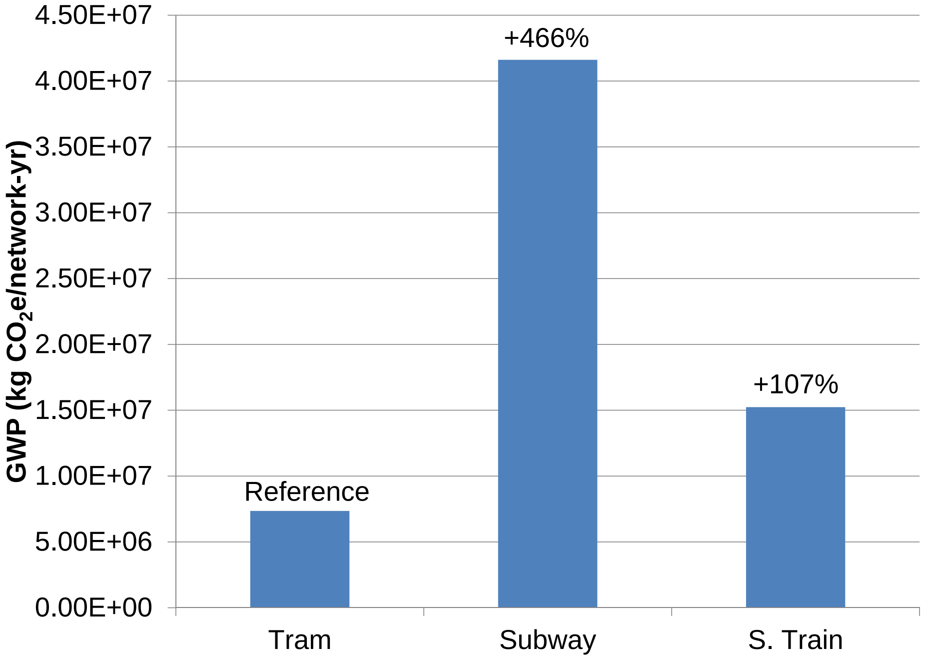

Figure 6.8: Public transportation infrastructure CO_2 emissions for entire network (all line and stations).

Finally, the public transportation system infrastructure per mode is evaluated based on system use (i.e., passenger-kilometers traveled per year) (see figure 6.9 on the facing page). Passenger-kilometers for 2012 are given in table 6.17 on page 100. The analysis shows that the general results of significantly higher emissions for the subway still hold. The subway has the largest emissions followed by the tram and then the suburban train. Using the metric of emissions per Pkm results in a lower impact for the suburban train compared to the tram due to higher Pkm per year on the suburban train compared to the tram (almost 14 times higher). The suburban train also has almost 2.5 times higher passenger-kilometers than the subway, which results in a lower end result for the suburban train. The comparison based on passenger-kilometers is directly influenced by the distance traveled. Thus longer distances would lead to lower emissions per Pkm, but higher emissions overall.

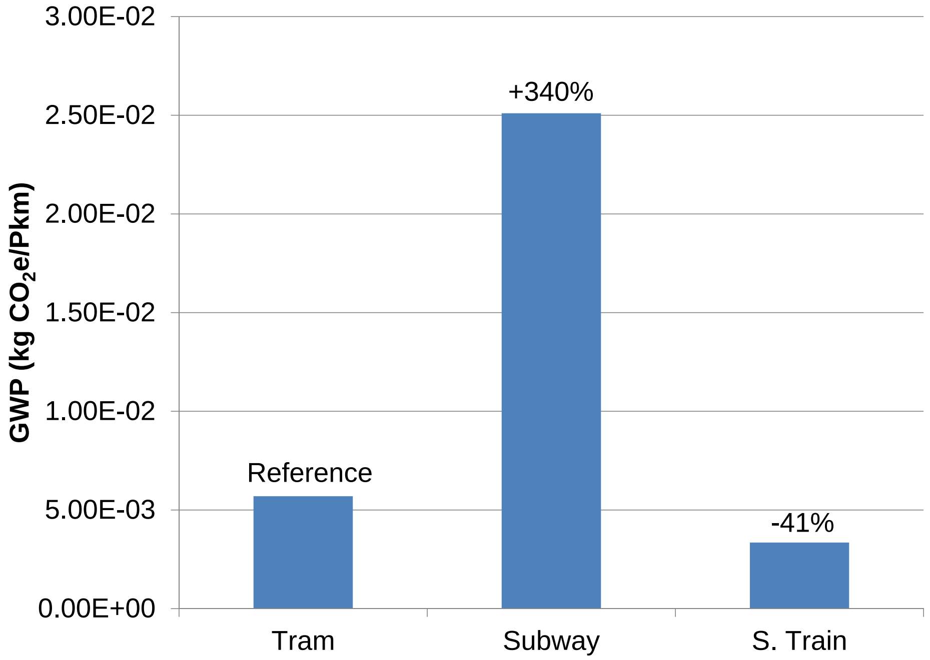

Figure 6.9: Public transportation infrastructure emissions per passenger-kilometers traveled.

6.5 Results and discussion

The embodied impacts for transportation have been calculated for vehicles and infrastructure. Using these results it is possible to compare the transportation embodied impacts for different modes. As a first result, the emissions per length of each system are evaluated (see figure 6.10 on the following page). These results account for the impacts of the lines and exclude all stations. For roads, only the road network of Munich is included (i.e., there is no parking, etc.). Figure 6.10 on the next page clearly shows that, even without account for stations, the road network has the lowest emissions on a per kilometer basis. That means that the average emissions for a unit length of road are less than the emissions for a unit length of public transportation infrastructure. However, it should be noted that tunnels, bridges, and underground road infrastructure were not evaluated. This would significantly increase the results based on the findings from the subway infrastructure.

Second, the impacts for the entire network per mode are evaluated (see figure 6.11 on page 111). This includes all lines and stations for public transportation. Vehicles are not included. The road calculations are given for the City of Munich and the average of the districts. Accounting for the entire network, the results show that the subway network has the largest emissions. The district road network, based on the assumptions previously outlined, has the second highest emissions. The road network in Munich and the suburban train network are almost identical. The network for the suburban train is lower than the subway due to the

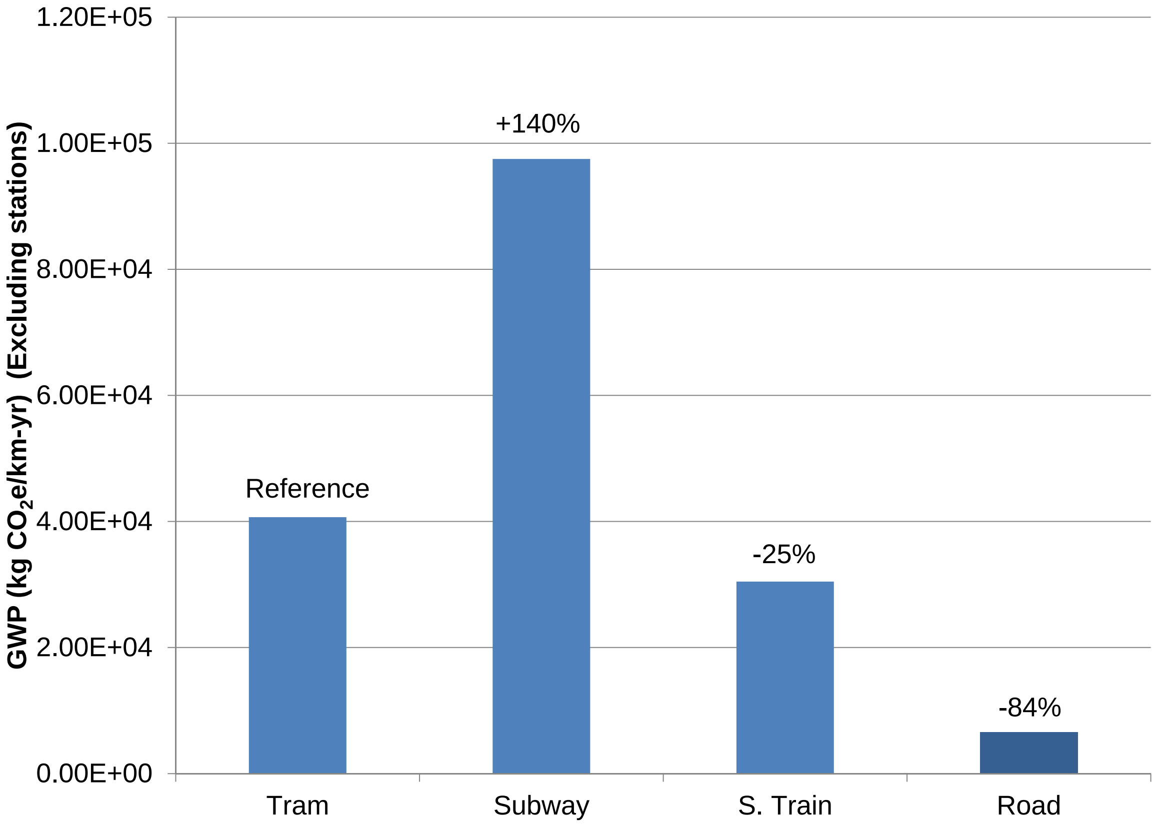

Figure 6.10: Public transportation infrastructure emissions for the entire networks (all tracks) per km. Road emissions are for the Munich network.

dominance of above ground lines and stations for the suburban train. The tram network has the lowest emissions, which is due to the absence of stations for the tram.

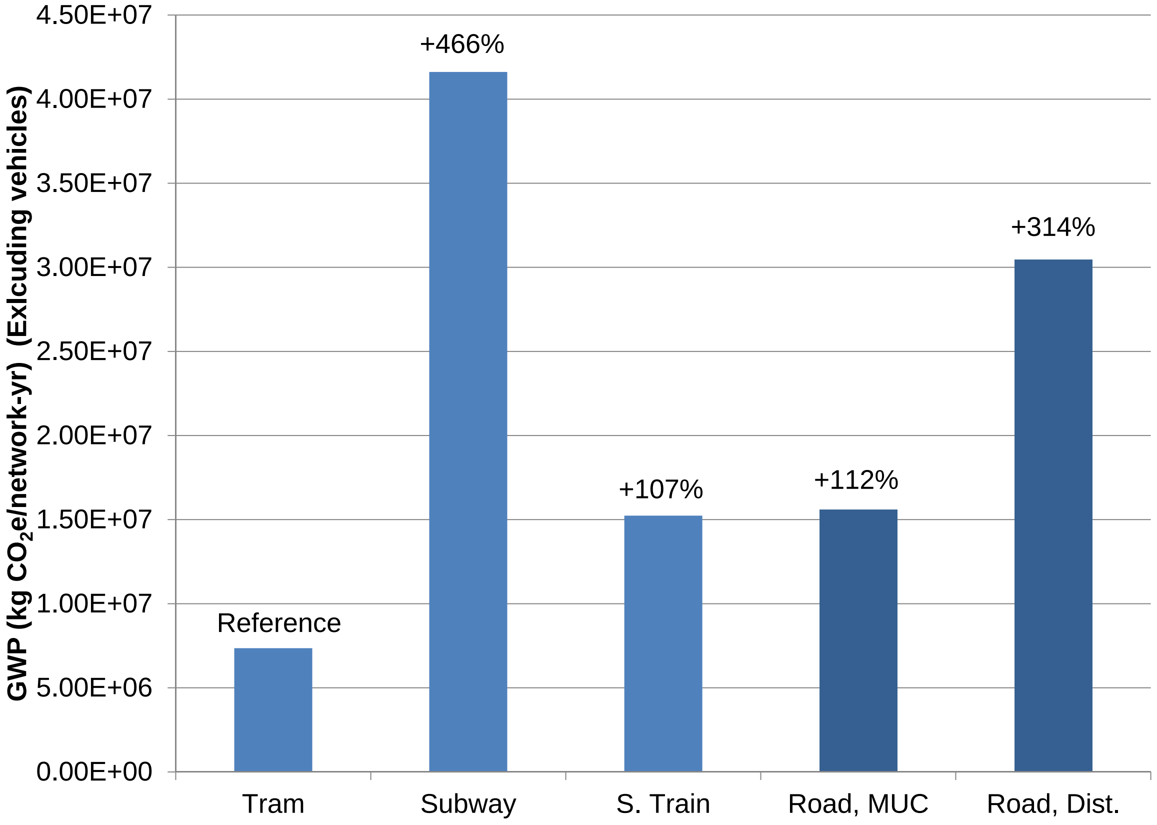

Figure 6.11: Public transportation infrastructure CO_2 emissions for the entire networks (all tracks and stations included).

Finally, the emissions are shown for each mode including the embodied vehicle impacts (figure 6.12 on the next page). The findings show the clear dominance of the road network based almost entirely on the vehicle embodied emissions. Compared to the tram network, the road network in Munich has 4,279% greater emissions and the road network in the average district has 5,697% greater emissions. This result is due to several factors. First, the vehicle stock of automobiles in Munich (5.82E+5) and in the surrounding districts (7.52E+5) is extremely large. This is based on the vehicle ownership rate per resident (0.462 in Munich and 0.583 in the surroundings) [131]. In total there are thus over 1.3 million automobiles in Munich and the surroundings. This is compared to the 107 trams, 275 subway trains, and 238 suburban trains. The sheer magnitude of automobiles therefore dominates the network emissions.

Also, it must be noted that the lifespan (i.e., the rate of exchange) of vehicles has a significant influence on the results. Automobiles have an average lifespan of 12 years; whereas the lifespan of public transportation vehicles is more than double that at 30 years. Thus, not only are there 1.3 million automobiles compared to 620 public transportation vehicles, but the automobiles are exchanged twice as fast. Interesting, the impact of vehicle embodied impacts, which until now has been only studied in limited cases [35], dominates the embodied impacts for transportation.

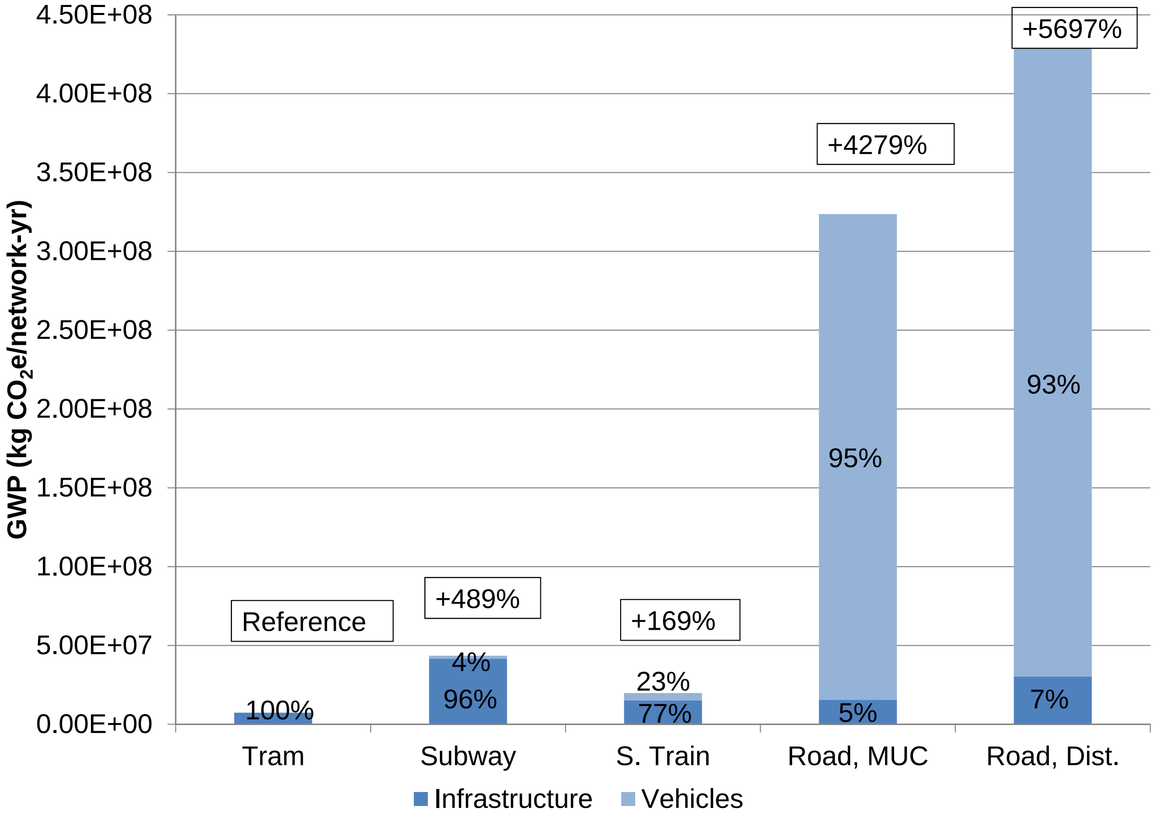

Figure 6.12: Cumulative infrastructure emissions.

Finally, the transportation embodied emissions are compared per passenger-kilometer (figure 6.13 on the facing page). The results per passenger-kilometer illustrate important differences compared to the findings per network-year (figure 6.12). While the network-year analysis is dominated by automobile networks, the Pkm analysis shows a significant variation in public transportation modes. In particular, emissions for the subway are of the same order of magnitude as the road networks. However, the suburban train maintains low emissions as well as the tram. The low suburban train emissions are due to the high annual passenger-kilometers traveled with this mode (see table 6.17 on page 100). As the passenger-kilometers is the denominator of the calculation, a high Pkm value result in decreased emissions. This trend is also observed for the road networks. The work shows that there are lower emissions for the districts compared to the City of Munich although the yearly impacts show the opposite relationship. This is due again to the larger number of Pkm in the surrounding districts.

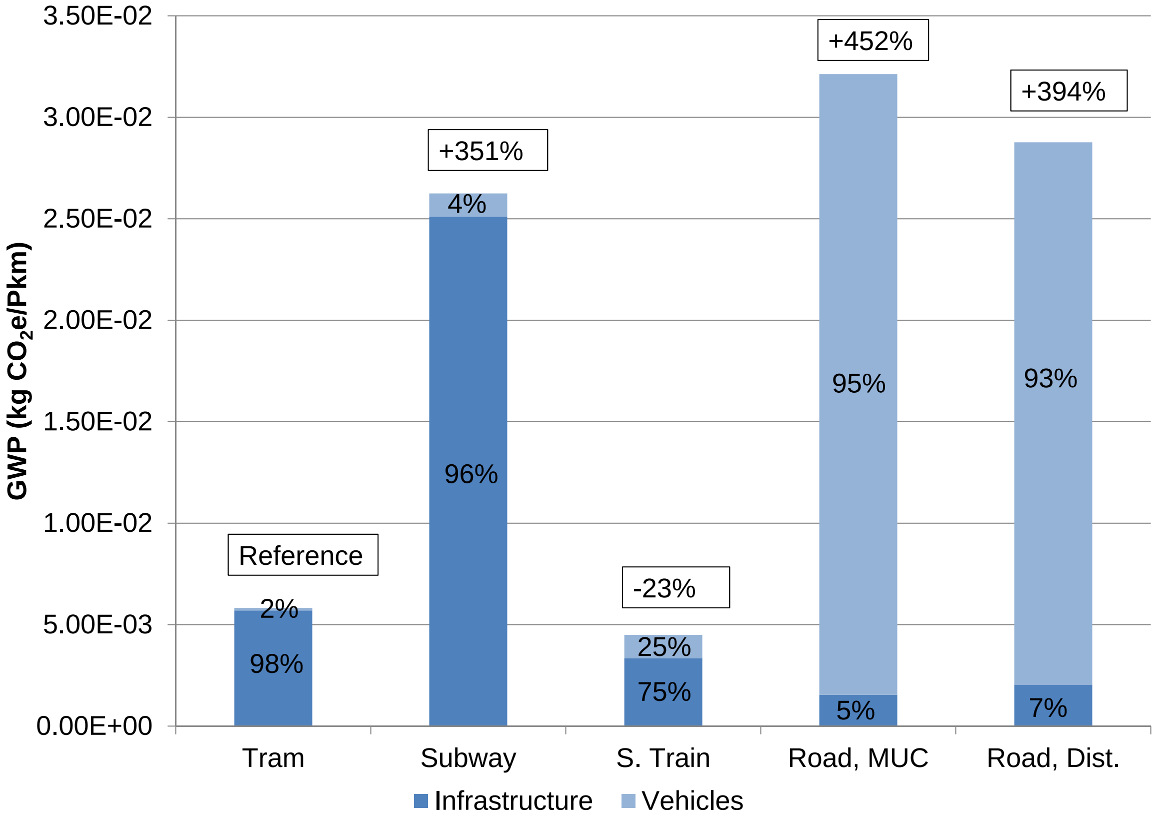

Figure 6.13: Cumulative infrastructure CO_2 emissions per passenger-kilometer.

6.5.1 Sensitivity analysis of district road infrastructure

As mentioned in section 6.3.2 on page 95, the total road infrastructure in the districts was approximated based on the best available data. Having calculated the emissions from all transportation modes, a sensitivity analysis of total emissions due to variations in district road infrastructure is conducted. For the current results of the road network in the districts, roads make up 7.1% of all impacts—the remaining impacts are from vehicles (figure 6.12 on page 112).

The dominance of road network emissions from embodied vehicle calculations indicates that significant changes in the road infrastructure will only have small effects on total emissions. If the road infrastructure in the districts is increased by 50%, the total road network in districts only increases by 3.6%. If the infrastructure is increased by 250% (2.5 times more roads than originally estimated), total district road network emissions increase by 10.7%. Therefore, while more accurate data for district road networks are required, the sensitivity analysis illustrates that even drastic changes in road infrastructure play a small role in total emissions, which are dominated by vehicle embodied impacts.

6.6 Conclusion

The traditional focus on operational impacts to evaluate the environmental performance of transportation has to be expanded. Embodied transportation impacts from vehicles and infrastructure (line and stations) must also be included. The research evaluates the embodied impacts for private (i.e., automobiles) and public (i.e., bus, tram, subway, and suburban train) networks. Detailed calculations for all roads in the City of Munich per road class and the length are determined. Similarly, road impacts for the surrounding districts are found. Public transportation impacts are calculated for vehicles, lines, and stations.

The analysis shows that buses have the lowest vehicle embodied emissions and automobiles the highest on a per vehicle-passenger-year basis. Once the results are normalized by passenger-kilometers, the automobile clear has the highest emission values. The public transportation infrastructure evaluation shows that the subway has the highest impacts. This is due to the underground lines (i.e., tunnels) and stations, which are extremely material intensive. The suburban train and tram have results of the same order of magnitude, and the mode with lower emissions depends on the normalization of the results (e.g., per passenger-kilometers or per km of the system). The impacts for the road network in Munich and the surrounding districts are also presented.

The holistic comparison of all transportation systems illustrates the dominance of private transportation on a network basis. This is due to the massive number of automobiles and their relatively short lifespan. On a passenger-kilometer basis, the impacts from the subway network increase dramatically. In summary, transportation embodied impacts are shown to be sensitive to vehicle lifespans and the presence of below ground infrastructure.

Chapter 7

Transportation operational impacts

This chapter presents the environmental impacts from transportation operation. The data, methodology, analysis, results, sensitivity analyses, discussion, and conclusions for transportation operational impacts are presented. The analysis utilizes a comprehensive travel survey containing over 42,000 trips and 5,800 households for all modes of travel within the *Munich transportation authority area of operation*. The calculation methodology and data handling are presented in detail to clearly outline all assumptions. While use-phase emissions are a major focus area in research and practice, the work adds to the state-of-the-art by expanding the analysis of transportation operational impacts beyond simple tail-pipe emission analysis.

The detailed travel data is used to calculate comprehensive environmental impacts for all modes on a per person basis. Impacts are then geographically mapped to the residential location at three different scales: the city traffic cell, the city neighborhood, and the district. The analysis mapping personal emission to residential locations does not show a correlation between house location and distance to the city center at either the traffic cell or city neighborhood level. However, transportation operational emissions at the district level show that the City of Munich clearly has the lowest impacts per person. In addition, sensitivity analyses reveal critical findings about future tail-pipe emission reductions in 2030 and the impacts of long distance air travel.

