SUSTAINABILITY MANAGEMENT INTEGRATIVE CAPSTONE PROJECT SPRING 2019

EMBEDDED CARBON FOR DECISION-MAKING

Client: Port of Seattle

Project Manager: Savannah Wilson
Deputy Project Manager: Scott Osicka
Editor: Prerna Shetty

Tal Bar On, Ji hye Choi, Shruti Deshpande, Dmitriy Golodnikov, Laura Malo Yague, Jasmine Okbinoglu, Saiba Sharmeen, David Tu

Faculty Advisor: Susanne DesRoches

Table of Contents

Acknowledgements

This report was prepared by graduate students from Columbia University's Master of Science in Sustainability Management Program co-sponsored by the Earth Institute and the School of Professional Studies working under the direction of Faculty Advisor, Susanne DesRoches.

The team would like to include a sincere thanks to Arlyn Purcell, Leslie Stanton and Stephanie Meyn of the Port of Seattle whose high level of engagement, enthusiasm and expertise provided a strong foundation for our research and overall enjoyable learning experience. We would also like to thank Susanne DesRoches for her guidance and thoughtful insight throughout our rigorous process. In addition, special thanks to Christoph Meinrenken, adjunct assistant professor in the Department of Earth and Environmental Engineering and associate research scientist at the Earth Institute and Lenfest Center for Sustainable Energy, who provided key advice on evaluating life cycle assessments for construction materials.

Executive Summary

The Port of Seattle has recognized its role in addressing global warming and aims to be the greenest port in North America. To meet that goal, the Port of Seattle has a robust understanding and accounting process for tracking its operational carbon emissions that contribute to global warming. Nonetheless, they have realized that the carbon emissions associated with their capital projects represent an information gap in their greenhouse gas (GHG) inventory accounting. These carbon emissions are those that arise from the energy and industrial processes that occur during the production of construction materials as well as during the physical construction of buildings and infrastructure. These emissions are referred to as embedded carbon.

As opposed to operational carbon which can be addressed over time, embedded carbon is locked in place once an infrastructure project is complete. Importantly, the relative amount of embedded carbon to operational carbon is increasing as operational emissions are declining due to new technologies and increased efficiencies, further emphasizing the growing significance of embedded carbon to an organization's total emissions.[1] Early decision-making is required to address embedded carbon impacts on new capital developments. Similarly, it is also necessary to measure embedded carbon on current projects in order to manage and try to minimize it. However, the Port of Seattle has also recognized that there are a number of ways to evaluate and quantify embedded carbon, which have influenced wide variations in results. This report further evaluates the methodologies, assumptions, and calculations behind embedded carbon data to provide a conclusion on its reliability of being used at the Port of Seattle to accurately measure their embedded carbon impact.

This is a pivotal moment for the Port of Seattle and its embedded carbon profile as the Seattle-Tacoma International Airport, otherwise known as Sea-Tac, plans for over $4 billion in capital projects to meet increased passenger and cargo demand. Those projects are outlined under the Sustainable Airport Master Plan which includes near-term projects that are estimated to be completed or under construction by 2027. This upswing in construction in the coming years will equate to higher embedded carbon levels if action is not taken to minimize it. The report further aims to assess the embedded carbon impacts of construction materials used at Sea-Tac. Due to their high volume and common use, the Port of Seattle further narrowed the research to the following three materials for the in-depth analysis: asphalt, concrete and steel.

Each material's carbon impact was assessed using Environmental Product Declarations, or EPDs. EPDs are third-party verified, manufacturer-published life cycle assessments that report carbon emission factors, or EFs. The emission factors represent carbon emitted at each step of the life cycle and enable comparisons between materials manufactured by different processes. The material analysis resulting from the comparison of EPDs aims to guide the Port of Seattle on how to collect and ensure quality life cycle data as well as how to effectively communicate and leverage the importance of measuring embedded carbon. The overarching goal is improved decision-making to achieve more efficient, lower carbon capital projects.

Material Results Summary

Ideally, materials manufactured by similar processes should produce similar carbon emissions. However, the Capstone team's research showed a wide range of carbon emissions between comparable materials due to two key reasons: uncertainty and variability in the data. Uncertainty arises from incomplete data or an inaccurate understanding of specific life cycle process steps. Uncertainty can be reduced or eliminated with more or better data.[2] In contrast, variability describes the inherent differences in emission factors from different sources at each process step of a life cycle assessment.[3] Specifically for construction materials, emission factor variability illustrates the different means of extraction, manufacturing or transportation that exist in a material's life cycle. Variability can be addressed by targeting the most carbon intensive steps of a material's life cycle process steps, and while it cannot be completely removed, it can be better defined to allow for more transparency in the data. Table A summarizes the range of emission factor data reported for the three selected materials, the key factors influencing that variability, and potential alternatives to reduce the variability and carbon intensity within each material.

	Asphalt	Concrete	Steel
Uses at Sea-Tac	Roads, runway surface layer, runway repairs	Building structure, runways, sidewalks	Building structure
Researched Emission Factor Range	25.10-64.40 kilograms CO_2e/ton	285.51-443.00 kilograms CO_2e/m^3	1160.00-2390.00 kilograms CO_2e/m^3
Factors Influencing Variability	Temperature of manufacturing processes and amount of recycled content	Cement content	Pre-fabricated steel manufacturing process and energy source used
Design Alternatives	Implement warm mix asphalts	Maximize structural efficiency to use less	Maximize structural efficiency to use less
Material Alternatives	Utilize higher recycled asphalt content or lower temperature heating methods	Specify low-carbon concrete mixes with fly ash, slag, calcined clays or lower-strength concrete where feasible	Utilize higher recycled steel content

Table A: Material Results and Variability Summary

Recommendation Summary

The Port of Seattle seeks transparent and comparable emission factors for the purpose of measuring embedded carbon. Due to the high levels of uncertainty and variability, the Capstone team concludes that the Port of Seattle cannot currently use existing data as a means for accurately measuring embedded carbon in their upcoming capital projects. Until further advancements are made to standardize the input data and calculation methods used to estimate EFs, there is no clear way to assess the accuracy of those numbers. However, the Capstone team recommends three key actions the Port of Seattle can take to improve the quality of embedded carbon data for their GHG accounting process.