7.1 Introduction

As presented in the literature review (see Chapter 3: *Methodology*), transportation is a central theme dominating the environmental performance of cities. As such, it is essential to include transportation impacts when assessing the environmental performance of the built environment. Embodied impacts for transportation vehicles and infrastructure required for transportation systems have been covered in Chapter 6: *Transportation embodied impacts*. This chapter focuses on the environmental impacts for transportation operations (i.e., the transportation use-phase).

This chapter aims to determine how varying residential locations within the urban region of

Munich affect transportation operational impacts. It is important to note that residential location is only one of a multitude of factors influencing travel behavior. Transportation behavior is dependent on demographics (e.g., employment, income, age, gender, family context, lifestyle, preference), trip activity (e.g., work, leisure, tourism, distance to activity, distance to public transport station, distance to work), transport options (e.g., walking, cycling, public transport, ride sharing, automobile, taxi, car ownership), land use (e.g., density, mix, walkability, connectivity, transit service proximity, roadway design), and price (e.g., fuel prices and taxes, vehicle taxes and fees, road tolls, parking fees, vehicle insurance, transit fares) among other factors [188]. The transportation operational impacts will be analyzed and then compared to other impact categories (i.e., building embodied impacts, building operational impacts, and transportation embodied impacts) to determine the importance of each category and to ascertain variations based on residential location.

7.2 Defining the scope for transportation analysis

Induced impacts from transportation operation result from typical daily mobility. Limiting the analysis to trips within a home region will purposely exclude long-distance trips. The main reason is that the research focus is on how home location influences mobility, which is not an issue for long distance travel. Long-distance travel (i.e., outside the region) has limited mode choice (i.e., plane, train, or car) and non-motorized trips are not realistic. Additionally, inclusion of long-distance trips would skew the data and dominate the environmental impacts; hence removing the possibility for detailed analysis of the results.

To carry out the analysis of transportation operational impacts, data for actual daily mobility within the *urban region of Munich* are required. The data must represent a large sample size, covering individuals from different locations within the region. In addition, focus is placed on trips within one's home region to determine the influence of the daily starting location for mobility, and in turn, the influence on environmental impacts. The analysis must also account for all daily travel for an individual, including the mode used, the distance traveled, and the time of the trip (i.e., speed of travel).

7.3 Data sources

In order to determine the transportation operational impacts actual transportation information is required which can either be collected for the study or obtained from existing transportation survey data. The two main transportation surveys in Germany are “Mobilität in Städten - SrV (System repräsentativer Verkehrsbefragungen)” (Srv) [189] and “Mobilität in Deutschland” (MiD) [190]. Both surveys collect residential transportation data through regular household surveys and provide results and trends for transportation to support transportation planning and policy. The reason for two national surveys is that the SrV comes from the previous German Democratic Republic and the MiD comes from the Federal Republic of Germany.

The SrV survey covers roughly 111,500 persons, 74 cities and communities, and 4 large cities and their surroundings (Berlin, Kassel, Leipzig, and Dresden). The focus of the SrV survey is on the municipality level, covers only workday travel, and provides city specific results [189]. While the focus of the SrV is on cities, specific location information for the questioned households is not available due to privacy restrictions. The second national survey, MiD, covers over 60,000 persons and provides regional average results and findings based upon city size and structure (i.e., main cities, densely populated counties, and rural counties) [190]. Additional local surveys for the MiD are provided for selected cities (Hamburg, Hanover, Berlin, Munich), but are carried out and financed at the local level. At the national level, the MiD data does not provide detailed information on household locations. Household geographical information for the local surveys is available only for the Munich regional data. The decision to use data from the Munich local survey rather than collecting new data was determined by the large size of the survey (13,136 persons) and the diverse household locations.

7.4 General MiD information

This section discusses general information about the transportation data, which is used to calculate the transport operational impacts. The data set used is the *Mobilität in Deutschland 2008 - Aufstockung München* (MiD-MUC) [131]. This is a regional data set for the *Munich Transport and Tariff Association area of operation* (Germ. MVV-Verbundraum), which supplements the national transportation survey, *Mobilität in Deutschland 2008* (MiD) [190]. The MiD-MUC data covers both the City of Munich and the surrounding districts of Bad Tölz-Wolfratshausen, Dachau, Ebersberg, Erding, Freising, Fürstenfeldbruck, Miesbach, München, and Starnberg. The purpose of the MiD travel survey is to provide data and analysis on the *actual daily mobility* within Germany. The MiD-MUC has the same goal, but focuses on the *Munich Transport and Tariff Association area of operation*.

The methodology for the MiD survey is described in detail in the *Methodology Report* [191], which serves as the methodological basis for the MiD-MUC survey. Information regarding the use of the data is outlined in the *User Handbook* [192]. The final results for the national MiD survey are presented in the *Summary Report* [190], and for the MiD-MUC survey in the *Munich and Region Summary Report* [131]. While the data procurement, methodology, and results are described in great detail in the above reports, some general data information will be discussed here to justify the use of the MiD-MUC data for the research.

The MiD and MiD-MUC surveys provide an extensive database for the analysis of current daily mobility in Germany and the *Munich Transport and Tariff Association area of operation*, respectively [192]. Data are collected for daily mobility, as well as for regular professional trips and long-distance travel. Similar to the 2009 *National Household Travel Survey* in the United States of America, data are collected from all trips, modes, purposes, trip lengths, and areas of the country [193]. Professional trips (Germ. regelmäßige berufliche Wege) covers trips by workers (e.g., craftsmen, bus drivers, postmen, representatives, and suppliers) as well as intermittent official business trips [191]. Trips to a regular workplace are not included in this category. A long-distance trip (Germ. “Reise”) is defined by an overnight stay away from one’s residence, and was requested for a time period going back three months. The data was collected between the end of January 2008 and the middle of April 2009.

Over the survey period, households were randomly chosen from addresses provided by the Local Registration Administration and were asked about their mobility for a predefined survey day. The focus of the survey was on everyday mobility, thus every day of the week (i.e., Monday to Sunday) was used for the survey. From the original data, the percentage of trips falling on each day of the workweek is as follows: Monday–15.7%, Tuesday–15.9%, Wednesday–15.3%, Thursday–14.6%, Friday–15.2%, Saturday–14.0%, and Sunday–9.3%. Both mobile and non-mobile persons were recorded in the survey. Obviously, non-mobile persons did not have a trip record. In the MiD-MUC data set non-mobile persons were 9% of the survey, which is comparable to the federal level of 10% (i.e., 91% of persons are mobile in the *Munich Transport and Tariff Association area of operation*, and 90% of persons in Germany are mobile on a daily basis). Data were collected for every member of the household over 0 years of age, thereby including children in the survey. Both German and non-German citizens were questioned. In the survey a *trip* includes the entire travel from the start point to the end point, and may include various trip legs (i.e., the trip accounts for mobility between activity locations). The final activity location defines the trip purpose (e.g., a trip from work to residential location has a purpose of going home).

On average, a resident in the City of Munich has 3.4 trips/day compared with 3.5 trips/day for residents in districts outside Munich (the personal average for all of Germany is 3.4 trips/day) [131] [190]. The modal split for the original MiD data is shown in figure 7.1 on the next page [190]. For the City of Munich, the modal split shows that a significant percentage of trips are made by walking (28%) and by bike (14%). In the districts, walking and biking decrease slightly, but are still important modes (walking is 20% and biking is 11%). The main shift from the City of Munich to the rural region is the percentage of trips by public transport, which falls from 21% in the City of Munich to 7% in the rural districts. In addition, the trip purpose for the original MiD data is presented in figure 7.2 on page 120. While there is a minor variation between residential locations, it is not as dramatic as the modal split. For the entire *Munich Transport and Tariff Association area of operation* (i.e. total survey area) 33% of trips are for leisure followed by 22% for shopping, and 12% for private chores. Work trips (i.e., commuting) only makes up 13% of all trips.

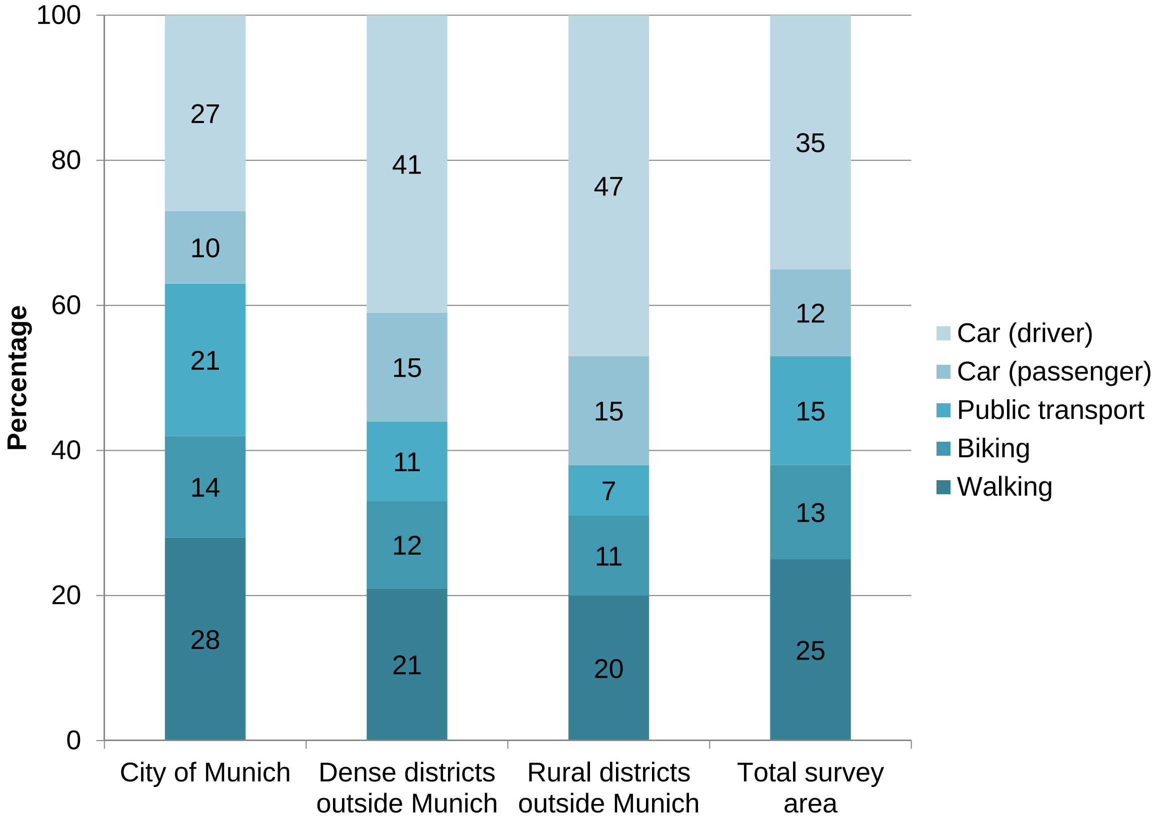

Figure 7.1: Modal split for the original MiD travel survey illustrating the high percentage of non-motorized trips in Munich (42%)

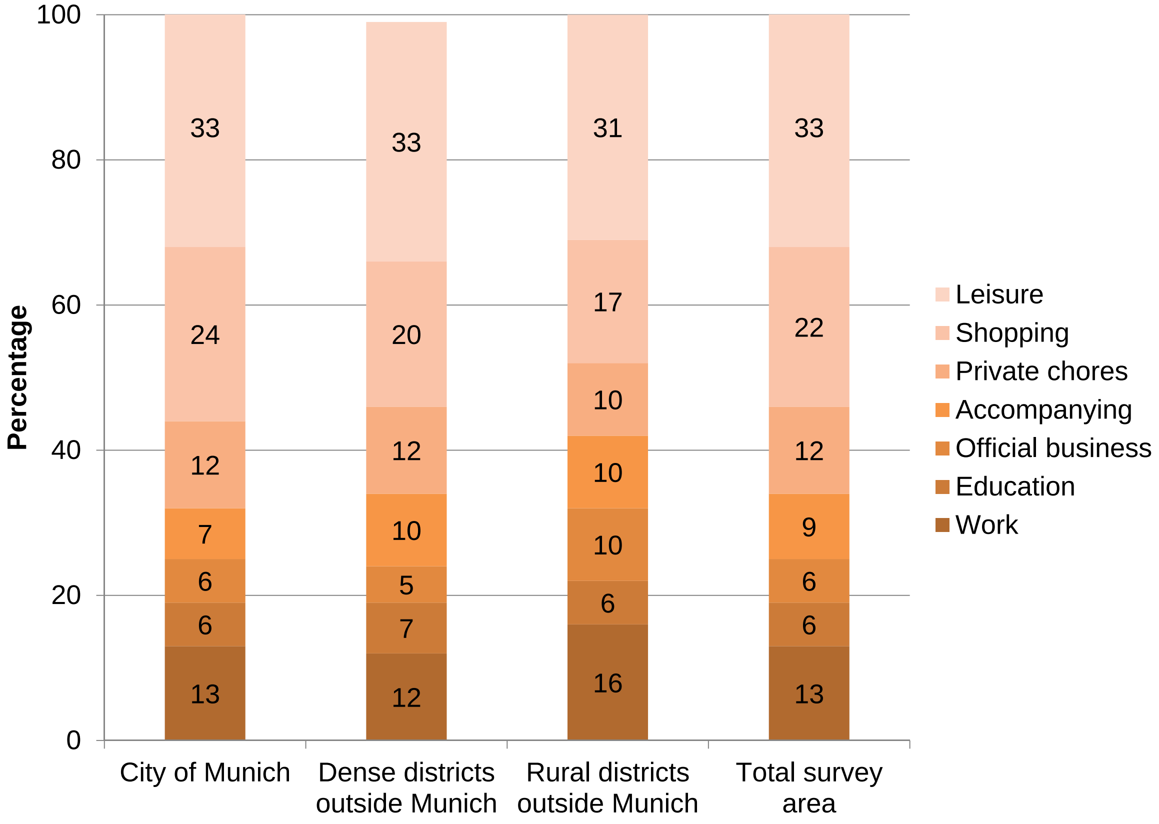

Figure 7.2: Trip purpose for the original MiD travel survey illustrating the fairly constant trip purpose between difference locations.

7.5 Data preprocessing

In order to analyze the transportation data, data preprocessing is required to make the data usable and to satisfy the research scope. The MiD-MUC data set used has five data sets: *Households*, *Persons*, *Trips Travel* (this includes starting and ending locations for each trip), and *Autos* (see table 7.1). Long-distance trips (Germ. Reise) are included in the *Trips* data set. There are a total of 42,074 trips in the original *Trips* data set. The *Trips* data set is used as the primary data set as it contains individual trip information (42,074 trips total), household and person information, as well as mode, distance traveled, time of travel, and location information in addition to numerous other variables. The *Trips* data set is linked to the other data sets using the Household Identification and the associated Persons Identification. Exact household residential location is, however, not provided in any of the data sets. The resolution of this issue is discussed below in section 7.6.

Data preprocessing is required to ensure that the data analysis fits the research scope. The data preprocessing is done in *Excel* and the data are read and analyzed by a program written in the *Python* programming language. Data preprocessing is done on the *Trips* data set to enable analysis of the data.

Table 7.1: MiD-MUC data set size and number of variables.

Data set	Data points Munich	District	Total	Variables
Households	3,561	2,334	5,895	104
Persons	7,468	5,668	13,136	121
Trips	23,505	18,569	42,074	120
Travel	6,358	3,932	10,290	51
Autos	3,719	3,376	7,095	55

7.6 Data assumptions

The MiD-MUC data set is extensive (42,074 trips with 120 variables for each trip); however, not all the data are relevant to the scope of the research. The objectives and scope of the research, as outlined previously are to determine the environmental impacts from transportation operation at different locations. The assumptions made for data processing are presented below with the associated reasoning for data processing and background information.

1. *Remove all trips of length zero.*
   Mobile and non-mobile persons were recorded in the MiD-MUC data. The *Trips* data set contains all the trips for Munich and the surrounding area. As the *Trips* data is only for trips made, it should not contain any non-mobile persons (i.e., only mobile persons should be included in the *Trips* data set). However, there were 19 trips of a distance of 0

km (i.e., these are not actually trips). As this represents non-mobile persons in the data set that should only contain mobile persons, this data must be removed from the *Trips* data set. These 19 trips of 0 km are done by a total of 10 different households. However, only one household is entirely removed from the data set as the remaining 9 households have other mobile persons taking trips. See table 7.2.

Table 7.2: Revised *Trips* dataset after carrying out assumption 1.

	Households	Trips
Before assumption	5,254	42,074
After assumption	5,253	42,055
Data removed	1	19

It should be noted here that the initial households for the *Trip*s data set is 5,254 compared to 5,895 as listed in table 7.1 on page 121. This difference is due to the inclusion of non-mobile households in the *Household*s data set compared to the *Trips* data set.

2. *Remove trips where distance is not known or is unrealistic.*
   In the MiD-MUC *Trips* data set, some trip lengths (wegkm_k: corrected distance in kilometers) have been identified as unrealistic (variable value of 9994), were not given (variable value of 9997), or the respondent did not know (variable value of 9998). As no additional distance information is given for these trips, it is not possible to calculate the associated emissions of these trips and they are thus removed (table 7.3).

Table 7.3: Revised *Trips* dataset after carrying out assumption 2.

	Households	Trips
Before assumption	5,253	42,055
After assumption	5,205	41,458
Data removed	48	597

3. *Remove all professional trips (Germ. regelmäßige berufliche Wege).*
   The MiD-MUC data includes professional trips—trips by workers (e.g., craftsmen, bus drivers, postmen, representatives, suppliers) as well as intermittent official business trips [191]. Trips to a regular workplace from one's residence are not included in this category and are classified as a commuting trip. On one hand, a professional trip could start at one's residential location and end at the non-regular work location. On the other hand, it is also possible that a trip starts at one work location and ends at another work location.

   The research aim of this chapter is to determine the transportation operational impacts, which will be tied back to residential location. While numerous factors influence travel demand as discussed above, the research will also examine if residential location has an influence on travel. The professional trips are, however, problematic for the research objective. First, the trip mode used may be predetermined by work (e.g., a bus driver has to use a bus for their professional trips; a craftsman may have to use a company vehicle to transport tools). These limitations for the professional trip are not given in the data, but may constrain travel demand. Further, as only the trip purpose is given, rather than the starting location and end location, these trips may or may not illustrate the influence of residential location. Consequently, professional trips are removed (table 7.4). All work related non-professional trips (i.e., commuting trips to a regular office location) are maintained in the data.

Table 7.4: Revised *Trips* dataset after carrying out assumption 3.

	Households	Trips
Before assumption	5,205	41,458
After assumption	5,196	39,856
Data removed	9	1,602

4. *Remove trips where no mode is given.*
In order to calculate the emissions for each trip, the mode used and the trip length are required. The *Trips* data set is checked to ensure that every trip has an associated mode of transportation. As this is the case, no data points are removed.

In addition, all trips with a mode “not know” or “not given” must similarly be removed as it is not possible to calculate the environmental emissions if the mode is not stated. Thus, all trips for the transportation mode “not known” are removed (table 7.5).

Table 7.5: Revised *Trips* dataset after removing mode: not known.

	Households	Trips
Before assumption	5,196	39,856
After assumption	5,196	39,855
Data removed	0	1

5. *Remove trips with irrelevant modes for the research scope.*
As previously outlined, the research focuses on daily mobility within the *urban region of Munich*. The MiD-MUC data set contains trip information for several transportation modes that are outside the scope of the research, and thus need to be removed from the data set. It should be noted that the mode listed for each trip is the main mode for the trip. A trip could consist of several trip legs, but will only have one main mode for the trip (e.g., walking to public transport, taking public transport, and then walking to the destination would have a main mode of public transportation). The irrelevant modes are heavy goods vehicles, ships or ferries, or airplanes. As heavy good vehicles are not a typical daily transportation mode for individuals, these trips are removed (table 7.6 on

the next page).

Table 7.6: Revised *Trips* dataset after removing mode: heavy goods vehicle.

	Households	Trips
Before assumption	5,196	39,855
After assumption	5,195	39,840
Data removed	1	15

Trips are also given for the transportation mode ship or ferry. These trips are similarly removed as this not a typical transportation mode for the *urban region of Munich* (table 7.7).

Table 7.7: Revised *Trips* dataset after removing mode: ship, ferry.

	Households	Trips
Before assumption	5,195	39,840
After assumption	5,195	39,825
Data removed	0	15

All transportation by airplane are similarly removed as this represents long distance travel outside the *urban region of Munich* (table 7.8). Only 30 trips by airplane were removed in total (there were a total of 45 trips by airplane in the original data set).

Table 7.8: Revised *Trips* dataset after removing mode: airplane.

	Households	Trips
Before assumption	5,195	39,825
After assumption	5,190	39,795
Data removed	5	30

6. *Use average values for non-specified modes.*
   The MiD-MUC data have a combined transportation mode for tram and subway trips. Thus it is not specifically stated which of these modes was used for the trip at hand. As environmental data is available for both modes, the average is used for the combined mode. Alternatively, a weighted average based on total distances traveled by each mode could have been used. Similarly, another combined mode is suburban train and regional train. For this case the environmental data for suburban train are used. Finally, the MiD-MUC has a mode for taxis, which are classified under public transportation in the MiD methodology [191]. In order to obtain the environmental emissions from taxis, emissions for passenger vehicles are used.

7. *Define the residence location for each household.*
   Due to privacy protection, the MiD-MUC data does not contain exact addresses for

households in any of the data sets. However, there is general residential location information in the data. All households in the MiD-MUC data set (i.e., households both in the City of Munich and those outside the City of Munich) have a residential district (Germ. Landkreis). District location is the only location information given for households outside the City of Munich.

For households within the City of Munich, additional information is given for each trip, which consists of a starting and ending location. This information includes the starting and ending traffic cell (Germ. Verkehrszelle), the starting and ending neighborhood (Germ. Stadtbezirk), and the starting and ending district (in this case, all households have the City of Munich as their district).

Thus, the only location information known for sure for each household is the district. However, using the additional location information for households in the City of Munich, it is possible to more accurately define their location. Knowing the neighborhood for each starting trip, the assumption is made that the neighborhood for the first trip of the day is the household's neighborhood. This is also done for the traffic cell location of households. This assumption is only made for households in the City of Munich.

From the above assumption every household in the City of Munich is assigned a traffic cell, neighborhood, and district based on the location information of the first trip. However, for numerous households the known household district from the MiD-MUC data does not match the district based on the assumption from the first trip. Thus there is an inconsistency in the district locations for these households, and the entire household is removed from the data set (see table 7.9). The traffic cell, neighborhood, and district are checked for each person within each household. Again, this step is only concerned with households in the district of the City of Munich.

The reasoning for the inconsistency in household members may be due to a person in a household starting their first trip of the day at a location outside of the City of Munich or a person coming home late from a party, work, or a social event (i.e., their first trip of the day is after midnight, but resulting from the previous day). Given that the exact reasoning for the inconsistency is not available, and given the fact that the inconsistency affects the household, the entire household is removed. While this assumption removes numerous trips from the data set, this is done to have a consistent data set even if the number of total trips is reduced (table 7.9).

Table 7.9: Revised *Trips* dataset after carrying out assumption 7.

	Households	Trips
Before assumption	5,190	39,795
After assumption	4,837	36,718
Data removed	353	3,077

8. *Remove all households without a neighborhood.*

In the previous step, each household in the City of Munich is assigned a traffic cell and neighborhood. However, in the MiD-MUC *Trips* data set there are households within the City of Munich with a neighborhood value of 0 (i.e., theses households do not have a neighborhood in Munich). As each household in Munich must also have a neighborhood in Munich, households without a neighborhood are removed (table 7.10).

Table 7.10: Revised *Trips* dataset after carrying out assumption 8.

	Households	Trips
Before assumption	4,837	36,718
After assumption	4,825	36,598
Data removed	12	120

9. *Remove all households where the neighborhood location varies between persons in the household.*
   For households in the City of Munich, the neighborhood location is assumed to be based on the neighborhood of the first trip for each person as stated above. However, there are households where the starting neighborhood differs between persons in the same household. This is inconsistent as each household should have the same neighborhood location, and therefore these households are removed (table 7.11).

Table 7.11: Revised *Trips* dataset after carrying out assumption 9.

	Households	Trips
Before assumption	4,825	36,598
After assumption	4,778	36,082
Data removed	47	516

10. *Define a preliminary maximum trip length.*
    After carrying out all the above steps there are 31 trips over 500 kilometers in distance. As the research scope is on daily transportation within the *urban region of Munich* such long-distance trips are not of interest. Statistical analysis of the data can determine the outliers for long-distance trips, but the extreme long trips need to be removed first as they are outside the scope of the work. An initial distance limit of 350 kilometers per trip is set based on the approximate maximum travel distance within the general region (i.e., Berchtesgaden to Donau-Ries, circa 300 km) (table 7.12).

Table 7.12: Revised *Trips* dataset after carrying out assumption 10.

	Households	Trips
Before assumption	4,778	36,082
After assumption	4,767	36,014
Data removed	11	68

11. *Define a maximum trip length based on statistical analysis.*
    The revised *Trips* data set with 36,014 data points is then statistically analyzed to determine the maximum trip length. The sample size is 36,014 trips, with a minimum trip length of 0.09 km and a maximum trip length of 348.36 km. This maximum is from the assumed maximum limit of 350 km as stated previously. The lower quartile (Q_1, 25^{th} percentile) is 0.98 km, the median (Q_2, 50^{th} percentile) is 2.85 km, and the upper quartile (Q_3, 75^{th} percentile) is 8.55 km. The interquartile range (IQR), the difference between the upper and the lower quartile, is 7.57 km. The average trip length is 8.79 km. As a comparison, the average trip length for the original MiD-MUC data is 12.52 km [131]. The lower average is due to the removal of long-distance modes and long-distance trips.

    Outlier data points are those data points statistically removed from the other data, and can be classified as either mild or extreme outliers. The formulas to calculate the mild and extreme outliers at both ends of the data set are as follows:

$$Mild\ Outlier_{Lower\ bound} = Q_1 - 1.5 \times IQR \tag{7.1}$$

$$Mild\ Outlier_{Upper\ bound} = Q_3 + 1.5 \times IQR \tag{7.2}$$

$$Extreme\ Outlier_{Lower\ bound} = Q_1 - 3 \times IQR \tag{7.3}$$

$$Extreme\ Outlier_{Upper\ bound} = Q_3 + 3 \times IQR \tag{7.4}$$

    For the data variable km/trip the lower bound for outliers is zero, as negative length trips are not feasible. The upper bound for mild outliers and extreme outliers are 19.91 and 31.26 km/trip, respectively. The results of the analysis are presented in figure 7.3 on the next page.

    As a comparison, the data variable km/person-day and km/household-day were also statistically analyzed to determine the upper bounds for mild and extreme outliers. For the km/person-day data the upper bound for the mild and extreme outliers are 86.45 and 134.90 km/person-day, respectively. For the km/household-day data the upper bound for the mild and extreme outliers are 181.52 and 283.07 km/household-day, respectively. The upper bound outliers are summarized in table 7.13 on the following page.

    The statistical analysis for km/trip data has an upper bound for the extreme outlier of 31.26 km/trip, which illustrates the dominance of short distance trips in the MiD-MUC data set. However, removing all trips over 32 km would eliminate realistic daily trips within the *urban region of Munich*. Thus an upper bound of 32 km/trip is too restrictive and would remove too many trips of interest. The statistical analysis of the km/person-day and km/household-day are illustrative of the extreme outlier values for these variables;

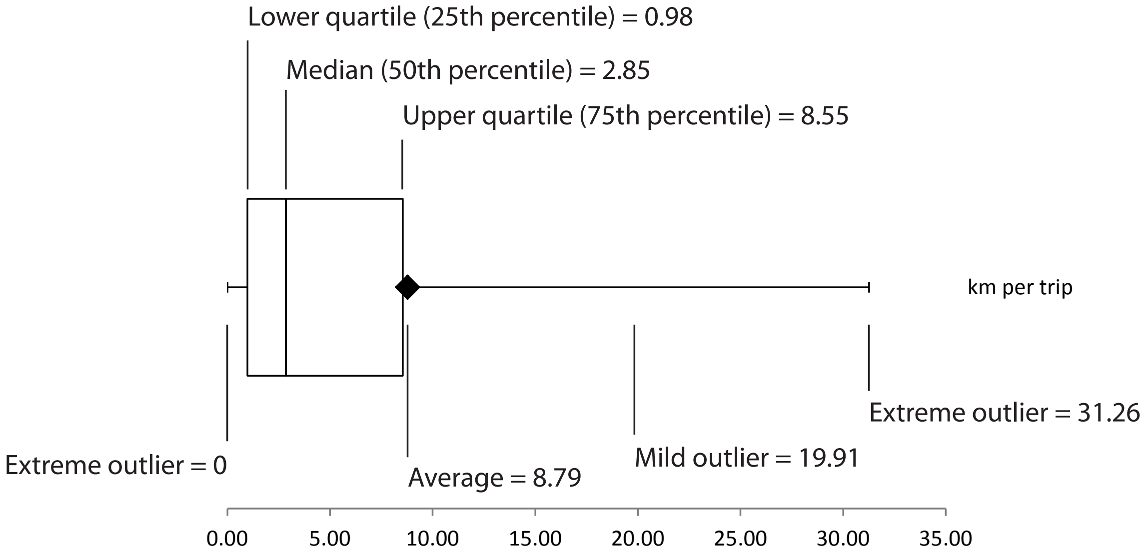

Figure 7.3: Statistical analysis of trip length (km).

Table 7.13: Statistical analysis of trip length. All lower outliers are zero as negative trip distances are not feasible.

	km/trip	km/person-day	km/household-day
Lower quartile (Q1)	0.98	5.70	12.25
Median (Q2)	2.85	15.39	33.08
Upper quartile (Q4)	8.55	38.00	79.96
Lower outlier (mild)	0	0	0
Upper outlier (mild)	19.91	86.45	181.52
Lower outlier (extreme)	0	0	0
Upper outlier (extreme)	31.26	134.90	283.07

however, the variable of interest is km/trip. However, the previous maximum trip distance of 350 km is too high.

A trip from Lenggries (District: Bad Tölz-Wolfratshausen) to Rudelzhausen (District: Freising) represents the rough extents of a maximum single trip within the *urban region of Munich* (130 km) [194]. Using this length as a basis, the maximum trip length is set at 200 km to allow for some variation within the region and to exclude as few trips as possible. The *Trips* data set is once again updated accordingly.

From the revised data set 85 trips (0.24 % of all the revised trips) are over 200 km. For an individual taking a trip over 200 km all subsequent trips are in a city outside the home location and may be influenced by the mode used to travel to this location. Trips prior to a 200 km trip may or may not be related to the long-distance trip. The first leg of a trip (e.g., driving to the train station) would already be included in the 200 km trip. However, to be consistent all trips for persons with a trip over 200 km are removed. Other persons in the same household not taking trips over 200 km remain in the data set. This explains the removal of the 211 trips instead of just the 85 trips. The final revised *Trips* data set after taking this into consideration is presented in table 7.14.

Table 7.14: Revised and final *Trips* dataset after carrying out the final assumption of a maximum trip length of 200 km.

	Households	Trips
Before assumption	4,767	36,014
After assumption	4,743	35,803
Data removed	24	211

The final revised *Trips* data set for the research has 4,743 households (a reduction of 9.7%) and 35,803 trips (a reduction of 14.9%).

7.7 Methodology

The MiD-MUC *Trips* data set is used for the transportation analysis as outlined above. After carrying out the data preprocessing and the assumptions the data set contains 35,803 trips for 4,743 households with 124 variables (e.g., trip distance, mode, district location). In order to analyze the large data set (i.e., a matrix of size 124 x 35,803) a software program is written using the *Python* programming language. *Python* is chosen as it is a flexible language capable of handling large data sets with numerous mathematical packages available and is increasingly used in scientific research. The software architecture for the MiD analysis program is presented in figure 7.4 on the following page. As illustrated in the architecture there is one main script, which calls upon three subscripts (i.e., mode_percentage.py, environmental_output.py, and excel_MIDoutput.py), where .py denotes a *Python* script. The code for the program is extensive (over 2,000 lines) and is therefore omitted for clarity.

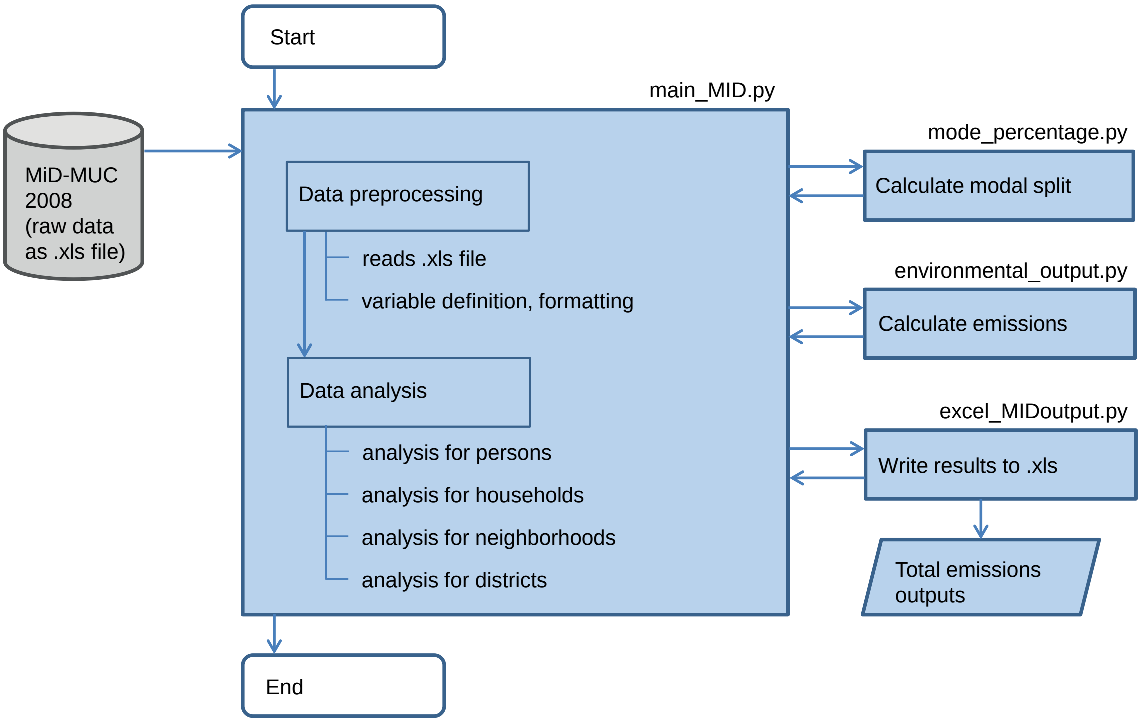

Figure 7.4: Software architecture for the program analyzing the MiD-MUC data (written in *Python*).

7.7.1 Emission factors

The environmental factors for transportation operation are from the *Handbook Emission Factors for Road Transport* (HBEFA) [195] and the *Transport Emission Model* (TREMOD) [79]. Emission for non-motorized transportation (i.e., walking and bicycling) are assigned a null value based on the MiD and MiD-MUC methodologies. The *Handbook Emission Factors for Road Transport* gives emission factors for passenger cars, urban buses, coaches, and motorcycles. The pollutants calculated with the HBEFA are fuel consumption, total hydrocarbons (CH_4, NMHC, benzene, toluene, xylene), CO, NO_2, NO_X, CO_2, particulate matter, CH_4, NMHC (non-methane hydrocarbons), Pb, SO_2, N_2O, NH_3, and benzene. The analysis years calculated are 2010, 2015, 2020, 2025, and 2030. The emissions calculated are for hot emission factors for an aggregate traffic situation including gradient distribution and for all road categories as per IFEU 2009 [195]. Fleet composition is taken as business-as-usual. Cold start excess emission factors, evaporation emission factors, and correction for air-conditioning are not included. The factors for motorcycles are used for both motorcycles and mopeds as specific moped emissions are not available.

In order to calculate energy for the HBEFA results, the energetic conversion factor (MJ/kg fuel) is used. These values are the same as used in TREMOD (gasoline: 43.543 MJ/kg, diesel: 42.96 MJ/kg) [79]. These conversion factors are multiplied by the fuel consumption values for each mode to get energy use. For passenger automobiles the fuel source breakdown at the national level is as follows: gasoline (67.37 %), diesel (31.61 %), liquefied gas (0.74 %), natural gas (0.15 %), electricity (0.01 %), and hybrid (0.11 %) [196]. For Bavaria these values are as follows: gasoline (70.94 %), diesel (27.70 %), liquefied gas (1.06 %), natural gas (0.17 %), electricity (0.01 %), and hybrid (0.11 %) [196]. Based on the fuel percentages for passenger automobiles, a weighted emission value is used for the calculations. The emissions are made up of 71.5% gasoline vehicles and 28.5% diesel vehicles to match actual vehicles percentages in Bavaria as best as possible. Urban buses are assumed to be fueled by diesel [37], coaches by diesel [37], and motorcycles by gasoline.

The emission factors from the HBEFA are given as g/km for the vehicle in question. In order to use these results for the MiD-MUC data, and in comparison with the TREMOD data, it is necessary to convert these values to kg/Pkm. This conversion requires that the possible occupancy and the occupancy rate of each mode is known. For passenger cars the federal average occupancy rate of 1.5 persons/automobile is used [197]. For the urban bus a capacity of 70 spaces (37 seating and 33 standing) is used for Munich buses [198]. The average national occupancy rate for city buses is 21% [170]. As Munich bus occupancy rates are not available [169, 199] and to have consistency in using national occupancy rates for all mode, the national average is used, thus giving an average of 14.7 persons per bus. For coaches a capacity of 50 persons is taken as an average based on the seating capacity for the Autobus Oberbayern buses [200]. Buses seating 41 to 50 persons make up the largest percentage of buses (31.9 %), followed by 51 to 60 persons (25.5%) and 32 to 40 persons (20.6%) [201] supporting this capacity of 50 persons. An occupancy rate of 60% is used [197] yielding an average of 30 persons per coach. Finally, the occupancy of motorcycles is taken as 1 due to the limited capacity of this mode and the absence of more specific occupation rates.

The environmental factors for TREMOD are given for long-distance trains, short-distance trains, trams, and subways [79]. The emissions given for TREMOD are CH_4, CO, CO_2, HC, N_2O, NH_3, NMHC, NO_X, SO_2, particulate matter, and energy, and are for an electric energy supply including all up-stream impacts. Based on the available modes given in the MiD-MUC data, emission factors are needed for the average of subways and short-distance trains, the average of subways and trams, short-distance trains, and long-distance trains. This data is taken from TREMOD and used for calculating the environmental impacts in the *Python* program.

7.8 Results

The data from the MiD-MUC *Trip*s data set is analyzed using the *Python* program and the following results are presented in this section: general results (i.e., persons per household, trips per person), modal split, distance traveled, and environmental emissions. The results are compared with those from the national MiD transportation survey [190] and the regional MiD-MUC survey [131]. The objective is not to reanalyze all the data from the existing summary reports [131, 190], but rather, to calculate key statistics to verify the reliability of the program and results.

7.8.1 General transportation results

While there are numerous statistical values available from the large data set, general information on the persons per household and trips per person are fundamental to understanding the data. Analysis of the MiD-MUC data shows that there is an average of 2.08, median of 2.00, and a standard deviation of 1.11 persons per household. The maximum number of persons per household is 7; the MiD-MUC methodology sets a maximum of 8 persons per household. The frequency distribution for the persons per household is shown in figure 7.5. The household sample size is 4,764. The relative frequencies, *y*, for one to seven persons are 36.6, 35.5, 14.1, 10.9, 2.4, 0.4, and 0.1%, respectively (see figure 7.5). This statistic is not reported in either the national [190] nor the regional [131] summary reports.

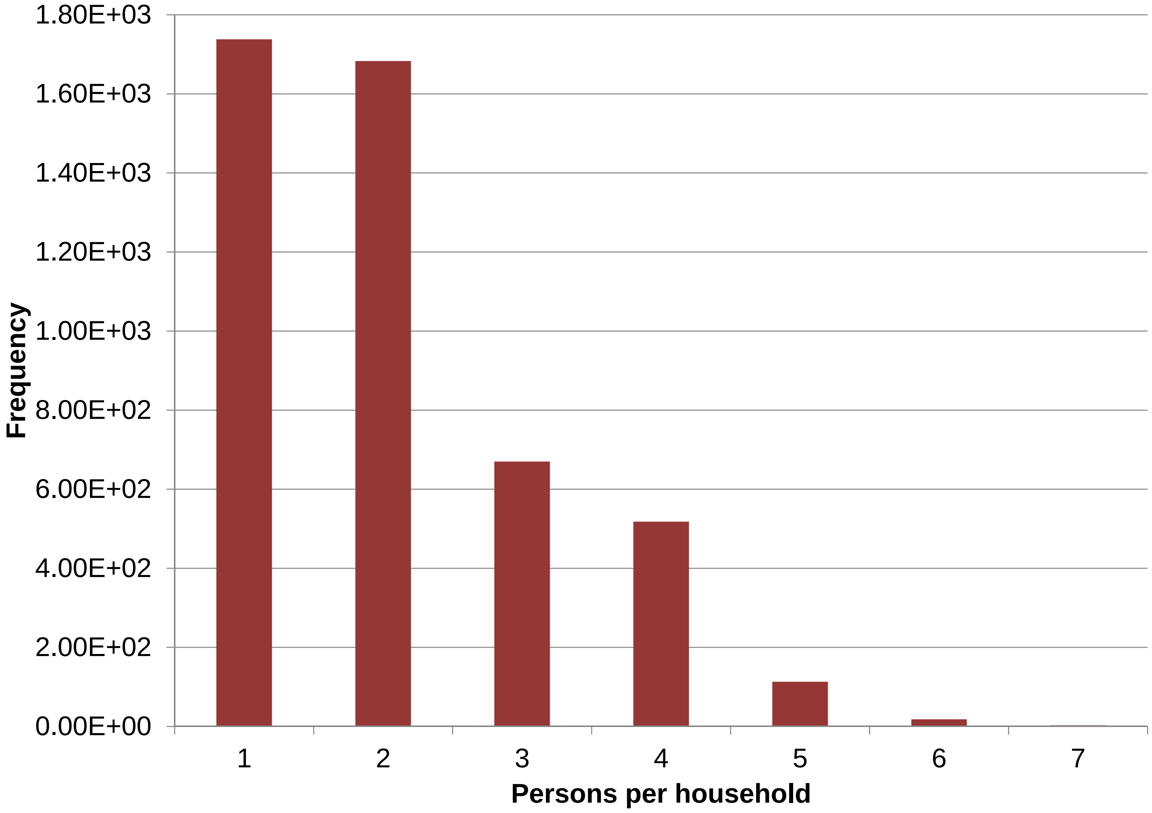

Figure 7.5: Frequency distribution of persons per household.

The data analysis for trips per person results in a mean of 3.62, a median of 3.00, and a standard deviation of 1.96. The maximum number of trips per person in one day is twelve as defined in the MiD methodology [191]. The frequency distribution of daily trips per person is shown in figure 7.6 on the next page for a sample size of 9,880 persons. The relative frequencies for one to twelve trips are 7.4, 30.7, 14.3, 21.1, 9.7, 8.4, 3.8, 2.3, 1.2, 0.5, 0.3, and 0.3%, respectively. The daily mean of 3.62 trips per person is in accordance with the results for the city of Munich (3.4 trips per person) and the surrounding districts (3.5 trips per day) [131]. The average number of daily trips per person is 3.4 at the federal level [190].

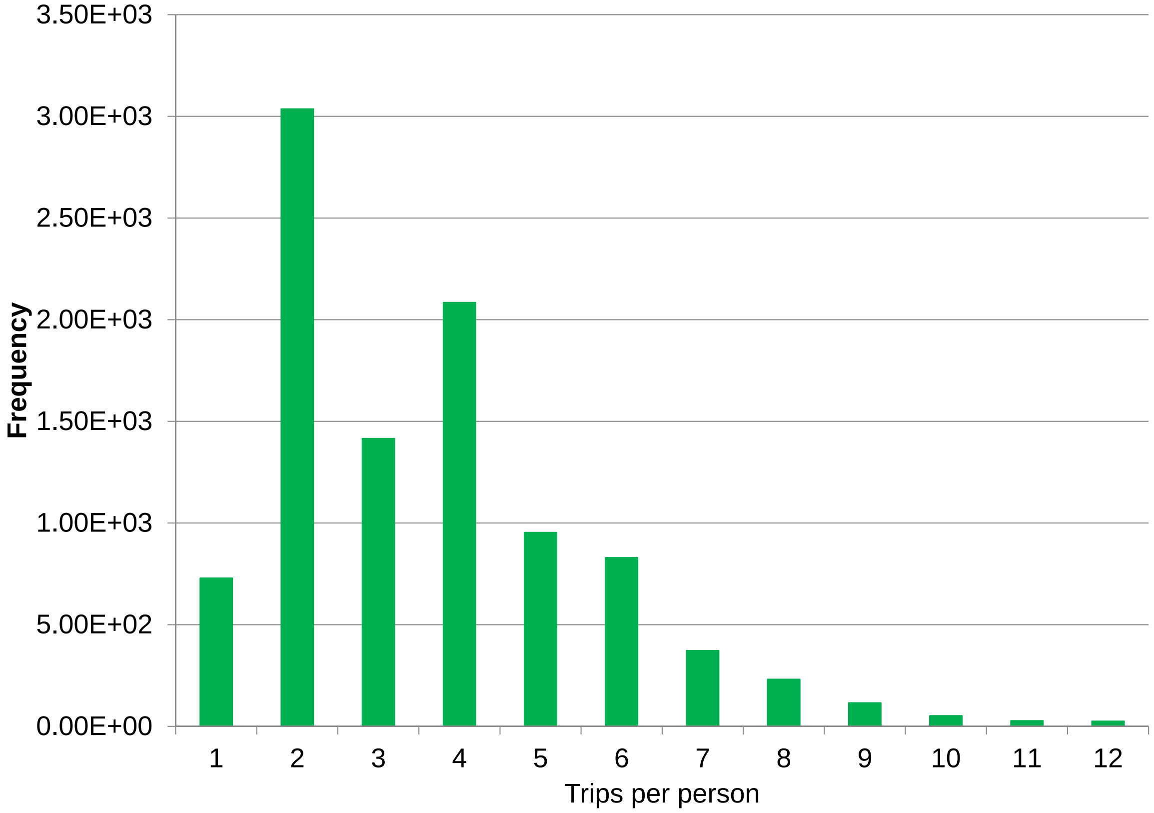

Figure 7.6: Frequency distribution of daily trips per person.

7.8.2 Modal split

Modal split percentages are calculated for the City of Munich, the surrounding districts, and the entire *Munich Transport and Tariff Association area of operation*. The modal split categorization is per the MiD methodology [192]. Thereby public transit includes the following modes: coach, short-distance train, subway, tram, urban bus, and taxi. Private motor vehicles (PMV) include passenger cars as driver and passenger, motorcycles as driver and passenger, and mopeds. The modal split calculations are shown and compared to the values from the regional [131] and federal [190] results (see figure 7.7 on the following page). The comparison shows that the calculations are very similar to the regional results, as expected. The modal split is also shown based on motorized, public transport, and non-motorized modes in figure 7.8 on page 135. This enables comparison between other cities in Germany and internationally.