The first proposed action involves lobbying for legislative policy changes at the local and state level to require standardized EPDs. The Port of Seattle should leverage its buying power and regional influence to commission standardized EPDs from suppliers and manufacturers that would meet the requirements of the legislation. Standardized EPDs will ensure identical methodologies are used to assess data and information can be presented in a consistent layout. In addition, the EPD data can be required to be verified only by Port-approved third-party verifiers.

The second proposed action calls for process improvements to help ensure quality data. The Port of Seattle should create an internal data rating and quality assessment system for EPDs to evaluate the reported data and its credibility.

The third proposed action promotes actively pursuing internal and external stakeholder partnerships to increase the probability of success in implementing these recommendations. The Port of Seattle may begin with identifying internal partners and industry leader allies to help communicate the importance and urgency of tracking embedded carbon.

These three actions together affecting policy, process, and people, have the potential to significantly improve the rigor and reliability of embedded carbon data related to construction materials allowing for improved decision-making by the Port of Seattle.

Common Terms and Abbreviations

ASTM International: formerly known as American Society for Testing and Materials, ASTM is an international standards organization that develops and publishes with full transparency voluntary consensus technical standards

BOF: Basic Oxygen Furnace

Carbon dioxide equivalent (CO_2e): a CO_2e unit of measure is employed to express the impact of the greenhouse gas effect associated with a certain process in a consistent manner

Cradle to Gate: a life cycle assessment system boundary beginning at the raw material extraction stage and ending at the processing and manufacturing stage, or essentially, the factory's gate

Cradle to Grave: a life cycle assessment system boundary beginning at the raw material extraction stage and ending with disposal at the end of life stage

Cradle to Practical Completion: a life cycle assessment system boundary beginning at the raw material extraction stages and ending with the completion, or handover, of the constructed site

Declared Unit: the consistent unit of measurement of a product, material or activity being studied in a life cycle assessment, i.e. one kilogram of Portland Cement; normally defines specific characteristics of that product, i.e. the mix description and process of the Portland Cement and the manufacturing region

EAF: Electric Arc Furnace

Embedded carbon: also known as embodied carbon, accounts for greenhouse gas (GHG) emissions that arise due to the energy and industrial processes occurring in the extraction, transport and manufacturing of raw construction materials and products as well as during the physical construction of buildings or infrastructure

Emission factor (EF): a representative number given to estimate the emissions of any given greenhouse gas for any given source or activity, relative to a specified unit amount of that source

EN: European Standard

Environmental Product Declaration (EPD): third-party verified, manufacturer-published life cycle assessment that reports carbon emission factors; comparable to a nutritional label for a material or product, stating what it is made of and the associated carbon emissions

Federal Aviation Administration (FAA): federal agency with oversight to regulate all aspects of civil aviation within United States airspace

Functional Unit: See "Declared Unit"

Global Warming Potential (GWP): an impact category studied in a life cycle assessment to determine the impact that the product, material or activity has on global warming

Greenhouse gas (GHG): gases that contribute to global warming by trapping heat in the Earth's atmosphere. Carbon dioxide (CO_2) from the burning of fossil fuels accounts for the vast majority of GHG emissions. Methane (CH_4), nitrous oxide (N_2O) and fluorinated gases released from fossil fuel, agricultural or industrial processes comprise the remainder of GHG emission gases.

GHG Accounting: the practice of calculating, documenting and monitoring the amount and rate of greenhouse gas emissions from an organization's operations; broken down into Scope 1, 2 and 3 emissions as defined by the GHG Protocol (See "Scope 1 Emissions," "Scope 2 Emissions," and "Scope 3 Emissions")

HMA: Hot Mix Asphalt

Impact Category: the intended research objective that drives the assumptions and allocation methods within a life cycle assessment; an environmental or social issue of interest that is observed and measured in a life cycle assessment

ISO: International Organization for Standardization

Life Cycle Assessment (LCA): an analysis of the life cycle stages of a certain product or material to assess the carbon intensity of its life cycle stages through the collection and calculation of emission factors (See "Emission Factor") and according to defined system boundaries and objectives

NAPA: National Asphalt Pavement Association

Near-Term Projects: 30+ projects recommended in the Port of Seattle's Sustainable Airport Master Plan to meet the immediate needs of the airport to improve and expand (See "Sustainable Airport Master Plan")

Operational carbon: greenhouse gas emissions that arise from the use and maintenance of an organization's current operations

RAP: Recycled Asphalt Pavement

RAS: Recycled Asphalt Shingles

Seattle-Tacoma International Airport (Sea-Tac): primary commercial airport owned and operated by the Port of Seattle which serves the Seattle metropolitan area. It was the eighth busiest airport in the United States by passenger traffic in 2017 and is considered one of the fastest growing airports nationally.

Scope 1 Emissions: greenhouse gas emissions that arise from the generation of electricity for use at a specific site

Scope 2 Emissions: greenhouse gas emissions that arise from the secondary purchase of electricity to be used at a specific site

Scope 3 Emissions: greenhouse gas emissions that arise from the use, maintenance, and end of life stages of a product or project, excluding those that arise from electricity use (See "Scope 1 Emissions" and "Scope 2 Emissions")

Sustainable Airport Master Plan (SAMP): guidance document created by the Port of Seattle to recommend 30+ proposed near-term projects, estimated to be completed or under construction by 2027, to help accommodate forecast aviation demand and serve other airport goals.

Uncertainty: lack of knowledge regarding the true value of an emission factor at a given location and time period.[4] The lack of knowledge results from incomplete data or an inaccurate understanding of specific life cycle process steps. Uncertainty can be reduced or eliminated with more or better data.[5]

Variability: inherent differences in emission factors from different sources at each process step of a life cycle assessment.[6] Specifically, for construction materials, emission factor variability illustrates the different means of extraction, manufacturing or transportation that exist in a material's life cycle. Variability cannot be reduced, but it can be better characterized.[7]

WMA: Warm Mix Asphalt

INTRODUCTION

Introduction

The increasing global trends of population growth and urbanization are driving a need for more infrastructure development on both local and national levels. That new construction and development, in turn, is associated with a rise in carbon emissions. This project aims to specifically assess the underlying carbon emissions of constructing new capital developments at the Seattle-Tacoma International Airport, further referred to as Sea-Tac. Sea-Tac is owned and operated by the Port of Seattle and serves as a west coast–international travel gateway for passengers and an international logistics hub for cargo.

The client, the Port of Seattle prides itself on being environmentally conscious and continuously works to integrate sustainability into their overall business strategy through a number of ambitious objectives, including a reduction in their Scope 3 greenhouse gas (GHG) emissions of 80 percent below 2007 levels by 2050.[8] To achieve such goals, the Port of Seattle currently measures and monitors Scope 1, 2 and 3 emissions that relate to the use and maintenance of their current operations. Emissions that arise from such activities are referred to as operational carbon.

However, operational carbon does not account for emissions related to the sourcing and production of construction materials or the physical construction of buildings or infrastructure projects. These emissions are commonly known as embedded carbon. The Port of Seattle has recognized this gap in their GHG accounting and seeks to further understand both the methods and calculations behind embedded carbon as well as any underlying causes of variability or uncertainty that could impact the overall reliability of the data.

The current and most widely used method to estimate embedded carbon is to compile emission factors for each step of a product's life cycle processes. An emission factor, further known as an EF, is an expressive figure that is used to estimate the total emissions of any given GHG for a specified material or activity.[9] In multiplying the total volume or amount used of that material or activity with the EF, one can approximate the total carbon emissions of that source and its proportion of estimated influence to the entire product or, in this case, capital project.

As embedded carbon is a developing area of interest within GHG accounting, there is an understood level of uncertainty due to inconsistencies in data sources as well as incomplete or inaccurate input information that goes into EF calculation methods and assumptions. Additionally, there is natural variability that exists due to the inherent differences in life cycle practices across sources, such as different manufacturing methods for the same product. Variability also arises from variances in life cycle system boundaries, or the areas and impacts of the life cycle being studied, as well as from the interpretation of results. The uncertainty and variability is compounded as the complexity of the capital project grows, which is why it is crucial for the Port of Seattle to understand the current baseline of embedded carbon data as they plan for the addition of major new construction.

Sea-Tac is in a period of expansive growth, reflecting the strength of the regional economy, and has forecasted both increasing passenger and cargo demand in the coming years. This growth is prompting the development of a number of large-scale capital and infrastructure improvements at the airport. With the onset of this new major construction in conjunction with their GHG emission reduction goals, the Port of Seattle seeks to decouple the positive correlation between capital growth and GHG emission levels. To work towards achieving this, the Port of Seattle has tasked this Capstone team with assessing the current data on embedded carbon and providing a statement on its rigor and ability to accurately measure the emissions from their new capital projects.

Client Profile

Focus Region

King County, Washington is home to one of the nation's fastest growing regions: the Seattle-Bellevue Metropolitan Area. In 2017, the area's population grew by nearly 2 percent and employment opportunities rose by over 1.6 percent from 2016 figures.[10] That steady growth is projected to continue, and the area was named the second fastest growing city in America in 2018.[11]
Located along the eastern shore of the Puget Sound, King County is approximately 2,132 square miles and inhabits nearly 2.2 million citizens. Its largest city, Seattle, accounts for over a third of that population.[12] Of King County's 2,132 square miles, 1,670 are non-urban, meaning that nearly 80% of the land is rural, agricultural, or forested.[13] Influenced by its topography and general proximity to nature, King County and the Greater Seattle Area have been repeatedly recognized for its culture and efforts in environmental sustainability.

The Port of Seattle

Founded in 1911, the Port of Seattle was organized as a special purpose municipal corporation to serve King County, Washington. The Port primarily owns and operates the Seattle-Tacoma International Airport; however, it also oversees tourism and commercial fishing industries and aids in building road and rail infrastructure in the area.[14] The Port of Seattle also prides itself on being a leading sustainable entity and stewards environmentally responsible initiatives.