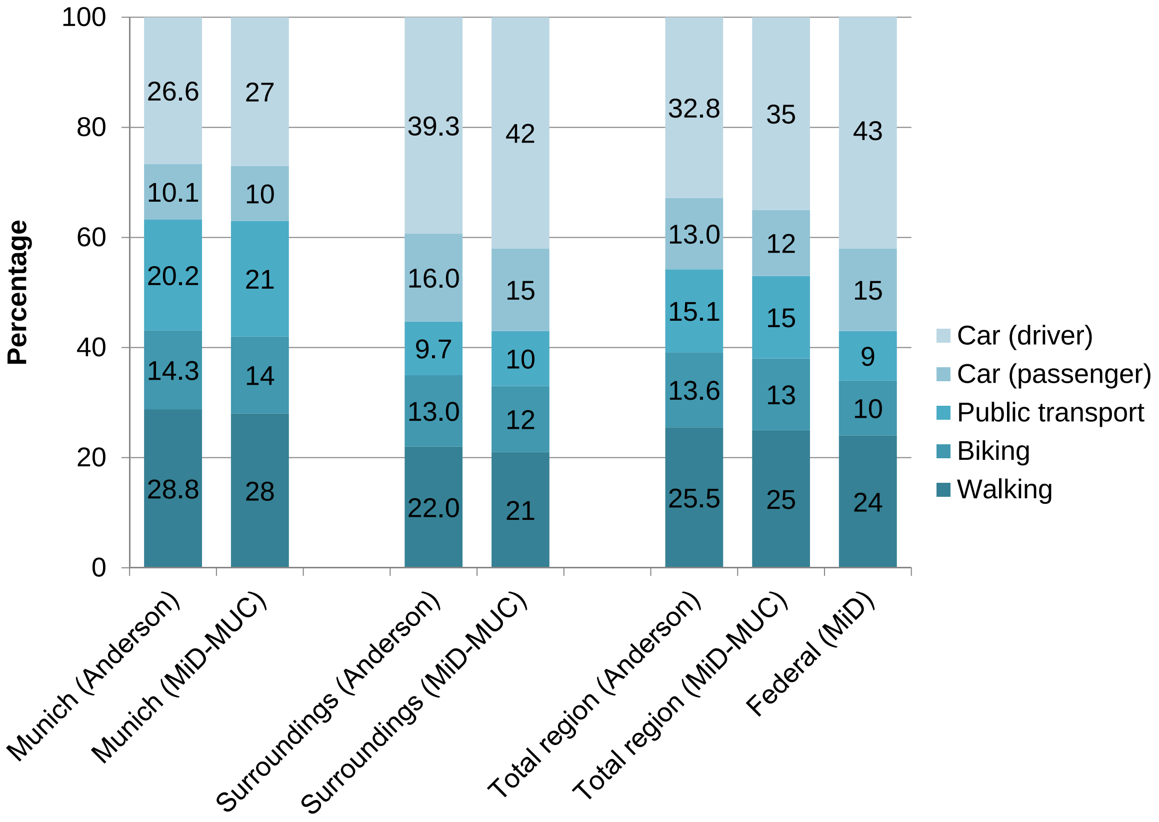

Figure 7.7: Modal split percentages from the research analysis compared to the MiD-MUC [131] and MiD [190] results.

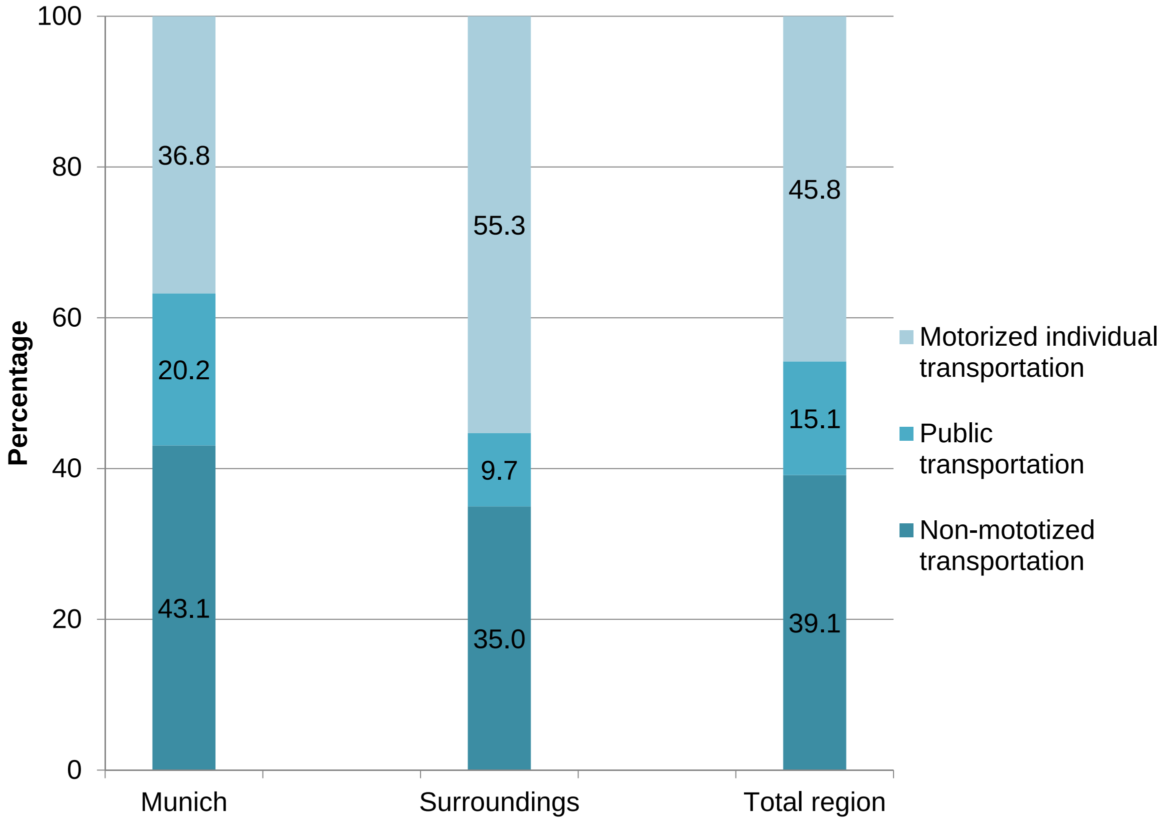

Figure 7.8: Modal split percentage results from the research analysis for motorized individual transport, public transport, and non-motorized transport.

7.8.3 Distance traveled

For the 35,803 trips in the data set, the average distance per trip is 8.19 km, with a median of 2.85 km, and a standard deviation of 16.24 km. As a comparison, for the original data, the average distance per trip is 12.52 km, with a median of 2.85 km, and a standard deviation of 134.82 km [131]. Based on the data assumptions previously outlined, the minimum trip distance is 0.09 km and the maximum trip is 199.50 km. The frequency distribution of the 35,803 trips is shown over the full range of the data (see figure 7.9).

The distributions for trip lengths up to 50 km are shown in figure 7.10 on the next page and for trip lengths up to 10 km in figure 7.11 on page 138. The data analysis shows that trips under 1, 3, 5, 10, and 250 km constitute 28.3, 53.1, 64.9, 79.4, and 100% of all trips, respectively. The comparison to the original data is shown in table 7.15 on the next page. The calculated average trip distance (8.19 km) is lower than the given regional values (City of Munich: 10 km, and surrounding districts: 12 km) and the federal average (12 km). This is explained through the exclusion of overnight trips and long-distance trips over 200 km as outlined in the assumptions.

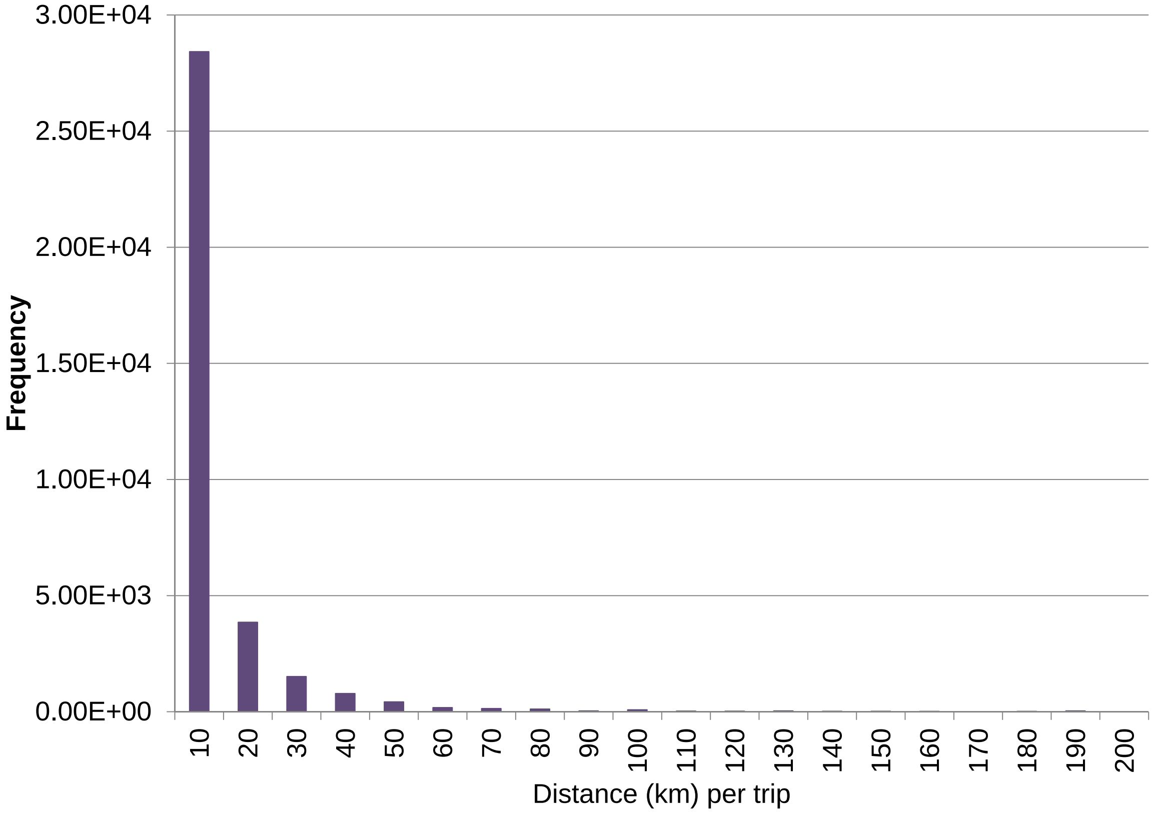

Figure 7.9: Frequency distribution of travel distance (km) per trip for all trips up to 200 km.

The analysis gives the daily travel distances per person with an average of 29.67 km, median of 15.22 km, standard deviation of 40.78 km, minimum of 0.1 km, and maximum of 410.88 km. The maximum daily travel distance per person is for an individual taking five trips

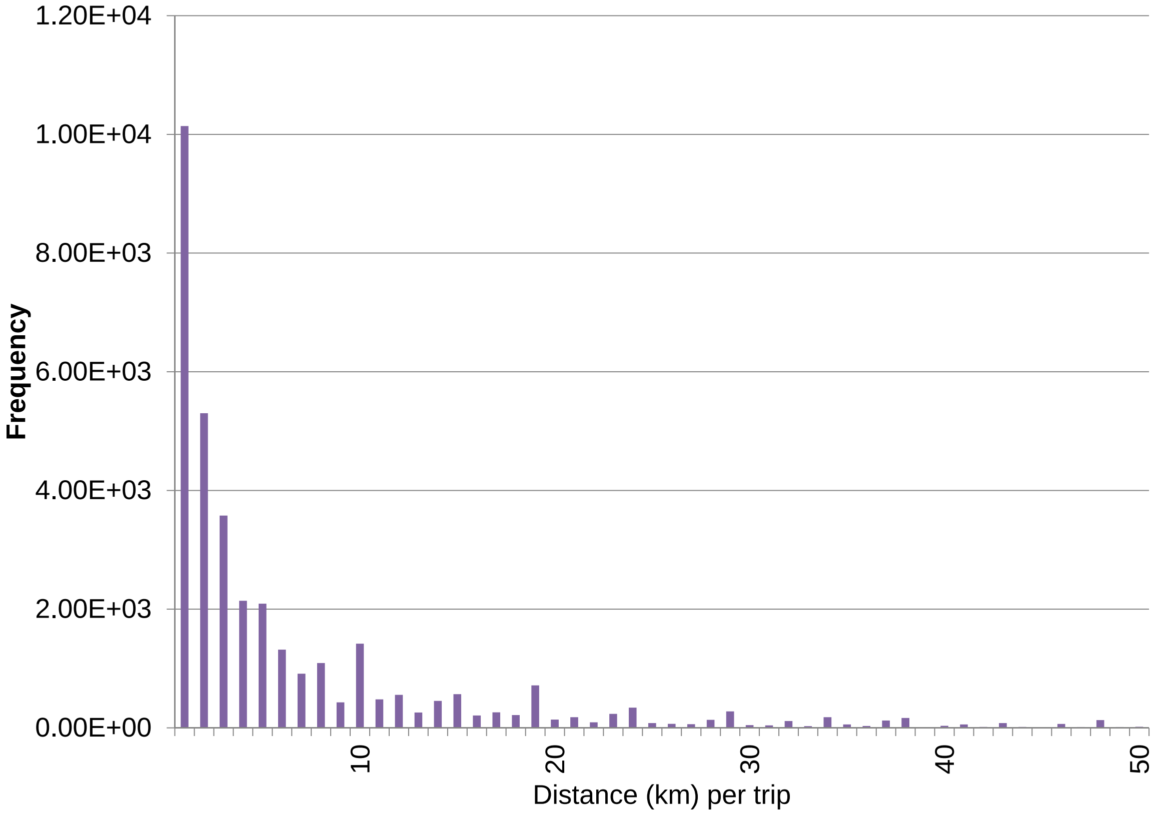

Figure 7.10: Frequency distribution of travel distance (km) for all trips up to 50 km.

Table 7.15: Trip length dataset.

	Original data set	Data after processing
Sample size	41,477	35,803
Trips under 1 km (%)	27.8	28.3
Trips under 3 km (%)	52.2	53.1
Trips under 5 km (%)	63.7	64.9
Trips under 10 km (%)	78.5	79.4
Trips under 250 km (%)	99.5	100.0

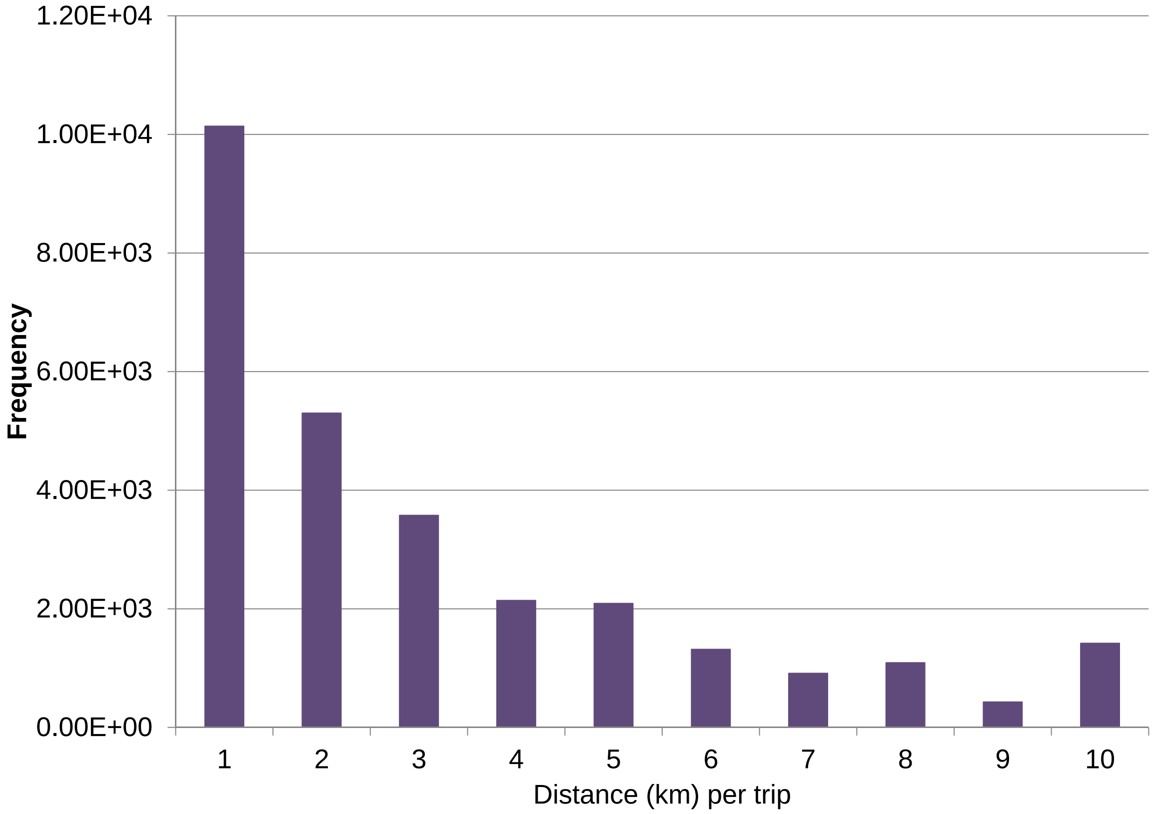

Figure 7.11: Frequency distribution of travel distance (km) for all trips up to 10 km.

(11.40 km driving, 180.50 km with the bus, 13.54 km with the bus, 194.04 km with the bus, and 11.40 km driving). The average daily travel distance is 25.7 km and 34.0 km for the City of Munich and the surrounding districts, respectively. These daily distance averages per person are lower than the results for the region (Munich: 34.9 km, surrounding districts: 42.9 km, and all areas: 38.9 km) and the federal level (39 km). Again, the lower calculated distances are due to the removal of all over-night trips and long-distance travel over 200 km.

The average daily travel length per person is shown geographically at three levels: for traffic cells in Munich (figure 7.12), for the 25 neighborhoods in Munich (figure 7.13 on the next page), and for the 10 districts in the *Munich Transport and Tariff Association area of operation* (figure 7.14 on page 141).

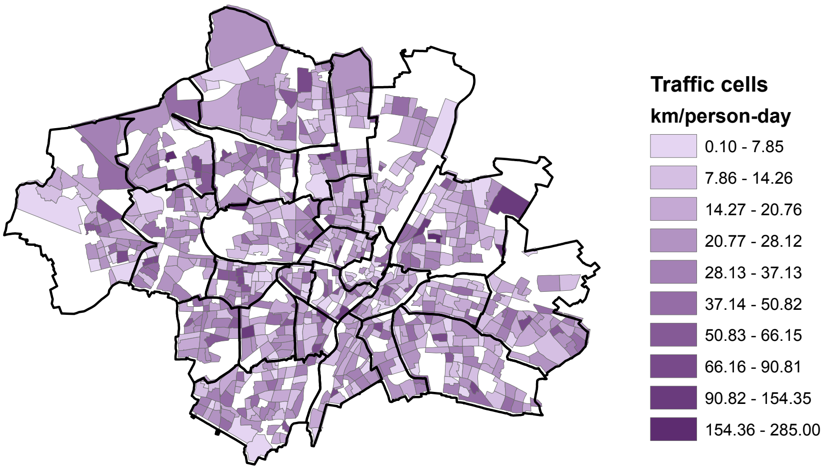

Figure 7.12: Traffic cell level in the City of Munich showing daily travel distance (km) per person. Neighborhoods are outlined in black.

At the neighborhood level in Munich, distance traveled per person ranges from 18.76 km/day (Au-Haidhausen (5)) to 41.12 km/day (Allach-Untermenzing (23)) (figure 7.13 on the next page). For the district level, distance traveled per person ranges from 25.69 km/day (Munich) to 38.95 km/day (Ebersberg) and 39.25 km/day (Miesbach) (figure 7.14 on page 141). The average for the surrounding districts excluding the City of Munich is 34.14 km/person-day, and the average for all districts (including Munich) is 33.30 km/person-day. From the MiD-MUC results, the average distance per person is 34.92 km/day (Munich), 42.87 km/day (surroundings), and 38.94 km/day (all areas) [131]. The average distance per person for all of Germany is 39 km in comparison [190]. All values are summarized in table 7.16 on the next page.

The daily distances per person calculated are lower than the results from the MiD-MUC and MiD results. This is expected as the analysis removed all trips above a specified trip

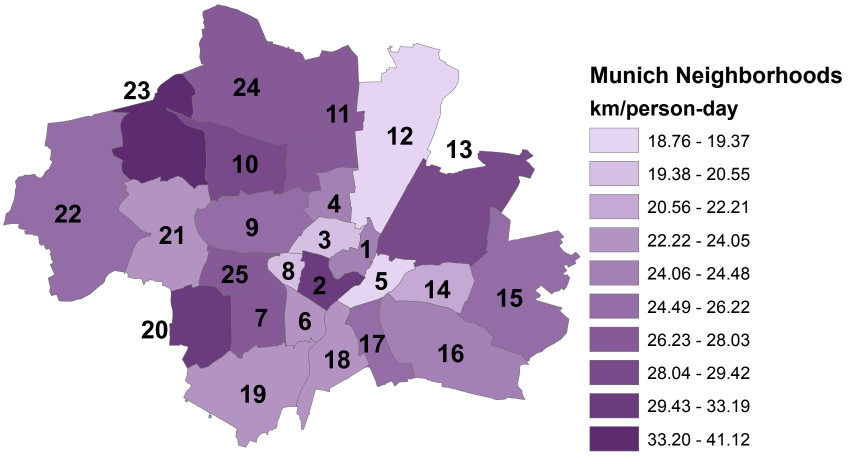

Figure 7.13: Neighborhood level in the City of Munich showing daily travel distance (km) per person.
Altstadt-Lehel (1), Ludwigsvorstadt-Isarvorstadt (2), Maxvorstadt (3), Schwabing-West (4), Au-Haidhausen (5), Sendling (6), Sendling-Westpark (7), Schwanthalerhöhe (8), Neuhausen-Nymphenburg (9), Moosach (10), Milbertshofen-Am Hart (11), Schwabing-Freimann (12), Bogenhausen (13), Berg am Laim (14), Trudering (15), Ramersdorf-Perlach (16), Obergiesing (17), Untergiesing-Harlaching (18), Thalkirchen-Solln (19), Hadern (20), Pasing-Obermenzing (21), Aubing-Lochhausen-Langwied (22), Allach-Untermenzing (23), Feldmoching-Hasenbergl (24), and Laim (25).

Table 7.16: Summary of distance traveled (km) per person-day.

	Analysis	MiD-MUC [131]	MiD [190]
Munich	25.7	34.9	-
Surroundings	34.0	42.9	-
Munich region total	29.9	38.9	-
Federal	-	-	39

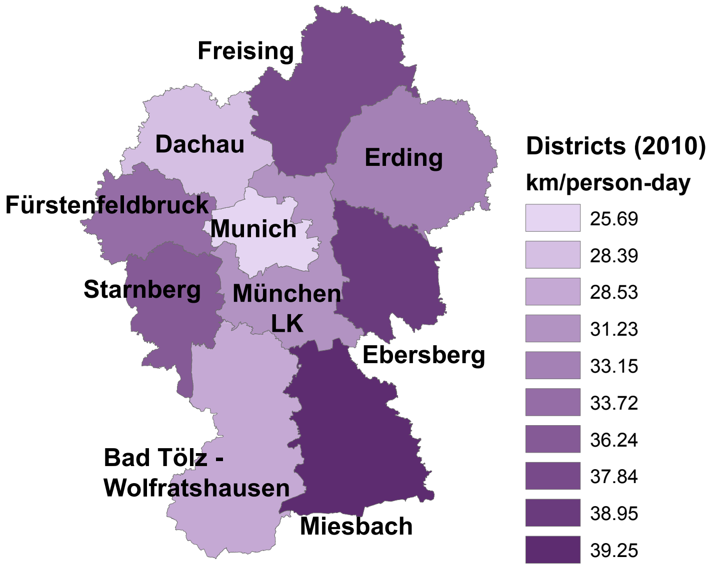

Figure 7.14: District level daily travel showing distance (km) per person.

maximum, consequently reducing the averages. Leaving these data points in gives distances similar to the MiD-MUC and MiD reports.

7.8.4 Carbon dioxide emissions

Utilizing the mode information and the travel distance it is possible to calculate the environmental emissions from each trip. The environmental factors for automobiles are given in the *Handbook Emission Factors for Road Transport* [195] and factors for public transportation modes are given in the *Transport Emission Mode*l [79]. The carbon dioxide emissions per trip have a mean value of 0.76 kg CO_2 , a median of 0.21 kg CO_2 , a standard deviation of 1.76 kg CO_2. The minimum carbon dioxide emission is 0.00 kg CO_2 and the maximum is 22.56 kg CO_2 per trip. The frequency distribution of carbon dioxide emissions for all 35,803 trips is presented in figure 7.15 on the following page. From this information the relative frequency of 80.1, 97.5, and 99.2% of the emissions are under 1, 5, and 10 kg of carbon dioxide per trip, respectively. The aim of the frequency distribution is to illustrate the wide range of emissions, and show the concentration of the emissions under the 10 kg level. Neither the regional survey [131] nor the federal survey [190] cite a value for the average carbon dioxide emissions per trip.