The Port of Seattle operates with the core goal to drive equal opportunity and development in the region and across the state by fostering trade and advocating economic growth through manufacturing and maritime operations. The current vision includes creating 100,000 new Port-led employment opportunities, bringing the total to 300,000 Port-related jobs, in the region all while performing at a lower carbon footprint.[15]

The Port's largest operations - the Seattle Seaport and the Seattle-Tacoma International Airport - serve the entire Puget Sound region. The Puget Sound population is expected to grow to over 4.7 million people by 2034,[16] meaning that the Port of Seattle needs to grow in response to satisfy the growing needs and demand of the public. To aid with this growth, the Port of Seattle has created the Century Agenda to further emphasize the Port's initial goal of equal opportunity development. The Century Agenda includes four separate strategies to secure its progress as a leading port. Strategy Four specifically states the Port's ambition to become the greenest, and most energy efficient port in North America.[17] The Port has already outlined multiple initiatives through their Long-Range Plan to meet this goal, including focusing their energy profile on renewables, meeting storm water and air pollution requirements, restoring and enhancing surrounding habitats as well as the informal goal to have all major new construction certified LEED Silver.[18]

Seattle-Tacoma International Airport

Sea-Tac is the leading hub airport for the growing Puget Sound and Washington State areas. In 2018, it was the 8th busiest airport in the United States, carrying nearly 50 million passengers and approximately 432,000 metric tons of cargo in that year alone.[19] Along with an estimated rise in cargo traffic and volume, Sea-Tac's forecasted passenger demand is set to exceed 66 million by year 2034, an estimated 32 percent increase in just 15 years.[20]

To specifically accommodate this growth, the Port of Seattle created the Sustainable Airport Master Plan, further abbreviated as SAMP. The SAMP was developed to aid in meeting passenger and cargo demand, as well as to increase operational efficiency while complying all new construction to the FAA airfield standards and guidelines. The SAMP recommends over 30 Near-Term Projects, estimated to be completed or under construction by 2027, to continuously improve and support the safety, access, efficiency and sustainability of both new and existing facilities. Most notable of these projects are the plans to add nineteen new gates and an additional terminal to the airport.[21]

Project Scope

This project evaluated the variability and uncertainty that exists within the calculations for embedded carbon of three focus materials: asphalt, concrete and steel. The decision to narrow the scope to these materials was a based off of a client-driven choice due to the broad applications and large volumes used at Sea-Tac. The Capstone team further analyzed multiple sources to identify relevant EFs, prioritizing those that were specific to the Washington state region and correlated with Sea-Tac specifications. These EFs, along with extensive knowledge of the respective material's life cycle processes, allowed the team to isolate key influences that contribute to the material's overall carbon intensity.

To understand how the team further narrowed the scope, it is necessary to be familiar with life cycle assessments. Studies that collect, calculate, analyze and interpret EFs across a product's life cycle processes, including raw material extraction, transportation, manufacturing, use, and end of life, are known as life cycle assessments, or LCAs. Every LCA that is conducted must have a clear and well-defined system boundary, or essentially a scope of the life cycle areas being studied. As defined by European Standard EN 15978, life cycle stages are numerically categorized on a scale from A to D. Possible system boundaries include cradle to gate (A1-A3), cradle to practical completion (A1-A5), cradle to grave (A1-C4), and cradle to grave including benefits and loads beyond the system boundary, which include product reuse, recycling, or recovery (A1-D). Each of these stages and boundaries are illustrated in Figure 1 below.[22]

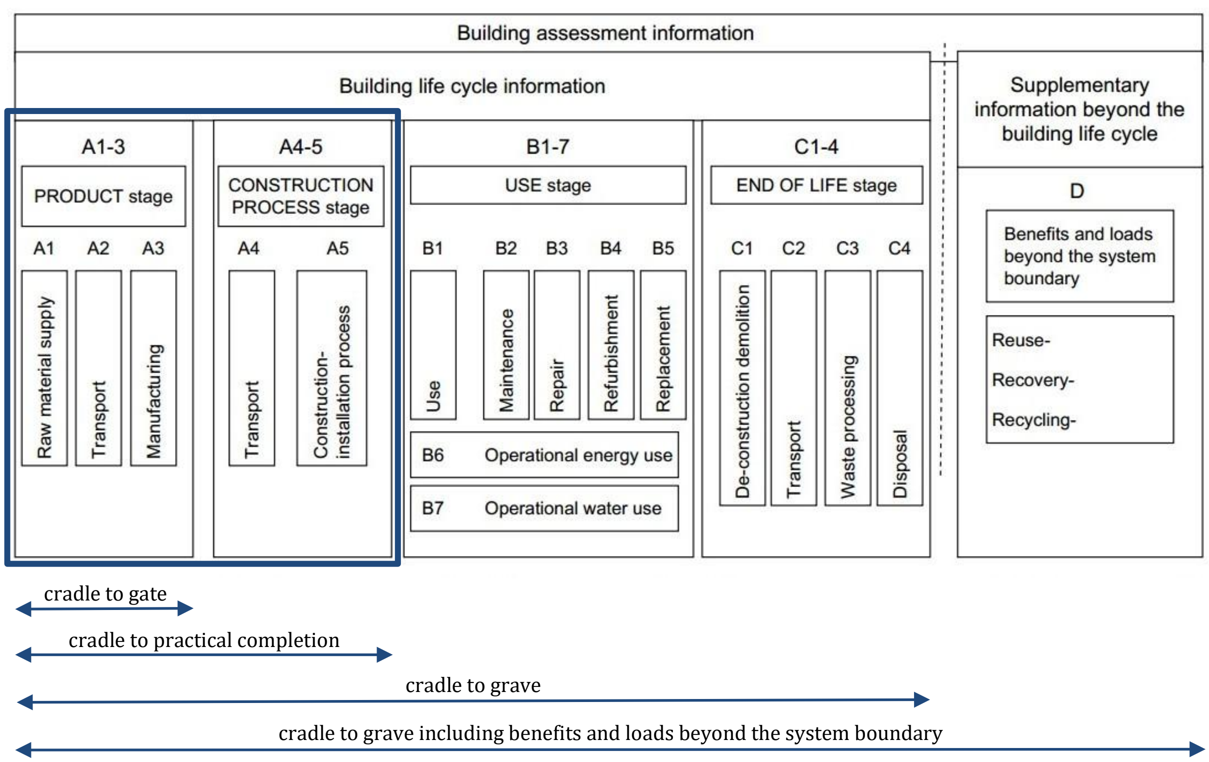


Figure 1: Typical LCA System Boundaries Per EN 15978

In the context of this project, the Capstone team set the system boundary as the LCA stages associated with cradle to practical completion, or A1 through A5, which define the scope as beginning at raw material sourcing and ending at the practical completion of the capital project, or essentially the handover of the completed construction site for its intended use. Specifically, these are the five life cycle stages that are associated with embedded carbon. While the main sources in this report will focus the majority of available data on cradle to gate boundaries, it would be insufficient to exclude stages A4 and A5 as this would not assess the entire impact of embedded carbon.

However, based on the current research, the Capstone team has concluded that both stages A4 and A5 are dependent on external factors that material manufacturers cannot easily measure, and is thus the reason why they are typically not included in EPDs. As mentioned, stage A4 is the transportation step from the manufacturing plant to the construction site. Calculations of EFs at this stage are solely dependent on the mode of transportation, fuel type and vehicle miles traveled. While the mode of transportation and fuel type may be known to the manufacturer, this stage becomes difficult to measure as the manufacturer cannot provide one single EF for transport when it is unclear where the materials will be transported. For example, the A4 EF will differ if the materials are transported from California to Washington versus from Florida to Washington. Likewise, for stage A5, unless the manufacturer has information on the methods of installation being used at the specific construction site, it is difficult to provide only one EF for this life cycle process. In the case of the Port of Seattle, this information would rather need to come from the third-party contractors that complete the construction. For these reasons, the specific material analysis will be focused primarily on stages A1 through A3, providing information on stages A4 and A5 as available.

In further defining scope, as the Port of Seattle already currently measures its operational carbon during the use, end of life and demolition/disposal life cycle stages, the Capstone team determined it was not necessary to include any cradle to grave system boundaries in the scope of this project.

Just as the system boundary must be distinctively outlined when beginning an LCA, the study's objectives must also be clearly defined. The desired objective is also known as an impact category and determines the direction of the research depending on what the publishers of the study aim to achieve with their results. By the ISO Standard 14044 definition, impact categories are subjects of environmental or social concern that are observed and measured in a life cycle inventory assessment.[23] As shown below, Table 1 from Sustainable Minds, a cloud-based LCA software, details a list of typical impact categories that are commonly studied in LCAs.[24]

Impact category	Unit	Weighting factor (%)
Acidification	kg SO_2 eq /year /capita	3.6
Ecotoxicity	CTUe /year /capita	8.4
Eutrophication	kg N eq /year /capita	7.2
Global warming	kg CO_2 eq /year /capita	34.9
Ozone depletion	kg CFC-11 eq /year /capita	2.4
Carcinogenics	CTUh /year /capita	9.6
Non-carcinogenics	CTUh /year /capita	6.0
Respiratory effects	kg PM2.5 eq /year /capita	10.8
Smog	kg O_3 eq /year /capita	4.8
Fossil fuel depletion	MJ surplus /year /capita	12.1

Table 1: Impact Categories for Life Cycle Assessments

While multiple impact categories can be studied in one LCA, the chosen impact categories are important as they drive the assumptions as well as allocation and calculation methods used to estimate EFs. As conveyed in the above table, global warming potential (GWP) has the highest weighting factor, indicating that global warming effects are scaled greater to reflect the significance of its impacts. This prioritization of GWP over other impact categories has bolstered numerous related studies and increased its availability of data. Therefore, for the purposes of this project, the Capstone team will only be analyzing the GWP of each material in units of carbon dioxide equivalent, or CO_2e, as the sole impact category.

Further assumptions related to scope are individual to each focus material and will be outlined in the respective material analysis sections as necessary.