Average daily carbon dioxide emissions per person are shown geographically at three levels: for traffic cells in Munich (figure 7.16 on the next page), for neighborhoods in Munich (figure 7.17 on page 143), and for the 10 districts (figure 7.18 on page 144). The statistic of greater interest is the daily carbon dioxide emissions per person.

For daily carbon dioxide emissions per person the mean is 2.74 kg, the median is 1.14 kg,

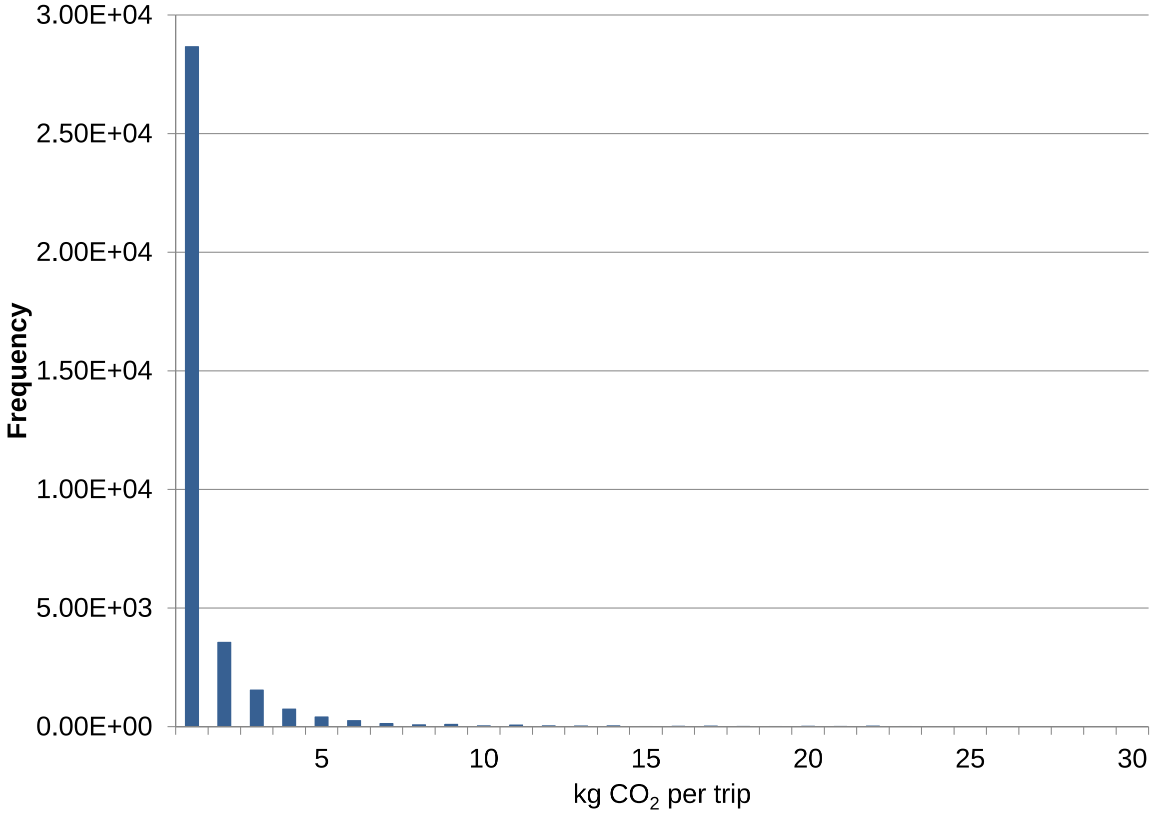

Figure 7.15: Frequency distribution of CO_2 emissions (kg) per trip illustrating the wide range of emissions and the dominance of emissions under 10 kg CO_2/ trip.

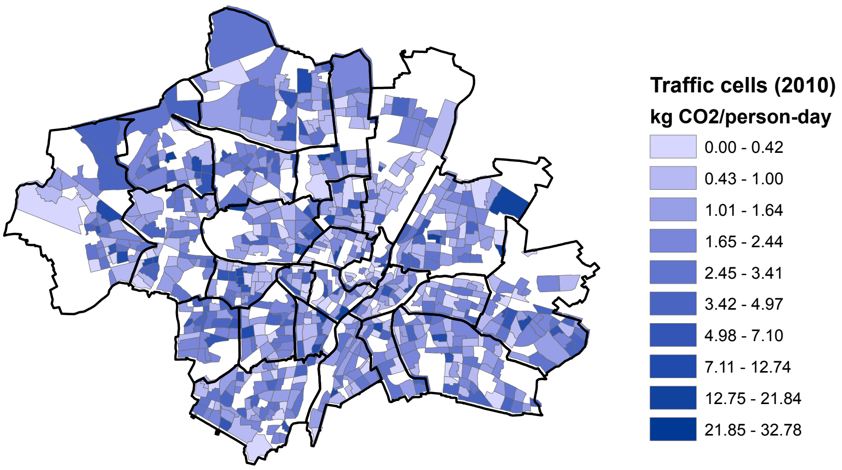

Figure 7.16: Traffic cell level daily CO_2 emissions

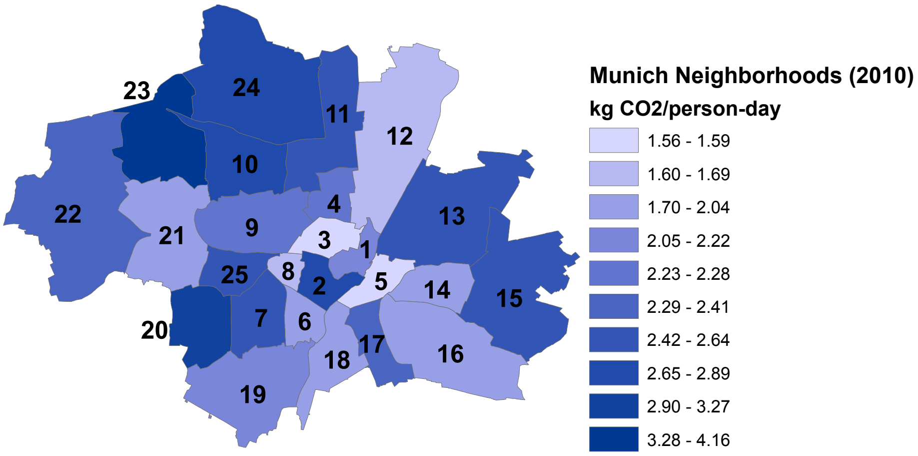

Figure 7.17: Neighborhood level in the City of Munich showing daily travel CO_2 emissions (kg) per person.
Altstadt-Lehel (1), Ludwigsvorstadt-Isarvorstadt (2), Maxvorstadt (3), Schwabing-West (4), Au-Haidhausen (5), Sendling (6), Sendling-Westpark (7), Schwanthalerhöhe (8), Neuhausen-Nymphenburg (9), Moosach (10), Milbertshofen-Am Hart (11), Schwabing-Freimann (12), Bogenhausen (13), Berg am Laim (14), Trudering (15), Ramersdorf-Perlach (16), Obergiesing (17), Untergiesing-Harlaching (18), Thalkirchen-Solln (19), Hadern (20), Pasing-Obermenzing (21), Aubing-Lochhausen-Langwied (22), Allach-Untermenzing (23), Feldmoching-Hasenbergl (24), and Laim (25).

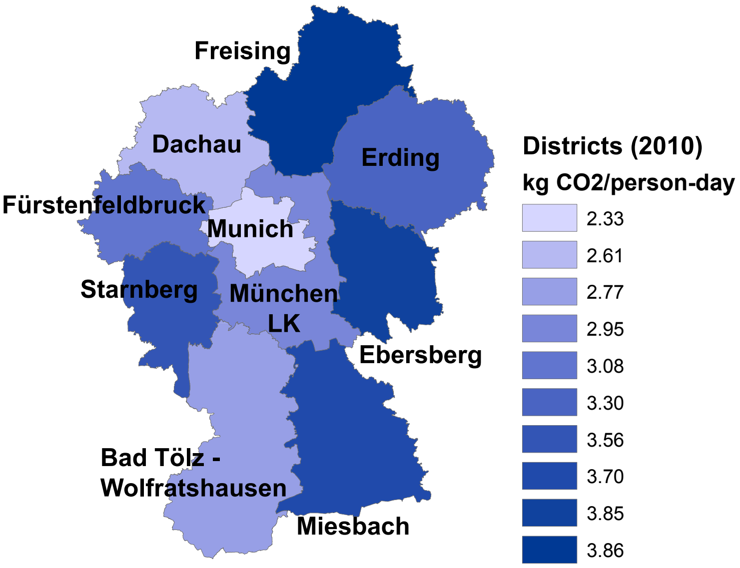

Figure 7.18: District level showing daily travel CO_2 emissions (kg) per person.

the standard deviation is 4.42 kg, the minimum is 0.00 kg, and the maximum is 45.12 kg. The maximum daily carbon dioxide emissions per person are for an individual taking two trips of 199.50 km each with a passenger car.

The average daily carbon dioxide emissions per person are 2.29, 3.21, and 2.75 kg for the city of Munich, the surround districts, and the entire region, respectively. These values are lower than the daily average value of 3.7 for Munich, 4.7 for the surrounding districts, and 4.2 kg carbon dioxide emissions per person-day for the entire *Munich Transport and Tariff Association area of operation* as presented in the summary report [131]. The national daily average of 4.5 kg carbon dioxide emissions per person [131] is higher than the calculated values. The carbon dioxide emissions for each district are shown geographically in figure 7.18. The city of Munich has the lowest daily carbon dioxide emissions per person (2.29 kg), and the highest values are found in Ebersberg (3.76 kg) and in Freising (3.78 kg). The results are summarized in table 7.17 on the next page.

Similar to the daily km/person results, the calculated values for CO_2/person are lower than the results from the MiD-MUC and MiD reports. As noted previously, the exclusion of long-distance trips results in a lower km/person-day, which in turn lowers the carbon dioxide emissions. In addition, the data set excludes the heavy polluting mode of air transportation further lowering the calculated results. Based on these factors it is expected that the calculated results are lower than those reported.

Table 7.17: Summary of CO_2 emissions per person-day.

	Analysis	MiD-MUC [131]	MiD [190]
Munich	2.29	3.7	–
Surroundings	3.21	4.7	–
Munich region total	2.75	4.2	–
Federal	–	–	4.5

7.9 Sensitivity analyses

7.9.1 Future carbon dioxide emissions

Thus far transportation operational impacts have been determined for the year of 2010. However, past trends and future projections indicated that tail-pipe emissions will change significantly in the future due to technology changes, alternative energy sources, governmental directives, and other influencing factors [79, 195]. Consequently, a sensitivity analysis is conducted to determine the effect on transportation operational impacts due to a variation in tail-pipe emissions.

The effect of varying tail-pipe emissions has a non-linear effect as total impacts stem from multiple different modes of transportation, differences in emission reductions per mode, and the inclusion on modes with assumed zero impacts (i.e., walking and bicycling). It must be noted that the original transportation travel patterns from 2010 is used again—the sole variable of the sensitivity analysis is tail-pipe emissions. Future projections for tail-pipe emissions for both private and public transportation are taken from the same sources as the original emissions [79, 195]. The sensitivity analysis is calculated for the years 2015, 2020, 2025, and 2030 in comparison with the base year of 2010. The transportation operational emissions for three different levels within the *urban region of Munich* are shown in figure 7.19 on the following page, figure 7.20 on page 147, and figure 7.21 on page 148.

The sensitivity analysis of tail-pipe emissions in 2030 shows a strong reduction in CO_2 emissions; however, the overall geographical distribution of emissions remains the same (compare figure 7.19 on the next page to figure 7.16 on page 142, figure 7.20 on page 147 to figure 7.17 on page 143, and figure 7.21 on page 148 to figure 7.21 on page 148). In addition, figure 7.22 on page 148 shows the relationship between all the districts for tail-pipe emissions in 2015, 2020, 2025, and 2030. For the reference case, 2010, the City of Munich as the lowest emissions and the district of Freising the highest—65.75% higher than the City of Munich (figure 7.22 on page 148). The change between each increment is shown in figure 7.23 on page 149. From 2010 to 2030 there is a reduction of 22.99% in the City of Munich, while emissions in Freising decrease by 24.34% in this same time period. However, the reductions for each 5-year time interval are very similar (see figure 7.23 on page 149).

Finally, even given the reductions in total emissions due to tail-pipe emission reductions, the outer districts still have significantly higher emissions than the City of Munich. For example,

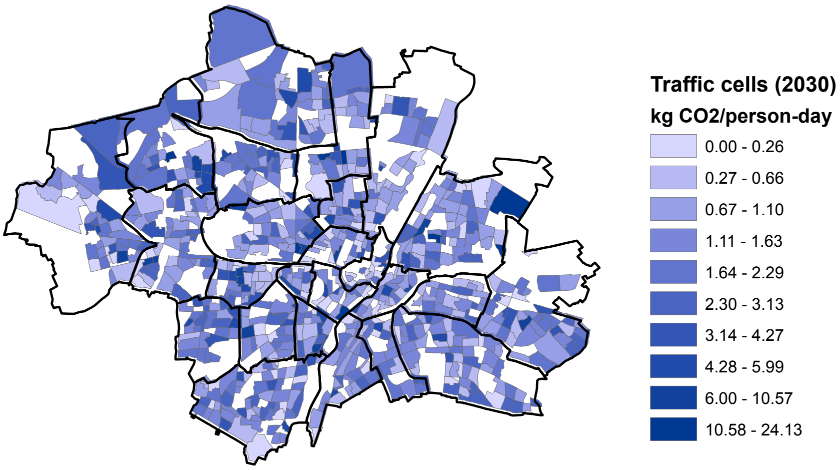

Figure 7.19: Traffic cell level sensitivity analysis of CO_2 emissions (kg) per person in 2030.

the 2030 emissions in Freising are 25.41% higher than the original 2010 emissions in the City of Munich. This illustrates the importance of modal split, non-motorized modes, distance traveled, in addition to only concentrating on tail-pipe emissions.

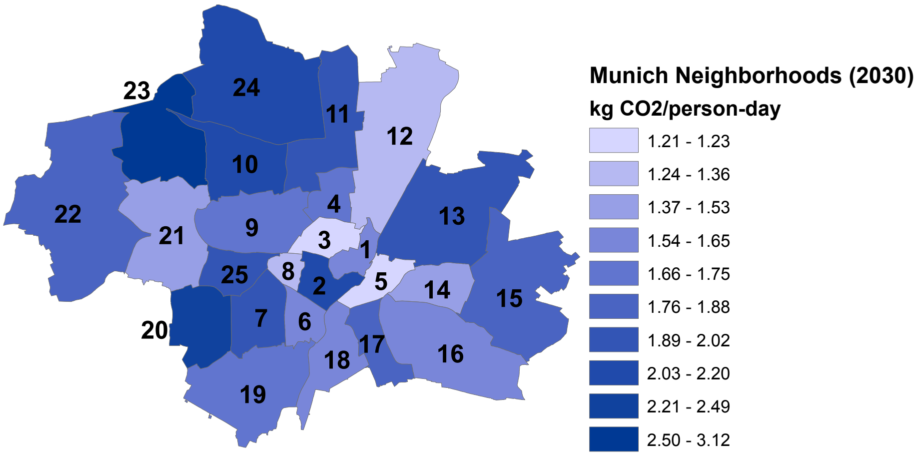

Figure 7.20: Munich neighborhood level sensitivity analysis of CO_2 emissions (kg) per person in 2030.
Altstadt-Lehel (1), Ludwigsvorstadt-Isarvorstadt (2), Maxvorstadt (3), Schwabing-West (4), Au-Haidhausen (5), Sendling (6), Sendling-Westpark (7), Schwanthalerhöhe (8), Neuhausen-Nymphenburg (9), Moosach (10), Milbertshofen-Am Hart (11), Schwabing-Freimann (12), Bogenhausen (13), Berg am Laim (14), Trudering (15), Ramersdorf-Perlach (16), Obergiesing (17), Untergiesing-Harlaching (18), Thalkirchen-Solln (19), Hadern (20), Pasing-Obermenzing (21), Aubing-Lochhausen-Langwied (22), Allach-Untermenzing (23), Feldmoching-Hasenbergl (24), Laim (25).

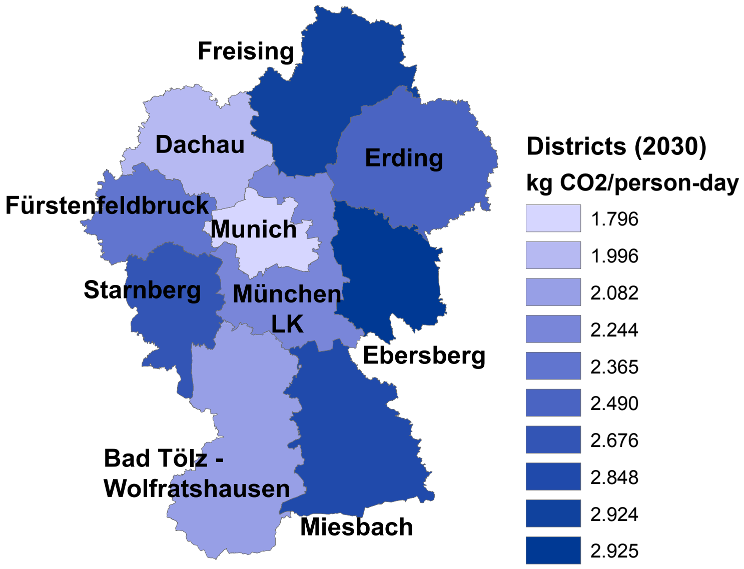

Figure 7.21: District level sensitivity analysis of CO_2 emissions (kg) per person in 2030.

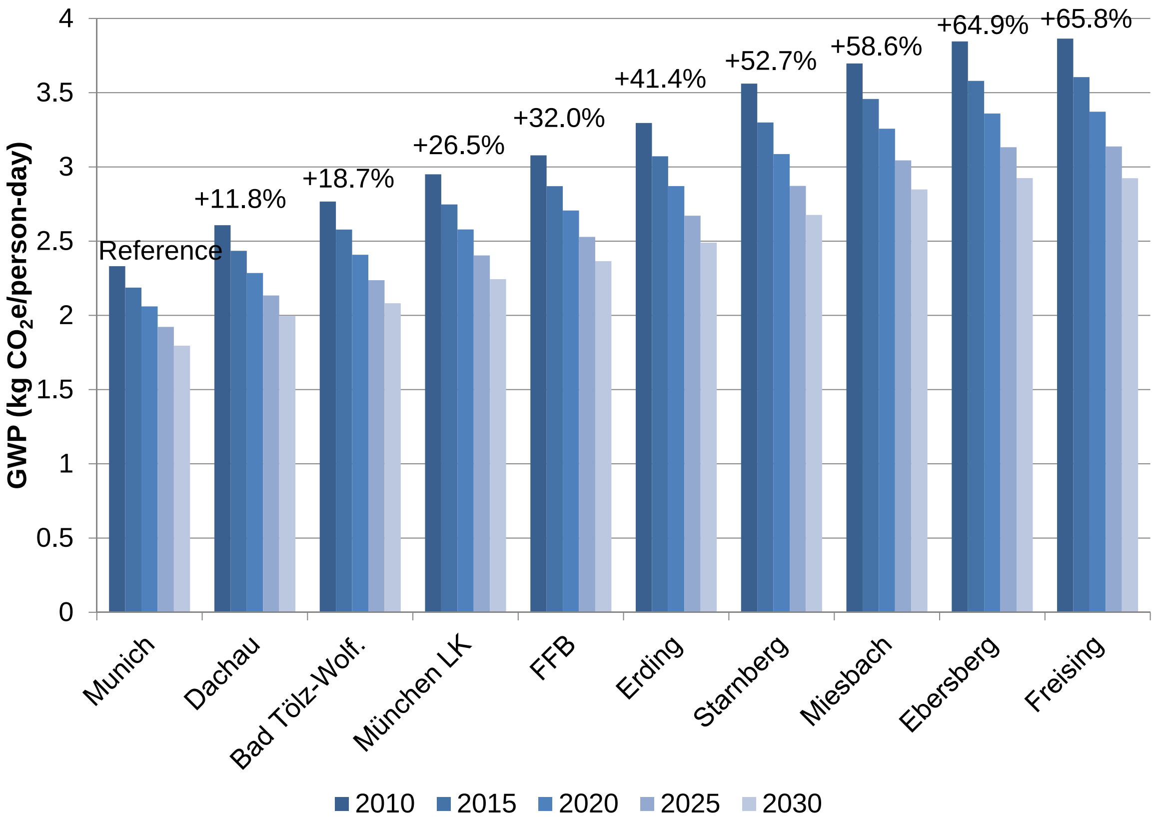

Figure 7.22: Sensitivity analysis of tail-pipe emission reductions for all districts over the time period from 2010 to 2030. (FFB denotes Fürstenfeldbruck)

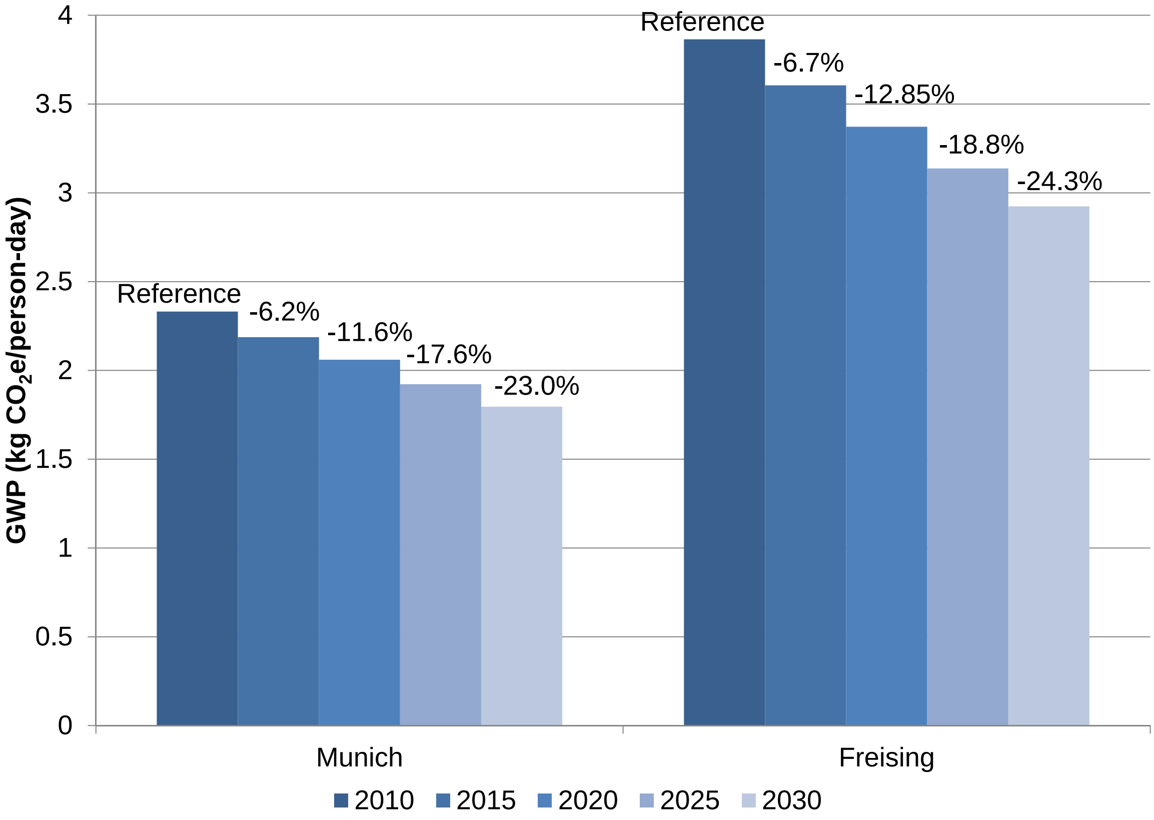

Figure 7.23: Sensitivity analysis of the detailed tail-pipe emission reductions for the City of Munich and the district of Freising from 2010 to 2030.