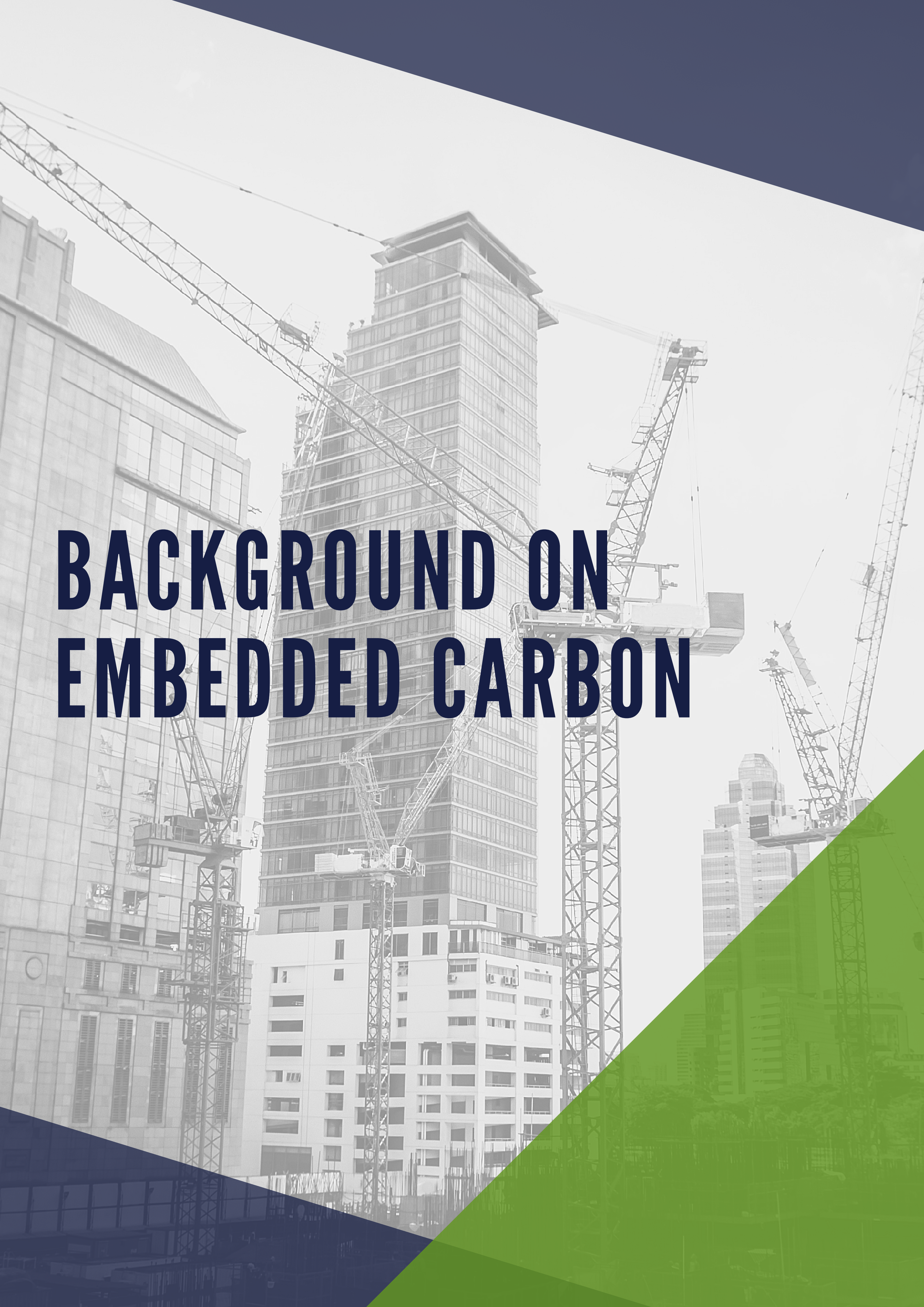
Research Methodology

The research methodology for this project is illustrated in the flowchart below.

Figure 2: Project Research Methodology

Following the definition of scope, the team proceeded with initial research and literature reviews of existing methodologies for calculating embedded carbon and EFs to comprehend the life cycle phases of each of the studied materials. Research was obtained from academic, industrial, and professional resources. In order of prioritization, the subsequent data collection focused on the compilation of relevant EFs, derived primarily from Environmental Product Declarations, which are manufacturer-published LCA studies specific to building materials and construction processes. Data was then sourced by existing academically and professionally published LCA studies and life cycle impact (LCI) databases and software packages. The research was concluded with the analysis and synthesis of the collected methodologies and EFs to gauge the estimated carbon impacts of each material as well as the range of variability and how each impacted the viability of the data.

BACKGROUND ON EMBEDDED CARBON



The Significance of Embedded Carbon

Global Trends

Global population is projected to increase from the 7.3 billion inhabitants on the planet reported in 2015 to 8.6 billion by 2030.[25] To provide the new homes, businesses and infrastructure necessary to support the increasing population, new construction is expected to increase 85 percent to $17.5 trillion globally.[26] Of specific relevance to the Port of Seattle and Sea-Tac, airline travel is expected to expand in relation to these global trends, increasing from under four billion global passengers today to over seven billion passengers by 2030.[27]

This growth will account for a range of increased activities that will all have associated GHG emissions. GHGs are gases that contribute to global warming by trapping heat in the Earth's atmosphere. Carbon dioxide (CO_2) from the burning of fossil fuels accounts for the vast majority of GHG emissions. Methane (CH_4), nitrous oxide (N_2O) and fluorinated gases released from fossil fuel, agricultural or industrial processes comprise the remainder of GHG emission gases.[28] To express the aggregated impact of each GHG associated with a certain process in a consistent manner, a carbon dioxide equivalent, or CO_2e unit of measure is acknowledged and employed.

Operational Carbon vs. Embedded Carbon

Embedded carbon in the construction industry consists of GHG emissions that arise from the energy and industrial processes involved in the extraction, processing, manufacturing, and installation of building products in addition to the transportation of those products to the building site.[29] As previously noted, embedded carbon does not include the carbon associated with the lifespan of the building, or operational carbon. Operational carbon is well understood and accounted for by many organizations. The increasing understanding of operational carbon has allowed for new technologies and processes to reduce the effects of operational carbon. In fact, the relative levels of embedded carbon to operational carbon are increasing as renewable energy sources become more prevalent and operational emissions decrease due to new technologies and increased efficiencies.[30]

Embedded carbon still represents a gap in the collective sustainability community's knowledge of tracking GHG emissions. Currently, there is a lack of transparency in data collection, and CO_2e factors associated with building materials and products can vary significantly by source.

Unlike operational carbon emissions, which can be addressed during the lifespan of a building with energy efficient upgrades or the use of renewable energy, embedded carbon emissions are locked in place once a building or infrastructure project is complete.[31] The most critical time to influence a building's embedded carbon footprint is during the design phases of the project where understanding and addressing the most carbon intensive materials for a given project can yield the greatest results.[32]

History of Carbon Disclosure and Accounting

The Paris Climate Agreement has necessitated action on the part of the building and construction sector to address global warming. The built environment is responsible for approximately 30 percent of global GHG emissions and 50 percent of global wealth. Global rates of new construction amount to the building of a new Manhattan every 35 days.[33] Currently, at least 5 percent of anthropogenic GHG emissions come from cement production and another 5 percent come from steel production.[34] Overall, structural materials such as steel and concrete contribute to at least 40 percent of the embedded carbon in a building.[35] The Intergovernmental Panel on Climate Change has further called out the urgency of mitigating carbon in the built environment by stating the building sector must reach zero carbon by 2050.[36]

An increasing amount of research shows that addressing embedded carbon is a critical part of reducing an organization's overall carbon impact. Recent figures show that over a 30-year period, embedded emissions will account for more than 50 percent of the total carbon emitted for some building types.[37]

Measuring Embedded Carbon

The most widely used and accepted method for measuring embedded carbon involves first determining the quantities of construction materials used in a project, followed by gathering respective EFs to multiply with those quantities to estimate the total carbon footprint of the material. These EFs can either be derived from primary data, meaning internally calculated, or secondary data, which is obtained through external databases or published LCA studies. As previously discussed, an EF is a representative figure that attempts to measure the emission rate of a specific GHG for a particular product or activity, in relation to a specified unit of measure. The figure is generally expressed as the mass of the specified GHG divided by the mass of the product, e.g. kilogram CO_2e per one kilogram of concrete. In some cases, the figure can be divided by factors such as distance traveled or duration of time of the activity, e.g. kilograms of CO_2e per vehicle miles traveled. To quantify embedded carbon specifically, EFs are calculated for each life cycle stages that are attributed to those emissions, or life cycle stages A1 through A5. To many experts, this is considered the best, and potentially only, method for attempting to estimate GHG emissions.[38]

Nonetheless, the calculation of EFs come with numerous limitations. Due to the lack of industry standards that define best practices and guidance on how to accurately and consistently populate these figures, there is a wide range of EFs available for each life cycle process for every material measured. The foundation of these inconsistencies is due to the volume of data sources available; though the extent and range of the variability is exacerbated by the use of different assumptions and life cycle boundaries used per calculation as well as the general uncertainty in the input data.

For example, as per the EPA, the general equation for calculating the total emission rate of a particular product or activity using EFs is relatively simple and constant. Each source will base their calculations on the below equation;[39] however, the strategies and assumptions used to estimate each variable in the formula will differ depending on the types of products and life cycle stages being measured and the desired results of the product study.

$$E = A \, x \, EF \, x \, \frac{1 - ER}{100}$$

Where:

$E = emissions$
A = activity rate
EF = emissions factor, and
ER = overall emissions reduction efficiency, %

Overall, the EPA notes that the resulting variability and uncertainty that occurs during the calculation of carbon footprints is not inherent in the formula, but in the differing inputs and assumptions of each variable, which become further intensified by the lack of consistent data available and the pitfalls of averaging industry data.[40]

The variability of the formula inputs stems primarily from two main factors: natural dissimilarities in each material life cycle stage process and relative differences in impact categories of the EF calculation.

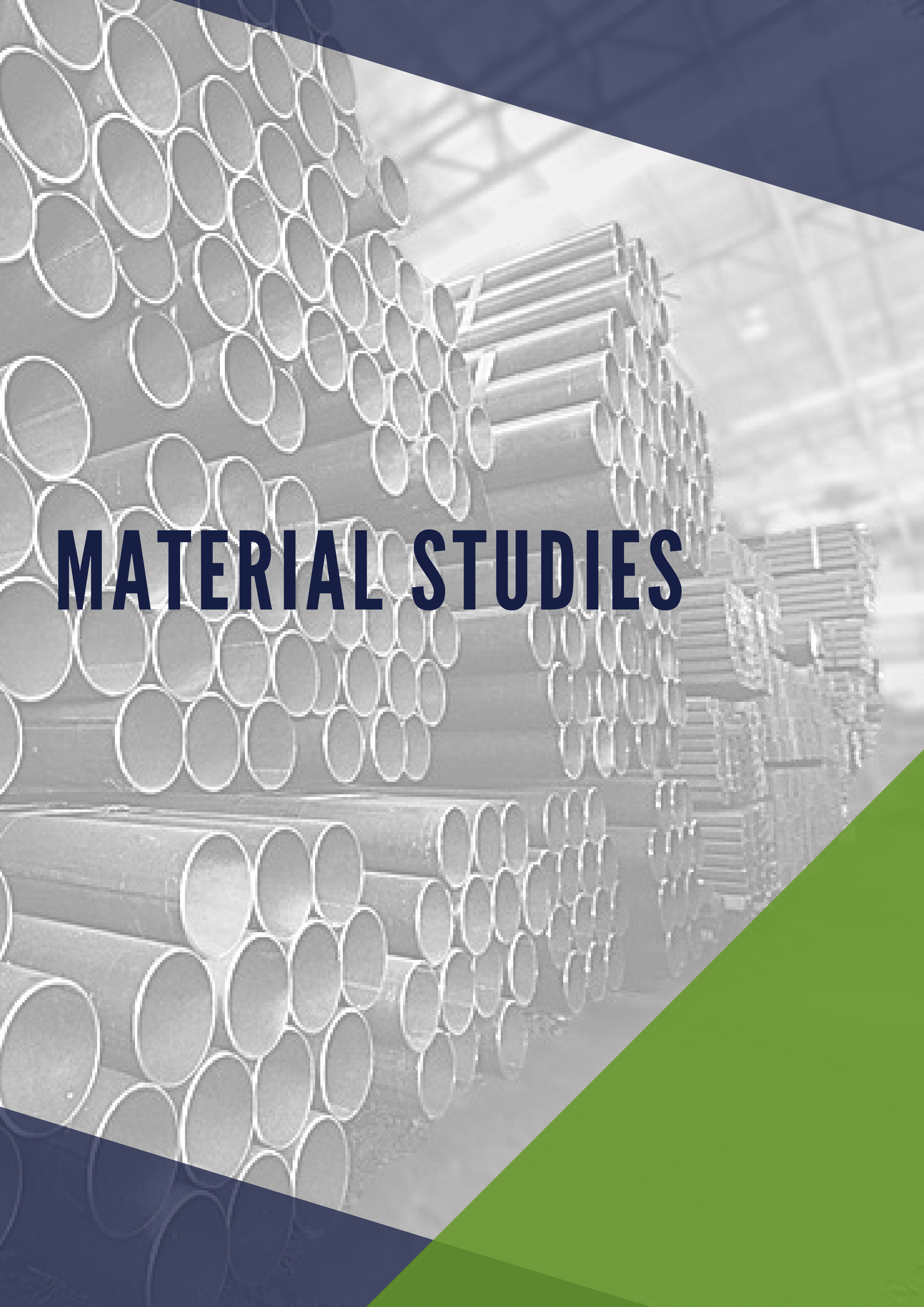
First, the deviations in each life cycle stage as well as the assumed efficiency level of that stage can vary greatly from one material's EF to another EF for that same material. One of the main sources of variability in LCAs is essentially having multiple production techniques for the same material across manufacturers. Further, the efficiency at which these different life cycle stages are executed also varies per supplier. For example, one manufacturer of steel will use different processing methodologies, different electricity mixes, and different technological systems than another steel manufacturer. Therefore, EFs from separate sources will likely and ultimately contrast based on the inherent practices and conditions used at each life cycle stage.