7.9.2 Long-distance airplane trips

The original data assumptions set a maximum trip length of 200 km to prevent skewing the data and to better capture trips influenced by residential location. However, it is important understand the importance of long distance airplane trips. Two scenarios are examined: a domestic flight and an international flight. From the MiD-MUC data, there are a total of 45 plane trips taken, which have an average distance of 422 km [131]. This approximately represents the flying distance from Munich to Berlin (465 km) [202]. In addition to the Munich-Berlin domestic flight, a longer distance international flight is considered. For the sensitivity analysis, a flight from Munich to San Francisco, U.S.A. (9447 km [202]) is chosen.

Airplane emissions are obtained from the *LIPASTO Inventory of Traffic Emissions* [203]. For the domestic flight, a European short distance (less than 463 km) aircraft is used, and a long-haul aircraft is used for the international flight. The short distance aircraft has higher CO_2 emissions compared to the long-haul aircraft (257 versus 113 g/Pkm). For each analysis (i.e., domestic and international) only one flight to the noted destination per year is made. A return flight is made with the same mode within the same calendar year. The emissions resulting from the domestic flight are 217 kg CO_2 per person, and the emissions for the international flight are 2135 kg CO_2 per person. These values are normalized to a per day basis and compared to the average results for the City of Munich (the lowest emissions) and the district of Freising (the highest emissions). The results of the two sensitivity analyses are presented in figure 7.24 on the next page.

The long distance analysis reveals the large emissions resulting from airplane travel. A single return-trip domestic flight increases the daily emissions for a City of Munich resident by 28.1% and 16.9% for a Freising resident. Even more significant is the overwhelming dominance of daily emissions due to a single return-trip international flight. The single international flight is 3.5 times the amount of daily travel emissions in Munich and 2.5 times the daily travel emissions in Freising. If the international flight is taken in addition to the original travel in Munich, emissions raise by 250.88%.

Comparing the findings of the sensitivity analyses gives important insights into transportation operational impacts. First, while future reductions in tail-pipe emissions can reduce emissions by 23% (for Munich), one domestic flight is responsible for an increase of 28%, and an international flight is responsible for an increase of 251%. Thus, a single domestic flight once a year can easily cancel out any tail-pipe emission reductions, and one international flight dominates all transportation emissions. While reductions in air travel emissions are to be expected, the large magnitude of these impacts would likely still dominate transportation operational emissions.

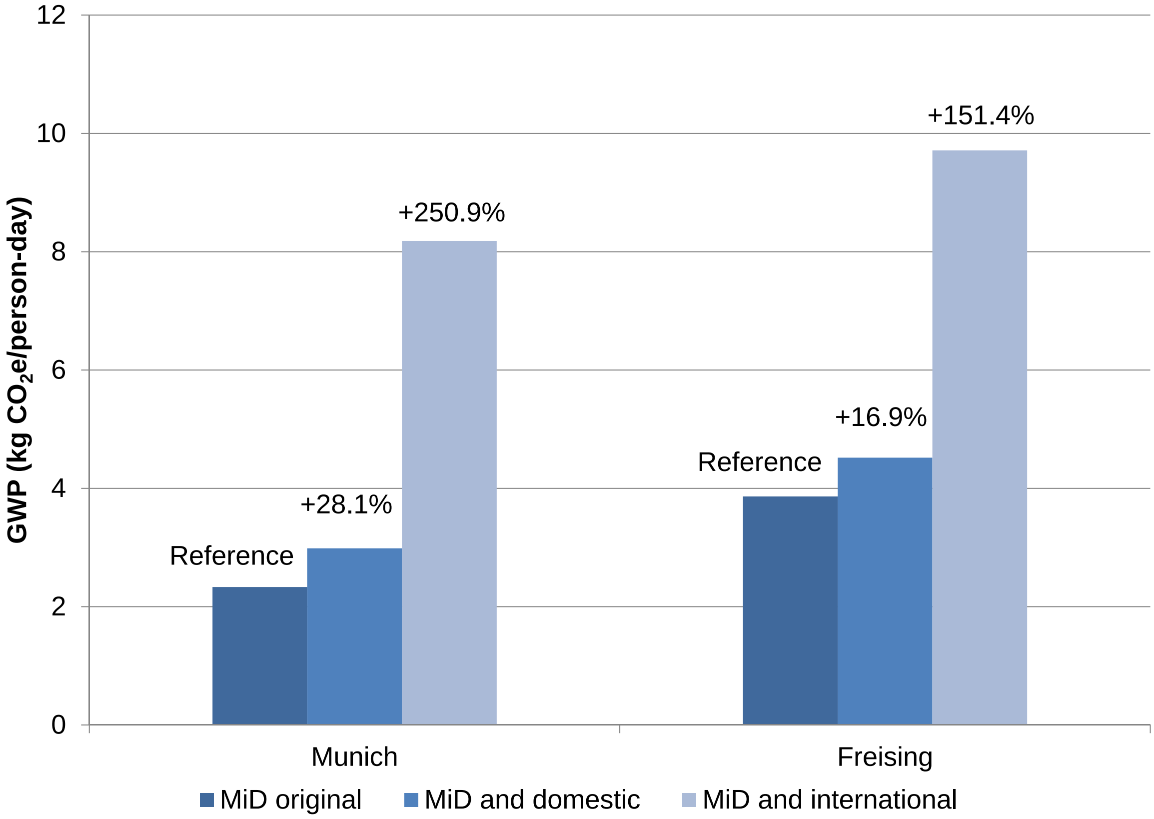

Figure 7.24: Sensitivity analysis comparing the original results from the MiD-MUC data set (MiD original), the original results plus a round-trip domestic flight of 465 km each way(MiD and domestic), and the original results plus a round-trip international flight of 9447 km each way (MiD and international).

7.10 Discussion

The research shows the daily distance traveled and emissions at three spatial resolutions: traffic cells, neighborhoods, and districts. At the traffic cell and neighborhood level there is not a clear association between the distance from the city center (neighborhood 1) and distance traveled nor carbon dioxide emissions (see figure 7.13 on page 140 and figure 7.17 on page 143). At the district level it is clear that the dense City of Munich has lower travel distances and emissions compared to the surrounding districts (figure 7.14 on page 141 and figure 7.18 on page 144). As the district level is very aggregate, it is difficult to conclude other trends from the district level analysis. Further, the sample size for the outer districts is very low compared to the City of Munich. For example, the MiD-MUC data for the district of Miesbach contains 217 persons, whereas the City of Munich has 7,468 persons. The largest sample size for the outer districts is München LK with 490 persons. Based on such low sample sizes it is difficult to make broad statements explaining travel in the districts. The susceptibility to skewing from a few data points is much higher in these low sample districts. Consequently, the take away message is that the City of Munich has lower travel distances and emissions compared to the surrounding districts. However, within the city itself a similar geographical gradation of travel distances and emissions is not seen.

The absence of gradation within the city may be caused by several factors. First and most important, there might not be a correlation between the residential location within the City of Munich and total distance traveled nor CO_2 emissions. While numerous studies suggest that city residents have lower transportation operational impacts, this may not be the case in Munich. In comparison to North American cities where residential density drops significantly outside the city center, all of Munich has high residential density by North American standards. While there is a decrease in density in Munich, this might not be sufficient to create significant travel distance and emission changes. Second, the public transportation system in Munich is well developed and serves the entire city. While non-motorized trips might be affected by the proximity to the city center, the extensive public transportation network in Munich allows residents at the city periphery to utilize the system as well. Thus the reduced emissions for public transportation compared to car use can be utilized by all residents in the city. Therefore, a gradation would not be seen. Third, the level of analysis at the traffic cell may be too aggregated. The aggregation may obscure local influences such as proximity to public transportation stops. Finally, as leisure makes up 33% of all trips in the City of Munich, it is possible that other local effects override any residential location influence. For example, a weekend trip to the Alps by private automobile would not be affected by one's residential location within the city, but rather by one's leisure inclinations and tendencies. Therefore, the geographical gradation of travel distances and emissions within the city are shown to be much more complex than a simple correlation from residential location and the distance to the city center.

From the travel (km/person-day) and emissions (kg CO_2/person-day) results it is possible to calculate the *emission factors* (kg CO_2/km-person-day) for each neighborhood and district (table 7.18 and table 7.19 on the next page). The emission factor in Munich varies from 0.075 to 0.099 kg CO_2/km-person-day. The average emissions factor is higher for outer districts (0.094 kg CO_2/km-person-day) compared to Munich (0.089 kg CO_2/km-person-day). There are several reasons for the lower emissions in the City of Munich. First, the modal share for non-motorized trips is much higher in Munich (43.1%) than the surrounding districts (35.0%). As these modes are assumed to have a zero impact, this larger share of trips by non-motorized modes results in lower emissions. Second, Munich also has a higher modal split for public transportation (20.2%) compared to the districts (9.7%). The emissions per passenger-km are much lower for public transportation again leading to lower emissions in the City of Munich. Third, the daily distance traveled per person in Munich (25.7 km) is lower than the surrounding districts (34.0 km). Thus, the use of lower emission modes combined with short travel distances leads to lower emissions in the City of Munich compared to the outer districts.

Table 7.18: Neighborhood summary of relative km and CO_2 emissions per person-day compared to the neighborhood average.

No.	Neighborhood	km change (%)	CO_2 change (%)	Factor (kg CO_2/km)	Sample size (Per./trips)
1	Altstadt-Lehel	-5.2	-7.1	0.088	62/ 245
2	Ludwigsvorstadt	23.9	23.3	0.089	123/ 479
3	Maxvorstadt	-20.4	-33.4	0.075	117/ 455
4	Schwabing-West	-5.2	-4.0	0.090	172/ 672
5	Au-Haidhausen	-27.3	-32.2	0.083	201/ 756
6	Sendling	-7.6	-13.5	0.084	143/ 551
7	Sendling-West.	6.5	7.0	0.090	204/ 750
8	Schwanthaler.	-20.5	-27.5	0.081	59/ 201
9	Neuhausen-Nymph.	-2.1	-2.9	0.089	363/ 1,302
10	Moosach	13.9	15.8	0.091	193/ 686
11	Milbertshofen	4.5	10.4	0.094	181/ 630
12	Schwabing-Frei.	-25.0	-29.7	0.084	208/ 745
13	Bogenhausen	10.3	12.2	0.091	289/ 968
14	Berg am Laim	-14.0	-19.0	0.084	131/ 466
15	Trudering	-2.0	5.9	0.096	241/ 863
16	Ramersdorf-Per.	-5.9	-14.7	0.081	409/ 1,345
17	Obergiesing	-3.0	-0.5	0.092	135/ 489
18	Untergiesing-Harl.	-9.7	-13.6	0.085	215/ 783
19	Thalkirchen-Solln	-6.8	-5.3	0.091	399/ 1,412
20	Hadern	28.6	39.4	0.097	204/ 716
21	Pasing-Ober.	-8.5	-15.5	0.082	357/ 1,293
22	Aubing-Lochhausen	1.6	1.8	0.089	197/ 721
23	Allach-Unter.	59.3	76.8	0.099	137/ 509
24	Feldmoching-Hasen.	6.1	17.3	0.099	206/ 685
25	Laim	8.6	9.1	0.090	173/ 642

The relative travel distances and carbon dioxide emissions per person-day are shown in table 7.18 and table 7.19 on the next page. At the neighborhood level, these results show that

Table 7.19: District summary of relative km and CO_2 emissions per person-day compared to the district average.

No.	District	km change (%)	CO_2 change (%)	Factor (kg CO_2/km)	Sample size (Persons/trips)
D1	Munich	-22.8	-26.9	0.089	5,129/ 18,397
D2	Bad Tölz-Wolfs.	-14.3	-13.3	0.095	353/ 1,220
D3	Dachau	-14.7	-18.6	0.090	956/ 1,070
D4	Ebersberg	17.0	20.0	0.097	956/ 3,477
D5	Erding	-0.5	3.1	0.098	488/ 1,656
D6	Freising	13.7	20.6	0.100	301/ 1,044
D7	FFB	1.3	-3.8	0.089	282/ 1,044
D8	Miesbach	17.9	15.7	0.092	184/ 622
D9	München	-6.2	-8.0	0.092	1,432/ 5,501
D10	Starnberg	8.8	11.1	0.096	464/ 1,772

although emissions (kg CO_2/km-person-day) tends to increase at a greater rate for increasing distance traveled (except for Maxvorstadt (3)), it is not always the case. For example two neighborhoods show a similar rate of increase for emissions and distance (i.e., Sendling (6) and Schwabing-Freimann (12)), and three neighborhoods have a lower rate of increase for emissions compared to distance (i.e., Schwanthalerhöhe (8), Ramersdorf-Perlach (16), and Pasing-Obermenzing (21)). Thus increasing mobility (in this case through longer daily travel distances) does not necessarily demand higher emissions. This is an important finding as it challenges the assumption that reducing transportation operational emissions necessitates reducing personal mobility. In fact, the opposite is shown for the City of Munich. Even more provocative, is the fact that for districts outside Munich, as distance increases so do emissions; however, at a faster rate than distance. Thus, when the modal split is dominated by personal automobile travel, increased mobility does lead to higher emissions.

The sensitivity analyses present critical findings regarding transportation operational impacts. The analyses examine future tail-pipe emissions reductions and long distance air travel. While considerable attention is paid to reducing tail-pipe operational emissions, the ensuing reductions are of questionable value. Reduction estimations expected by 2030 will result in daily emission reductions of around 24%. This is significant, but it must be noted that even after these reductions, higher emission districts (e.g., Freising) still have 25% higher emissions (on a per person-day basis) than the City of Munich *prior* to any tail-pipe reductions. Thus a more appropriate strategy to reduce emissions would be to focus on modal shift to assumed zero-emission modes (i.e., walking and biking) and low emission modes (i.e., public transportation).

Further, the sensitivity analysis of long distance air travel is shown to dominate emissions. A single return-trip domestic flight increases emissions by 28% for a resident in Munich. This is equivalent to all the expected tail-pipe emission reductions in 2030. Even more dramatic is a single return-trip international flight (Munich to San Francisco), which overshadows all other transportation emissions (an increase of 250% for Munich residents). While shifting to lower emission modes does offer potential emission savings, attention must also include long distance air travel as these emissions rapidly consume any savings and dominate total emissions.

7.11 Conclusion

The chapter presents the analysis of the environmental impacts for transportation operation within the *Munich Transport and Tariff Association area of operation*. The data used are from the MiD-MUC daily travel survey with over 40,000 trips recorded. After processing the data to align with the research scope, the data is analyzed to determine the environmental impacts at the traffic cell, city neighborhood, and district level. A correlation between the distance from the city center and carbon dioxide emissions was not found at the traffic cell nor neighborhood scale. At the district level, the results shows that the City of Munich has the lowest daily distance traveled and emissions per person.

The lower emissions per person in the City of Munich are due to a higher modal split of non-motorized transportation and public transportation. The emissions for non-motorized mode are assumed to be zero and those for public transportation are lower than automobile emissions. In addition, residents of the City of Munich have lower daily travel distances, which also contribute to the lower emissions than the surrounding districts.

The results of the sensitivity analyses challenge the effectiveness of tail-pipe emission reductions and suggest that modal shift to lower emission modes would be a more efficient strategy. Long distance air travel is shown to dominate emissions—identifying a challenge in emission reductions. Finally, the discussion shows that for the dense City of Munich, increasing mobility (i.e., distances traveled) does not necessary increase emissions. However, for districts with higher automobile usage, increasing mobility (i.e., longer trip distances) results in higher emissions, which grow at a faster rate than distances.

The subsequent chapter combines building embodied impacts, building operational impacts, transportation embodied impacts, and transportation operational impacts. The chapter reviews the relative importance of each impact category, explores interdependences and interactions, and discusses the role of induced impacts on the environmental performance of the built environment.

Chapter 8

Results and discussion

This chapter combines and analyzes the findings from the preceding chapters to determine the induced impacts in the built environment. The indirect and direct induced impacts are determined from the previous four impact categories: building embodied impacts, building operational impacts, transportation embodied impacts, and transportation operational impacts. The cumulative results show that the city center has the lowest environmental impacts followed by the periphery and then the districts. In addition, induced impacts are determined and the interactions between the impact categories and their influence on each other are presented.

The chapter contributes to the state-of-the-art by quantifying and analyzing induced impacts in the built environment. The research also investigates the effect of varying the location of each building type within the *urban region of Munich*. In addition, a sensitivity analysis of four specific household scenarios reveals the range of environmental impacts in comparison with average values. The analysis verifies the validity of the expanded research methodology and offers key insights into achieving environmental goals within the built environment.

8.1 Introduction

The previous chapters present a comprehensive analysis of the life-cycle environmental impacts in the built environment. Chapter 4 examines the embodied impacts from three case study residential buildings—a multi-family house, a row house, and a single family house. Chapter 5 investigates the environmental impacts from building operations accounting for electricity, heating, and hot water for the case study buildings. The work also investigates future building energy renovations and the resulting influence on both operational impacts and embodied impacts. Chapter 6 assesses the embodied impacts for public and private transportation vehicles and infrastructure. Finally, Chapter 7 investigates transportation operational impacts for both private and public transportation utilizing a detailed travel survey for the region.

The previous chapters have generally treated the four impact categories separately. The impact categories are building embodied, building operational, transport embodied, and transport operational. This chapter expands upon these results to determine the magnitude of induced impacts (both indirect and direct) and explores the interrelationship between the impact categories. Sensitivity analyses are used to illustrate these interconnections and provide a more integrated assessment approach.

8.2 Determining induced impacts

The research aims to expand the use of life-cycle assessment in the built environment to capture induced impacts. As previously summarized, research to date focuses either on individual buildings (investigating only embodied and operational impacts) or on larger urban systems (e.g., entire transportation systems). However, this framework treats the building as a standalone element devoid of interactions with its surrounding urban context. In addition, focus on large urban systems ignores typical patterns of construction (i.e., new buildings or building renovations in existing urban environments with existing systems). Therefore, the introduction of a new impact category, induced impacts, is required. Induced impacts are the environmental impacts resulting from the interactions of an individual building and its surrounding built environment.

Induced impacts are composed of direct and indirect induced impacts. As mentioned, direct impacts are simply the impacts resulting from the direct interaction of the building residents with the urban environment. These impacts are captured through transportation impacts (both embodied and operational). In addition, environmental impacts are also affected by 1) the building type and 2) the building location. These represent indirect induced impacts: building related and transportation related. While direct induced impacts make up a proportion of total impacts, indirect impacts are the relative changes in total impacts due to building type and location.

Direct induced impacts are determined through the transportation of the building residents. These impacts are captured through transportation embodied impacts and transportation operational impacts. Indirect impacts are determined by examining various building types at different locations within a metropolitan region. Consequently, analysis of the interconnections and interdependency of the previous four impact categories provides the means to assess and quantify induced impacts in the *urban region of Munich*.

8.3 Cumulative results

Prior to analyzing the induced impacts, the cumulative results for the four previously investigated impact categories are summarized and reviewed. The research determined the environmental impacts for building embodied, building operational, transportation embodied, and transportation operational impacts. Building embodied impacts are assessed for a multi-family house, a row house, and a single family house. All structural and architectural materials are evaluated. Building operational impacts are calculated for the same multi-family house, row house, and single family house. The scenario of a future energy renovation is also considered with regard to both operational and embodied impacts.

Transportation embodied impacts include both private and public transportation modes, and include both vehicle and infrastructure impacts. Embodied vehicle emissions are determined for automobiles, buses, trams, subway trains, and suburban trains. Transportation infrastructure accounts for roads and public transportation stations and transportation lines (e.g., tunnels, tracks, sleepers) for all networks (i.e., tram, subway, suburban train). Transportation operational impacts are found based on the extensive MiD-MUC travel survey. Analysis results are presented for varying geographical levels: transportation cells within the City of Munich, neighborhoods within the City of Munich, and the surrounding districts.

The cumulative research results (both absolute and relative) are summarized in table 8.1 on the following page and table 8.2 on page 161. Lifespans used for the analysis are given in table 8.3 on page 161. The summary is given for global warming potential (kg CO_2-Eq.) for brevity, but results are also calculated for total energy (MJ), ozone depletion potential (kg CFC-11-Eq.), acidification potential (kg SO_2-Eq.), eutrophication potential (kg phosphate-Eq.), and photochemical oxidant creation potential (kg ethylene-Eq.).

Table 8.1: Cumulative results for the research (1 of 2). Absolute and relative emissions values for all impact categories and subdivisions. (MFH - multi-family house, RH Avg. - row house average of middle and edge house, SFH - single family house, Init. - initial prior to renovation, Renov. - renovation.)

	Total ($kg\ CO_2$)	Relative ($kg\ CO_2/m^2$-yr)	Relative ($kg\ CO_2$/person-yr)
BUILDING EMBODIED			
MFH - Init.	3.67E+05	5.23E+00	1.91E+02
MFH - Renov.	3.93E+05	5.60E+00	2.05E+02
RH Avg. - Init.	6.78E+04	7.24E+00	2.82E+02
RH Avg. - Renov.	7.65E+04	8.17E+00	3.19E+02
SFH - Init.	6.38E+04	8.65E+00	3.55E+02
SFH - Renov.	7.31E+04	9.90E+00	4.06E+02
BUILDING OPERATIONAL			
MFH - Electricity	1.01E+06	1.44E+01	5.25E+02
MFH - Hot water	2.57E+05	3.66E+00	1.34E+02
MFH - Heating, Init.	4.58E+05	6.52E+00	2.38E+02
MFH - Heating, Renov.	2.38E+05	3.39E+00	1.24E+02
RH - Electricity	1.26E+05	1.35E+01	5.25E+02
RH - Hot water	3.97E+04	4.24E+00	1.66E+02
RH - Heating, Init.	9.47E+04	1.01E+01	3.94E+02
RH - Heating, Renov.	5.32E+04	5.68E+00	2.22E+02
SFH - Electricity	9.45E+04	1.28E+01	5.25E+02
SFH - Hot water	3.09E+04	4.19E+00	1.72E+02
SFH - Heating, Init.	1.31E+05	1.77E+01	7.26E+02
SFH - Heating, Renov.	7.28E+04	9.86E+00	4.04E+02

Table 8.2: Cumulative results for the research (2 of 2). Absolute and relative emissions values for all impact categories and subdivisions. (Trans. - Transportation, S. Train - suburban train, Infr. - infrastructure, MUC - City of Munich, Dis. - District., *unit* - see line for specific value.)

	Total (kg CO_2)	Relative (kg CO_2/-yr)	Relative (kg CO_2/*unit*-yr)	Relative (kg CO_2/Pkm)
TRANS. EMBODIED				
Roads - Infr. (MUC)	9.36E+08	1.56E+07	6.55E+03 /km	1.55E-03
Roads - Infr. (Dis. Avg.)	1.83E+09	3.04E+07	3.93E+05 /km	2.04E-03
Car - Vehicles (MUC)	3.70E+09	3.08E+08	5.29E+02 /veh.	1.55E-03
Car - Vehicles (Dis.)	4.78E+09	3.98E+08	5.29E+02 /veh.	2.04E-03
Buses - Vehicles	4.94E+07	1.65E+06	3.94E+03 /veh.	3.11E-03
Tram - Vehicles	1.23E+07	4.11E+05	1.02E+04 /veh.	1.26E-04
Tram - Track Infr.	4.41E+08	7.35E+06	4.07E+04 /km	5.70E-03
Subway - Vehicles	6.60E+07	2.20E+06	2.13E+04 /veh.	1.15E-03
Subway - Track Infr.	2.75E+09	3.71E+07	9.75E+04 /km	2.24E-02
Subway - Stations	4.56E+08	4.56E+06	4.56E+04 /stat.	2.75E-03
S. Train - Vehicles	2.16E+08	7.20E+06	3.02E+04 /veh.	1.14E-03
S. Train - Track Infr.	4.00E+08	1.35E+07	3.05E+04 /km	3.35E-03
S. Train - Stations	1.06E+08	1.77E+06	1.18E+04 /stat.	4.41E-04
TRANSP. OPERATIONAL				
Munich	–	1.17E+09	8.51E+02 /person	–
District, Avg.	–	1.94E+08	1.20E+03 /person	–

Table 8.3: Lifespans used in analysis. Tunnel infrastructure for the subway and underground suburban trains has a lifespan of 100. All other elements of the track infrastructure have lifespans as noted in the table. (Infr. - infrastructure, S. Train - suburban train.)

Lifespan	Years
Buildings	60
Roads	60
Cars - Vehicles	12
Buses - Vehicles	30
Tram - Vehicles	30
Tram - Track Infr.	60
Subway - Vehicles	30
Subway - Track Infr.	60
Subway - Stations	100
S. Train - Vehicles	30
S. Train - Track Infr.	30
S. Train - Stations	60

8.3.1 Results per location

The absolute and relative results for the analysis are presented for the four impact categories (table 8.1 on page 160 and table 8.2 on page 161). These general results are now interpreted based on the three locations within the *urban region of Munich*: city center, city periphery, and districts. This section describes the analysis of the impacts to each respective location.

The cumulative results are then evaluated at the three locations previous outlined. For the building embodied impacts, the multi-family house is assigned to the city center, the row house is assigned to the city periphery, and the single family house is assigned to the districts. The analysis reviewed a middle and an edge row house; for the cumulative results, an average of the two is utilized. For the building operational impacts, the operational results from the multi-family house are used for the city center, the row house results are used for the city periphery, and the single family house are used for the districts. Again, an average value of the middle and edge row house is used. The values are for a completed construction year of 2012. Building embodied and operational changes due to the renovation scenario are not included here, but are discussed later.

The differentiation of transportation embodied impacts per location is done as follows. First, for private transportation vehicles, the impacts for an automobile are known as well as the vehicle ownership rates in Munich and the surrounding districts. Based on this, the total fleet emissions for Munich and the districts are calculated per person. These values are used for automobile embodied impacts. For the periphery, an average between Munich and the districts is taken. Similarly, the embodied impacts for roads are known for the Munich network and the surrounding districts. An average is taken for the periphery again, as this location lies between the city center and outside the city.

Public transportation embodied impacts are applied to each location based on the area of service. The tram and subway networks serve the City of Munich as well as the periphery of the city. Thus these embodied impacts are applied to these locations only. On the other hand, the suburban train serves the districts in addition to the City of Munich and the periphery. Accordingly, the suburban train embodied emissions are allocated to Munich, the periphery, and the districts based on the population of the MVV-service area (2.55 Mio. persons) [131]. All other distributions are based on the population of the City of Munich for Munich and the periphery, and the population of the districts for the district location.

Transportation operational impacts are determined from the geographical analysis of transportation. The values for the city of Munich and the district average are used, and an average is taken for the periphery to be consistent with the other impact categories as noted.

The cumulative results for all impact categories are presented in figure 8.1 on the next page. The figure shows the CO_2-Eq. emissions for all three locations (i.e., city center, periphery, district). The results account for all impact categories: building embodied, building operational, transportation embodied, and transportation operational.

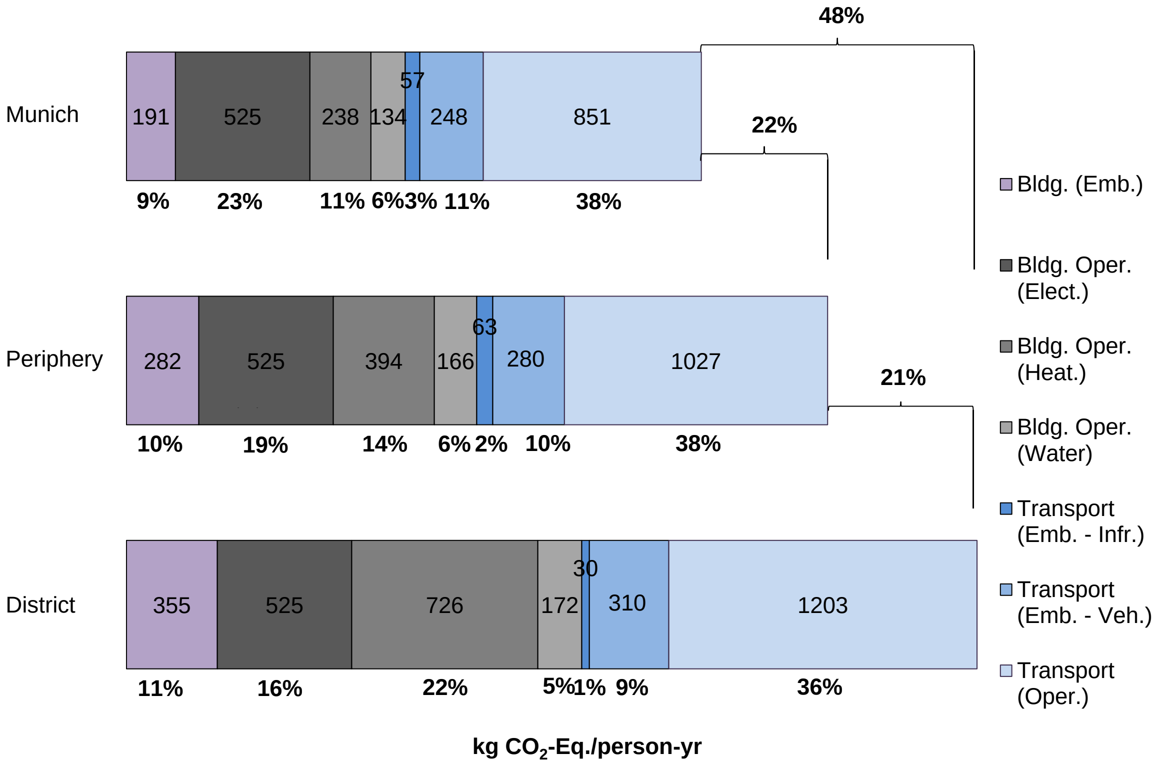

Figure 8.1: Cumulative location based life-cycle results for all impacts categories: building embodied, building operation, transportation embodied, and transportation operation. (Munich denotes the city center location.)

8.3.2 Discussion of location results

The major finding of the cumulative location based results is the difference between the total emissions for each location (figure 8.1 on page 163). Munich has the lowest total emissions (2.24E+3 kg CO_2-Eq./person-yr) followed by the periphery (2.74E+3 kg CO_2-Eq./person-yr) and then the districts (3.32E+5 kg CO_2-Eq./person-yr). The term Munich is used as a proxy for the city center location. Compared to Munich, the periphery has 22% higher emissions and the district has 48% higher emissions. The district emissions are 21% percent higher than the periphery. The contribution of each impact category is shown as a percentage for each location. For all three locations, transportation operation is the highest impact category making up 38, 38, and 36% of total emissions for Munich, the periphery, and districts, respectively. The lowest impact category for all locations is transportation embodied infrastructure at 3, 2, and 1% of total emissions for Munich, the periphery, and districts, respectively.

Building embodied emissions make up approximately 10% of total emissions. While the emissions per person differ significantly (191 to 355 kg CO_2/person-yr), the percentage increase is only minor (i.e., 9 to 11%) due to the increase in total emissions. Building operational electricity emissions are constant per person and thus do not change based on location; however, its percentage of total emissions drops decidedly (Munich: 23% to District: 16%), again due to the total emission differences.

Operational heating emissions are higher for the single family house followed by the row house and then the multi-family house (locations: district, periphery, Munich). The heating emissions per person-year increase from Munich to the districts (238 to 726 kg CO_2-Eq./person-yr), as well as the relative percentage of emissions (11 to 22%). This illustrates the increasing importance of heating demand for single family houses. Emissions for hot water are based on a fixed value per square meter. Thus higher living space demand locations (i.e., Munich) have lower emissions compared to lower living space demand locations (i.e., districts). Finally, transportation embodied emissions are less significant than vehicle embodied emissions (around 2% compared to around 10%). Also, while transportation embodied vehicle emissions are of importance (around 10% of total emissions on average), the actual emission values (248 to 311 kg CO_2/person-yr) do not vary greatly between locations.

The cumulative life-cycle results by the four impact categories (i.e., building embodied, building operation, transport embodied, and transport operation) are illustrated in figure 8.2 on the next page. The findings also account for the change in heating demand between the initial year of operation and following the building renovation. Renovating the building saves a total of 4.5, 5.0, and 8.1% of emissions for Munich, the periphery, and districts, respectively. The increase in embodied impacts due to the renovation is also included in this analysis. Thus, renovation holds the greatest percentage of potential savings for single family homes.

The results show that prior to the renovation the largest impact category is building operations for all locations (figure 8.2 on the facing page). Following the building renovation, the largest impact category shifts to transportation operations. This illustrates the importance of improving building operations up to a certain point, after which attention should be focused on

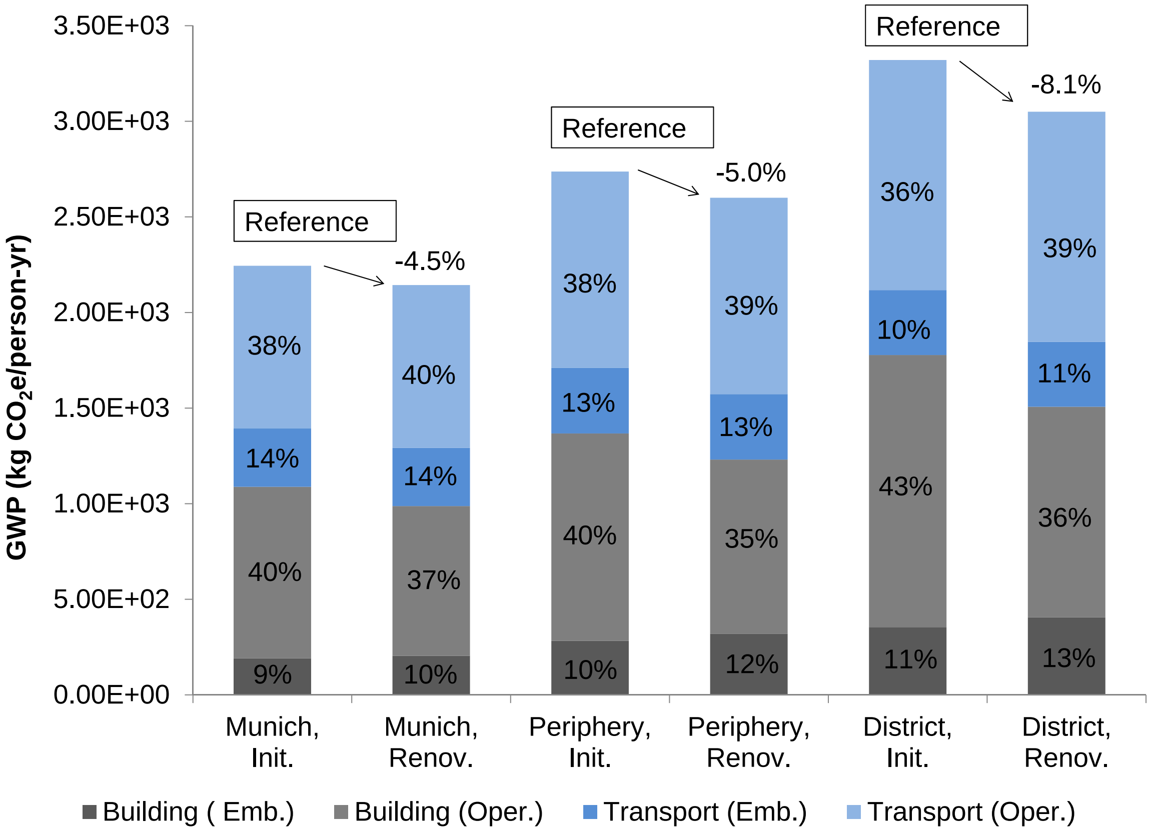

Figure 8.2: Cumulative location based life-cycle results accounting for the renovation of the building. Changes in both operational and embodied emissions are included. (Init.- initial prior to building renovation, Renov.- renovated building) (Munich denotes the city center location.)

transportation operational emissions. It should also be noted that the overall percentages for each impact category are comparable between the three locations.

Finally, the cumulative results are presented for the combined categories of buildings impacts and transportation impacts (figure 8.3). For all locations, the findings show that transportation emissions make up the majority of emissions for both in the initial and renovation scenarios. The share of transportation emissions are the highest for the city center (51.5%) followed by the periphery (50.0%) and then by the districts (46.5%). After the renovation scenario, the city location has the largest share of transport related emissions (53.9%) followed by the periphery (52.7%) and then the districts (50.6%).

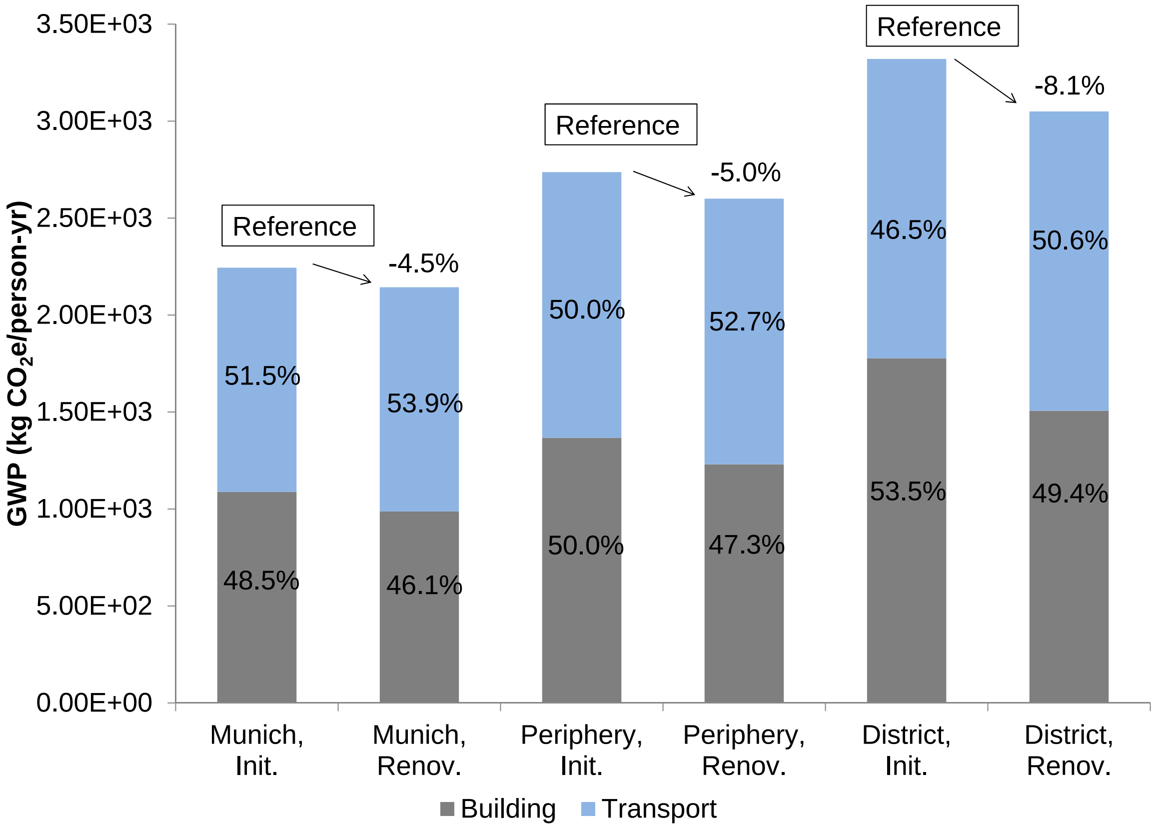

Figure 8.3: Cumulative location based life-cycle results comparing impacts from buildings and transportation. Changes in both operational and embodied emissions are included. (Init.- initial prior to building renovation, Renov.- renovated building)

8.4 Sensitivity analyses

Thus the cumulative results for average values at the three locations have been presented. However, in order to determine the magnitude of induced impacts further analysis is required examining the influence of moving building types to different locations. Further, while results based on average values are required for the general findings, investigation of specific household scenarios will illustrate possible variations in total environmental impacts. Therefore, two sensitivity analyses are conducted. First, the location of buildings is varied. Second, household scenarios are evaluated. The analyses and the insights drawn from them are then discussed.

8.4.1 Varying building locations

Having the cumulative results it is possible to carry out sensitivity analyses to see how total emissions vary by changing different variables. Until now, the work examined one building type per location based on typical building patterns in each location. However, not all buildings within one part of the city or region are uniform. For example, multi-family houses can be found in the outer districts and single family houses within the periphery. Thus, the sensitivity of total emissions from building type and location is investigated.

Each building type (i.e., a multi-family house, a row house, and a single family house) is evaluated at every location. The locations are the city center in Munich, the city periphery, and the districts. The building embodied impacts and the building operational impacts are fixed for each building type—moving the building will not change its characteristics. However, at each location the building residents will have different transportation embodied impacts and transportation operational impacts. This is due to the availability and use of different transportation systems in each of the locations as described previously. The results of the sensitivity analysis are presented in figure 8.4 on the following page.

The findings of the sensitivity analysis show that for a fixed building type, the city center location always has the lowest emissions. This is due to the lower transportation embodied impacts and transportation operational impacts in the city center location. Moving the building from the city center to the periphery results in a fixed increase of 2.14E+02 kg CO_2-Eq./person-yr for all building types. The move from the city center to the district results in a fixed increase of 3.87E+02 kg CO_2-Eq./person-yr for buildings. In accordance, moving a building from the periphery to the districts results in a fixed increase of 1.73E+02 kg CO_2-Eq./person-yr. These values represent the difference (on a per person-year basis) in the transportation impacts (i.e., transportation embodied and transportation operational) between the locations. These values are fixed as they are the difference between an average person's transportation impacts at each location.

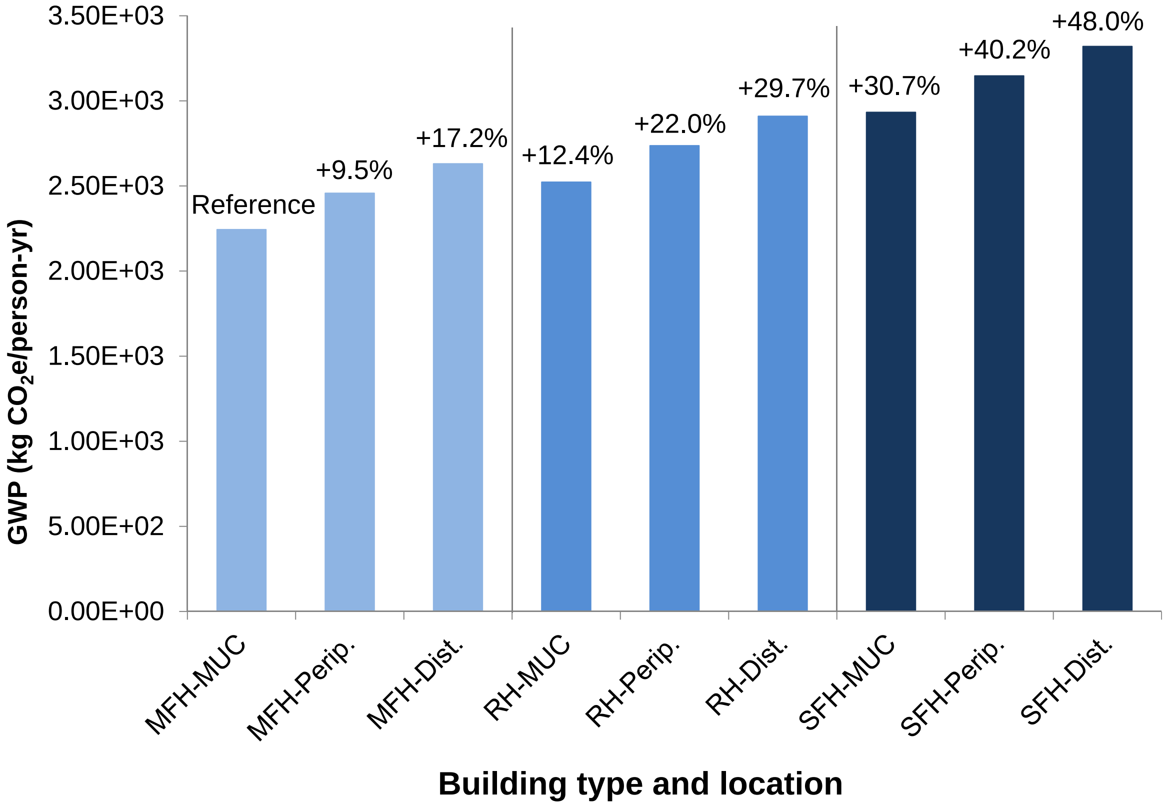

Figure 8.4: Sensitivity analysis for the variation of the location of each building type within the *urban region of Munich*. (MFH - multi-family house, RF - row house, SFH - single family house, MUC - city center location within the City of Munich, Perip. - periphery location, Dist. - district location.)

8.4.2 Household scenarios

Until now the results have been analyzed for average values. The results for the inner city illustrate the impacts for an average resident of the City of Munich with an average travel demand, living area, building heating use, and so on. Average values are of use to determine overall trends, but it is also important to investigate how actual scenarios relate to these average values. Four scenarios are thus developed to explore the sensitivity of the results to realistic situations within the area of study and to provide insights into the limitations of the average results.

The four scenarios examined are an urban couple (Scenario 1), urban students sharing an apartment (Scenario 2), retirees living at home without their children (Scenario 3), and a family with two children living outside the city (Scenario 4). Scenario 1 represents a professional couple living in an apartment in the city center of Munich. They do not have children and their living demand matches the typical demand for Munich (37.0 m^2/person). The couple does not have a car and relies on public transportation for their mobility. Scenario 2 consists of four university students living in a shared apartment in the city center of Munich. They do not own a car and in turn rely on public transportation and non-motorized transportation for their mobility. As the residents are students, it is assumed that they have less space than the professional couple (30.0 m^2/person).

Scenario 3 is a retired couple living in their row house on the periphery of the city. Their children have left the house and thus they now have a relatively large living space (78.0 m^2/person compared to the row house average of 40.0 m^2/person). The couple has one car, but also travel by public transportation as public transportation services are available at their location as well. Scenario 4 is a family (2 adults and 2 children) living outside the city in a rural location. The family has a living demand of 44.8 m^2/person as per typical single family houses in Bavaria. For transportation, the family uses their 2 cars as they do not have access to public transportation. Useful characteristics captured in the demographics and lifestyles of the scenarios include varying living demands and whether or not the household owns a car. The results from the scenario analysis are presented in figure 8.5 on the next page.

The sensitivity analysis for the four scenarios illustrates that the student apartment in the city center has the lowest emissions on a per person-year basis. This result is expected as the living space is reduced per person and hence also the building operational and building embodied impacts. The influence in living space demand is observable between Scenario 1 (urban couple) and Scenario 2 (student city apartment) as both scenarios have the same transportation emissions.

Scenario 3 (retirees) has the largest emissions. This is due in a large part to the high building operational impacts since they couple lives in a large house, which was previously used for their children as well. Their car ownership adds to their transportation embodied emissions, but their use of public transportation helps reduce the total transportation operational impacts.

Finally, Scenario 4 (rural family) has slightly lower impacts compared to Scenario 3 (retirees), but significantly higher emissions compared to the city center scenarios (Scenario 1

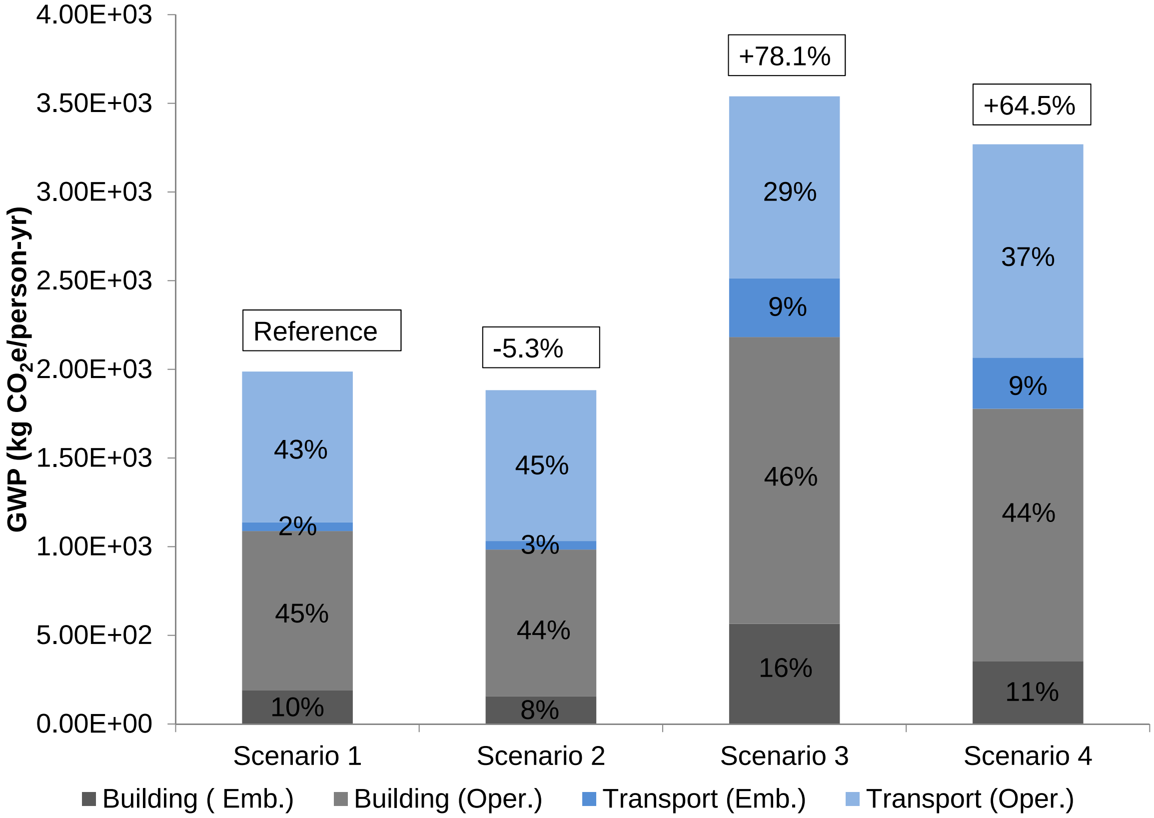

Figure 8.5: Sensitivity analysis for differing demographic and lifestyle scenarios. Scenario 1 (urban couple), Scenario 2 (student city apartment), Scenario 3 (retirees), Scenario 4 (rural family).

and 2). The rural family has four persons, which is advantageous when calculating impacts on a per person basis. However, the rural family has higher transportation operational emissions than all other scenarios due to their reliance on car travel. Both scenario 3 and scenario 4 have significant impacts (9%) from car ownership.

Finally, the scenarios can be compared with the average values for each location found previously. For multi-family houses in the city center, average emissions are 2.24E+03 kg CO_2-Eq./person-yr. This can be compared to the two multi-family house scenarios in the city center: Scenario 1 (urban couple) with 1.99E+03 kg CO_2-Eq./person-yr and Scenario 2 (student apartment) with 1.88E+03 kg CO_2-Eq./person-yr. Thus Scenario 1 is 11.4% lower than the average city center value, and Scenario 2 is 16.1% lower than the average. Scenario 1 is lower due to their absence of a car and their complete reliance on public transportation. The average value used for the city center accounts for a percentage of car ownership and car transportation. Scenario 2 (students) is lower for the same reasons and also due to their reduced living space.

Scenario 3 (retirees) is compared with the average for a row house at the city periphery. Scenario 3 has 3.54E+03 kg CO_2-Eq./person-yr, which is 29.3% higher than the average (2.74E+03 kg CO_2-Eq./person-yr). This increase is largely due to the higher living space compared to the average values. Last, the average single family house in an outer district is compared to the rural family (Scenario 4). Emissions for the average single family house is 3.32E+03 kg CO_2-Eq./person-yr and Scenario 4 is 3.27E+03 kg CO_2-Eq./person-yr (only 1.6% lower than the average). Thus Scenario 4 fairly accurately gives an example of what an average household in the districts might look like. The sensitivity analysis is useful as it gives a feel for realistic lifestyles. The results show that actual scenarios examined vary from over 29% to only 1% from the average emissions.

8.5 Induced impact results

Thus far, the absolute and relative cumulative results and sensitivity analyses have been presented. The four impact categories investigated are building embodied, building operational, transportation embodied, and transportation operational. Based on these results and analyses it is possible to quantify the induced impacts.

Prior to building renovations, direct impacts are shown to account for 51.5, 50.0, and 46.5% of all impacts for the city center, periphery, and district locations (see figure 8.3 on page 166). Indirect induced impacts are captured by varying building types at different locations. Building related indirect induced impacts result from varying the building type at a fixed location. Transportation related indirect induced impacts result from varying the location of a fixed building type. Total emissions for each building type at every location is shown in table 8.4 on the next page and figure 8.4 on page 168.

Building related indirect induced impacts are determined by varying the building type at each location. The influence on total emissions by building related indirect induced impacts

Table 8.4: Indirect induced impact matrix illustrating the emissions for each building type at every location. All values in units of kg CO_2-Eq./ person-yr. These values are shown in figure 8.4 on page 168.

	City center	Periphery	District
Multi-family house	2.24E+03	2.46E+03	2.63E+03
Row house	2.52E+03	2.74E+03	2.91E+03
Single family house	2.93E+03	3.15E+03	3.32E+03

are summarized in table 8.5. Analyzing the building related indirect induced impacts reveals that switching from a multi-family house to a row house (hold the building location constant) results in an increase of 2.79E+02 kg CO_2-Eq./person-yr. Again for a fixed location, going from a row house to a single family house increases emissions by 4.10E+02 kg CO_2-Eq./person-yr. Finally, changing from a multi-family house to a single family house increases emissions by 6.89E+02 kg CO_2-Eq./person-yr (the sum of the two previous values). See table 8.4. These increases are only due to the changes in building type regardless of location.

Table 8.5: Building related indirect induced impacts. Percentage variations in total emissions due to changing the building type at each location. (MFH - multi-family house, RH - row house, SFH - single family house.)

	City center	Periphery	District
MFH to RH	+12.4%	+11.4%	+10.6%
RH to SFH	+16.3%	+15.0%	+14.1%
MFH to SFH	+30.7%	+28.0%	+26.2%

Transportation related indirect induced impacts are determined by moving the same building to different locations. The influence on total emissions by transportation related indirect induced impacts are summarized in table 8.6 on the next page. Moving a fixed building from the city center to the periphery results in an increase of 2.14E+02 kg CO_2-Eq./person-yr. Relocating a fixed building from the periphery to the district causes an increase of 1.73E+02 kg CO_2-Eq./person-yr. Finally, shifting a building from the city center to the district results in an increase of 3.87E+02 kg CO_2-Eq./person-yr (the sum of the two previous values). Transportation related indirect induced impacts are calculated from table 8.4. These increases are due solely to changes in transportation impacts between locations and are regardless of building type.

Table 8.6: Transportation related indirect induced impacts. Percentage variations in total emissions due to changing the building location for each building type. (MFH - multi-family house, RH - row house, SFH - single family house.)

	MFH	RH	SFH
City center to Periphery	+9.5%	+8.5%	+7.3%
Periphery to District	+7.0%	+6.3%	+5.5%
City center to District	+17.2%	+15.3%	+13.2%

8.6 Discussion

The analysis results of the environmental impacts in the built environment using the expanded life-cycle methodology reveal numerous findings. First, the results confirm that the environmental performance of buildings is strongly influenced by induced impacts. This confirms the research hypothesis. Direct induced impacts are found to range from 46 to 54% of total emissions for buildings. Indirect induced impacts (due to building type and building location) are found to increase total impacts by 9.5 to 48% compared to the lowest reference value of a multi-family house in the city center (see figure 8.4 on page 168).

Second, the research results show that non-renovated buildings in the city center have significantly lower emissions than renovated buildings with low operational impacts in the country side (see figure 8.2 on page 165). Thus, focus on low-energy or nearly zero-energy buildings as a means to achieve environmental goals is misplaced. Attention should rather be placed on the urban structure of locations to enable the reduction in transportation impacts.

Third, building renovations are beneficial even when accounting for the additional embodied impacts (see figure 8.2 on page 165). The argument that building renovations are not useful due ot the additional embodied impacts of the renovation is not supported by the results. The additional materials for a building renovation are shown to have a short payback period. Renovations, however, reduce total emissions by 5 to 8% on an annual basis illustrating the usefulness of energy renovations. Fourth, environmental impacts for real household situations can vary significantly from average values. Here, socio-economic, demographic, and personal lifestyle choices play a decisive role in total impacts.

In addition to assessing impacts it is crucial to understand the environmental goals relating to these impacts. The most significant and pressing environmental goal currently is climate change and must be reviewed and discussed in light of the findings.

8.6.1 Environmental goals

Environmental goals for climate change mitigation require the stabilization of CO_2 concentration in the atmosphere. The different stabilization levels considered are 450, 550, 650, and 750 ppmv (parts per million by volume) of CO_2 [204]. Carbon emission levels of developed countries vary between 2 and 6 metric tons per capita. Average per capita carbon emission in Annex I countries are slightly more than 3 ton per year, and less than 0.5 tons per year in non-

Annex I countries. This gives a global average of 1 ton carbon emission per capita per year. Achieving stabilization at 450, 550, 650, and 750 ppmv would require yearly average carbon emissions of 0.3, 0.6, 0.9, and 1.2 tons per capita, respectively. This assumes a stabilization of world population at 10 billion people. [204]

Consequently, mitigating climate change requires average world emissions to be in the range of 0.3 to 1.2 tons per capita. In order to address climate change and other environmental issues the concept of the *2000 Watt Society* was established [205]. The concept sets a goal for average power demand of 2000 W per capita and an average annual carbon emission of 1 ton [206], [97]. The 1 ton carbon emissions results from 500 W of fossil-fuel generated output [206]. For comparison, a 2000 W energy supply generated entirely from fossil fuels would result in an annual carbon emission of 4.7 tons per capita [206]. The *2000 Watt Society* is beneficial as it takes a holistic environmental assessment by accounting for all aspects of life: living and office space, food and consumer goods, electricity, automobile travel, air travel, public transportation, and infrastructure.

Similarly to the *2000 Watt Society*, the research methodology expands environmental analysis of the built environment. The research of the thesis shows emissions for the built environment alone are much greater than these limits (see figure 8.1 on page 163). Thus significant reductions in emissions from the built environment alone are required to achieve environmental goals. The other impacts categories (e.g., food, consumer goods) must also be evaluated in an integrated manner to fully understand environmental impacts.

8.6.2 Time analysis of impacts

In addition to quantifying the environmental impacts it is important to note the importance of another variable: time. First, embodied and operational impacts occur at different times. The embodied impacts for a house are all assigned to day one of the buildings use. The operational impacts, however, only begin on day one and increase over time. As noted, a renovation will add embodied impacts at a later date of time, but the importance of time allocation should be address. Second, a significant portion of embodied impacts quantities for the *urban region of Munich* have largely already occurred. The embodied impacts for roads, the subway network, and so on have already been incurred and only maintenance and new projects add additional impacts.

Therefore, the time distribution of environmental impacts, especially carbon dioxide emissions, needs to be investigated. While the work has shown the importance of embodied impacts, these are emitted at a different time interval than operational impacts. Accounting for the upfront emission of embodied impacts compared to the distributed operational impacts over many years in the future is also required. Similar tools such as *discounting* and the concept of *net present value* from economics offer potential insights into this future research area.

8.7 Conclusion

The previous chapters provided detailed analyses of the four impact categories: building embodied impacts, building operational impacts, transportation impacts, and transportation operational impacts. In general, these impact categories were evaluated separately. This chapter brings together the individual impact categories and investigates their interdependencies.

The cumulative environmental impacts for the built environment are calculated using the expanded life-cycle assessment methodology. The results show that impacts are lowest for the city center followed by the periphery and then the districts. In particular, the importance of transportation operational impacts is shown.

The chapter quantifies the direct induced impacts from the summation of transportation embodied and transportation operational impacts. The direct induced impacts make up 50% of total impacts, revealing their central importance. The influence of indirect induced impacts is illustrated through the variation of building types for each location. In addition, household scenarios illustrate differences with the average results. Finally, specific requirements to meet environmental goals are presented in comparison with the results. The importance of time considerations for environmental impacts is also outlined.

Chapter 9

Conclusion

9.1 Introduction

The dissertation has assessed the environmental impacts in the built environment. The impact category of building embodied, building operational, transportation embodied, and transportation operational have been determined. In addition, a new impact category, induced impacts, was analyzed through an expanded life-cycle assessment framework. The case study of the *urban region of Munich* was used to verify the applicability of the new methodology.

9.2 Objectives of the research

The goal of the doctoral research was to expand the methodology of life-cycle assessment to quantitatively capture the environmental influence of induced impacts within the built environment. In addition, the work set out to determine the induced impacts for an actual case study. The work has three research motivations. First, buildings are not isolated objects, but rather they are integrated into an urban context. Additionally, the majority of construction is of single buildings within existing cities, rather than entirely new cities.

Second, environmental impacts from the building sector are not fully captured within current methodologies and analysis, due to the absence of the interactions between individual buildings and the larger urban environment. Third, the ability to meet environmental goals requires the quantitative assessment and evaluation of these induced impacts for a comprehensive analysis.

The research hypothesis states: *If the environmental performance of a building is influenced by its interactions with the surrounding urban context, then achieving environmental objectives within the built environment requires the identification and life-cycle evaluation of induced impacts.*

9.3 Summary of the findings

9.3.1 Expanded methodology through a new impact category

Having identified a potentially critical, and currently missing, impact category, the research proposes an expanded methodology to quantitatively assess induced impacts. First, the traditional impact categories (i.e., embodied and operational impacts) are retained, but examined for various locations within a metropolitan region. Thus the influence of location are captured though the following attributes: building type, building form, living space demand, construction materials, structural systems, shared building walls with neighboring buildings, area of heat transfer, and transportation.

Second, the interaction of building residents with the urban environment is captured through transportation impacts. Transportation serves as a critical metric for the interconnection of the individual building and the surrounding urban environment. The research therefore quantifies the embodied and operational impacts of transportation. Through the four impact categories as well as the examination of different building types at different locations, a new methodology was proposed.

9.3.2 Building embodied impacts

Based on building statistics and market research, three case study residential buildings representative of three locations (i.e., city center, city periphery, and district outside the city) are selected. The buildings selected are a multi-family house (city), a row house (city periphery), and a single family house (district). A detailed life-cycle assessment of the buildings was conducted.

The results of the life-cycle assessment show that material emissions and energy use are dominated by concrete for all case studies. Comparing materials, transportation to site, and end-of-life, materials account for over 95% of emissions. The multi-family house has the lowest embodied emissions (per person) followed by the row house (53% higher emissions) and then the single family house (100% higher emissions than the multi-family house). This trend is also found on a square-meter basis.

9.3.3 Building operational impacts

The operational energy for the three buildings was also evaluated. Operational impacts account for heating, hot water, and electricity. The results find that the multi-family house has the lowest operational emissions per person followed by the row house and then the single family house. Compared to the multi-family house, the row house has 28% higher emissions and the single family house has 59% higher emissions.

A sensitivity analysis is done for the influence on both operational and embodied impacts for a building renovation. The largest savings from the renovation are for the single family house (23% reduction in total emissions). This is compared to 13% reductions in total emissions for the multi-family house. The increases in embodied impacts for the renovation have payback periods of 1 to 3 years.

9.3.4 Transportation embodied impacts

The embodied impacts for transportation vehicles and infrastructure were also determined. Vehicles are examined for private transportation (i.e., automobiles) and public transportation (i.e., buses, trams, subway trains, suburban trains). The emissions on a per person-vehicle-year basis are slightly lower for public transportation vehicles. However, using passenger-kilometers as the functional unit shows that automobiles have drastically higher emissions.

Next, the environmental impacts for transportation infrastructure were determined. The road network for Munich was analyzed in detail using different construction classes for roads. These results are then extrapolated to the surrounding road networks for districts. A similar life-cycle assessment for public transportation stations and lines was conducted. The work shows that the road network in districts is the highest, followed by the subway network, the road network in Munich, the suburban train network, and finally the tram network when excluding vehicle embodied impacts. Accounting for the vehicles as well illustrates the dominance of the road networks compared to public transportation networks. This is due to the extremely large fleet size of private automobiles and their relatively short lifespan (i.e., 12 years.)

9.3.5 Transportation operational impacts

The final impact category, transportation operation, is then determined. Utilizing an extensive transportation data survey, the research found the transportation emissions for three geographical levels based on residence location: transportation cells for Munich, neighborhoods for Munch, and all districts. The enormous dataset for the transportation survey required the development of software to analysis the data following extensive data preprocessing to ensure the data fit the research scope.

The research finds the kilometer traveled and the environmental impacts for the traffic cells, neighborhood, and district resolutions. At both the transportation cell and the neighborhood scale, there is not a clear correlation between geographical household location and either kilometers traveled or environmental emissions. However, at the district level resolution there is a clear differentiation between travel and impacts for the city location compared to the surrounding districts. From this analysis, the transportation operational emissions based on location are determined.

Sensitivity analyses was done for future tail-pipe reductions up to 2030 and airplane travel. Tail-pipe reductions are shown to offer savings (23%), while airplane travel dominates total emissions (increases up to 252%).

9.3.6 Induced impacts

Next, the impact categories were combined and their interdependencies examined. The city center is found to have the lowest impacts followed by the periphery (22% higher than the city center) and then followed by the districts (48% higher than the city center).

The results also show that embodied impacts account for around 23% of all impacts. The embodied impacts account for building materials, vehicles, and infrastructure materials. Making up such a large percentage of the total impacts, embodied impacts are shown to be of central importance and must be accounted for in environmental analysis.

In addition, transportation emissions make up 51.5, 50.0, and 46.5% of all emissions for Munich, the periphery, and districts, respectively. Transportation associated emissions are hence the majority of emissions for two of the three locations. Given the significance of transportation emissions, these impacts must be accounted for in all locations.

Finally, induced impacts are determined. Direct induced impacts are shown to be 50% of total impacts. Indirect induced impacts can increase total emissions from 9 to 48%. In addition, average results are compared to realistic household scenarios to show potential variations.

9.4 Significance of the findings

The findings from the work make several contributions to the existing literature. First, the research identifies a gap in current environmental assessments of the built environment. While significant research is concerned with the environmental performance of buildings and the built environment, research focusing on the interactions between individual buildings and their urban context are missing. Second, the work defines a new impact category, induced impacts, to capture the currently missing impacts resulting from the interactions between individual buildings and the urban environment. Induced impacts must be quantitatively assessed in order to determine their significance and to enable meeting environmental objectives. Third, the research presents a new expanded life-cycle assessment methodology to capture induced impacts within the built environment. Fourth, utilizing the new methodology, the work determines the induced impacts for the case study of the *urban region of Munich*. Thereby illustrating the application of the expanded life-cycle assessment methodology to capture induced impacts in the built environment for an actual metropolitan region. The results show the quantitative assessment of induced impacts and their importance in relation to traditional impacts.

In addition to the expanded methodology and the new impact category, this is the first study to use statistical analysis and real estate market research to determine typical buildings for evaluation using life-cycle assessment. Until now, life-cycle assessment of buildings has been random and not representative of the larger building stock in question, which negates the usefulness of the past results. The research determines representative values for buildings typical of the *urban region of Munich*.

Further, the detailed assessment of the MiD transportation survey adds to the literature on the geographical distribution of transportation impacts across a metropolitan region at different scales. The analysis provides travel distances and environmental impacts at the traffic cell level in Munich, at the neighborhood level in Munich, and at the district level. The works adds to the literature on spatial distribution of transportation impacts.

Finally, taken together, the research provides an integrated and holistic methodology to assess the environmental performance of the built environment. The findings are specific to the *urban region of Munich*, but can be transferred to other metropolitan regions with diverse building typologies and numerous transportation modes as in the case study region.

9.5 Limitations of the current study

A few limitations of the work should be noted. The cumulative results are for average values. As illustrated in the sensitivity analysis for airplane trips and household scenarios, the average values can vary significantly from realistic scenarios. In this regard, socio-economic, demographic, and lifestyle choices play a crucial role in actual emissions. Household income, family situation, employment, and automobile ownership are just a few of numerous factors influencing environmental impacts from an individual. The influence of socio-economic, demographic, and lifestyle choices were not, however, the focus of the dissertation.

9.6 Outlook

9.6.1 Utilization of the research findings

The research results should enable a shift in attention from only operational aspects to a wider perspective encompassing embodied impacts. Current environmental discussions focus mainly on operational impacts for both buildings and transportation. Buildings have operational energy and emission certificates visible to the building users. Similarly, the energy consumption (i.e., gasoline) of automobiles is communicated with consumers. Similar communication strategies and tools should be used to illustrate the importance of embodied impacts for both buildings and transportation.

The work emphasizes the importance of targeted strategies for each location rather than application of broad standards across the board regardless of building type and location. Optimizing the environmental performance of the built environment should intelligently apply recommendations that achieve the highest percentage improvement for each building type and location.

The investigation introduces a new impact category, induced impacts, which needs to be introduced into environmental assessment of the built environment. Assessment of induced impacts is required to achieve environmental goals. From the findings, approximately 50% of the environmental impacts from the built environment are not currently being captured. This in turn calls into question the practicality of meeting environmental objectives. Only through the future inclusion of induced impacts will it be possible to comprehensively quantify environmental impacts, apply reduction strategies, and meet goals.

The focus of the work on *urban region of Munich* offers particular insights for local governments and institutions within the region aiming to mitigate environmental impacts. The City of Munich and the surrounding districts should utilize the findings of research to update their own environmental assessment methods to include induced impacts. The importance of building typologies and location within the region is shown to be essential to reduce environmental impacts and must be addressed from the urban level.

9.6.2 Recommendations for further research work

The research builds upon the foundation of scientific work in the field of environmental assessment in the built environment. The findings from the work lay the groundwork for several important and interesting future research areas.

First, the research investigated traditional transportation fuel based on the available literature. However, given the political and business interest in electric mobility, this is an area of increasing importance. Future research should investigate the life-cycle impacts of switching to electric automobiles within an integrated methodology as outlined in the thesis. Different scenarios for electricity production (e.g., electricity from renewables, electricity from fossil fuels) should also be reviewed. Such an analysis would provide insights into whether electric mobility offer environmental improvements or not.

Second, potential changes in transportation travel should be examined. The research used travel data from the 2008 MiD-MUC survey. However, current travel patterns, distances traveled, trips per day, and modal split might change decidedly in the short-term and long-term. Therefore, further work should analyze diverse scenarios for future transportation within the *urban region of Munich*. These scenarios could include increased non-motorized trips, reduced trip lengths, shifting to public transportation from private car, and so on. These findings could provide the critical insights that focus on reducing transportation impacts should focus on shifting to near-zero and low emission modes and reducing trip distances rather than reducing tail-pipe emissions.

Application of such scenarios within the integrated life-cycle framework also allows for detailed environmental assessment of planed transportation projects (e.g., the second line extension of the Munich suburban train). The real world application of the methodology would take advantage of the intricate and complex relationship of induced impacts. Further, additional aspects of the built environment influencing induced impacts (e.g., on-site parking requirements, bicycle infrastructure networks) should be reviewed to see how they affect total environmental impacts.

Third and final, the time distribution of environmental impacts, especially carbon dioxide emissions, needs to be investigated. While the work has shown the importance of embodied impacts, these are emitted at a different time interval than operational impacts. New assessment methods for emissions in the built environment should take into account the upfront emission of embodied impacts compared to the distributed operational impacts over many years in the future. Similar tools such as *discounting* and the concept of *net present value* from economics offer potential insights into this future research area.

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List of Abbreviations

AP Acidification potential

Avg. Average

DFH Double family house

Dist. District

E Scientific notation

Emiss. Emissions

EOL End-of-life

EP Eutrophication potential

Eq. Equivalent

FFB Fürstenfeldbruck

Germ. German

GWP Global warming potential

Init. Initial

Kg Kilogram

Km Kilometer

LCA Life-cycle assessment

LCI Life-cycle inventory

LCIA Life-cycle inventory assessment

MFH Multi-family house

Mio. Million

MJ Megajoule

MVG Münchner Verkehrsgesellschaft

MVV Münchner Verkehrs- und Tarifverbund

NA Not applicable

NMVOC Non-methane volatile organic compounds

ODP Ozone depletion potential

PE Polyethylene

PENERT Total non-renewable primary energy resources

Per. Person

PERT Total renewable primary energy resources

Pkm Passenger-kilometer

PM10 Particulate matter 10 micrometers or less in diameter

POCP Photochemical oxidant creation potential

Pop. Population

Renov. Renovation

RH Row house

S. Train Suburban train

SFH Single family house

Spec. Specific

Str. Straße, Street

TJ Terajoule

Yr Year