Secondly, the impact category of each EF may differ per source. Depending on the basis of the study, one source could be more interested in understanding the global warming potential of a specific product, whereas another source may be concerned with the social impact of the pollutant and may seek instead to measure the product's impact on smog levels. An EF used to represent global warming potential versus an EF used to represent smog levels will be noticeably different. Each different impact category affects the allocation assumptions and calculation methods for that specific EF. While this report only studies the EFs for global warming potential, it is crucial to understand that different studies will conduct their observations and calculations with the point of view of their intended impact category, thus introducing a tendency to calculate and interpret the EF results with that bias.

Together, both the differences in life cycle processes as well as the impact categories measured stand as the origin from which all other variances and dissimilarities between EFs begin. These factors are both innate within the material, as each has naturally different processes and impacts on the environment and society, as well as within the rights of those conducting each study to determining when assessing the input data. This exists as the main obstacle when trying to create industry standards to determine EFs as there is simply no way to effectively limit this variability.

Another complicating factor in EF calculations is uncertainty. The authenticity and reliability, or lack thereof, of the source data heavily influences the level of uncertainty in each EF. According to the GHG Protocol, there are a few main sources of data uncertainty that contribute to the overall ambiguity of each EF. In addition to data simply not being available for a particular process, the data that is available may be outdated, an incorrect representation for the region or technology methods, imprecise, or incomplete.[41] Compounded together with the existing sources of variability, this factor plays another role in furthering the inconsistencies in EF calculations.

MATERIAL STUDIES



Material Study

The following embedded carbon research focused on three common construction materials: asphalt, concrete and steel. This was a client-driven strategic decision to focus on materials that are widely used in capital projects at Sea-Tac. Additionally, concrete and steel are some of the leading carbon-intensive materials when measuring the overall embedded carbon footprint of construction projects.[42] This report aims to catalog the variables and uncertainty inherent in product sourcing, reporting, and procurement while providing Sea-Tac with insights to guide their material selection.

Asphalt is commonly used for main vehicle roadways and service roads throughout Sea-Tac. As a material that covers more than 90 percent of all roads in the U.S., asphalt is also used on runways, aprons, and rooftops of buildings.[43] Asphalt is both naturally occurring and manufactured, and its intended function informs the specific mix type required. Different asphalt mixes all have particular production methods that come with unique embedded carbon implications.

Concrete is the most widely used construction material in the world.[44] Reinforced structural concrete forms the superstructure of most major terminals and support facilities at Sea-Tac, while Portland cement concrete is specified for roads and pavement. The ubiquity of concrete worldwide is why it is one of the most impactful contributors of global GHG emissions. Understanding the root causes of its emissions variability is essential to helping Sea-Tac minimize embedded carbon from concrete in capital project planning and development.

Steel is also a critical structural component of many commercial and institutional buildings. Steel framing and trusses are designed as signature architectural elements in major airports. Reinforcement steel, or rebar, is paired with concrete to provide the flexible strength that forms structural concrete flooring, columns, and beams. Light-gauge steel framing is commonly used in commercial construction to frame walls, envelopes, and roofs. The production of steel varies greatly by region due to manufacturing processes and alloy content.[45] The differences in production methods and metal compositions can greatly affect the embedded carbon in structural steel.

Limitations in Vendor and Material Selection

The Sea-Tac Design Guidelines and Standards outline the general recommendations and requirements from material vendors. The document provides both specific material specifications for certain building features and minimum performance requirements for others. Areas that have legacy designs are required to source materials that match the existing conditions. Any variances from the Design Guidelines must be approved by the Port of Seattle project manager for the project.[46] Overall, all material and designs must meet the overarching construction codes and standards established by the Federal Aviation Administration and Washington State Building Code.[47]

Asphalt

Asphalt is a smooth, flexible, and durable material that makes it ideal for many surfaces for infrastructure and construction projects. It is most commonly associated with transportation infrastructure for surfacing roads but is also found on driveways, roofs and waterproofing agents. As of 2011, more than 92 percent of the 2.5 million miles of roads and highways in the U.S. were surfaced with asphalt.[48] Importantly, many airports utilize asphalt for paving runways. For example, one of Sea-Tac's recent capital infrastructure projects, the resurfacing of Runway 16C/34, is designed with asphalt concrete shoulders. Due to its applications and high total volume used, asphalt has been widely studied to understand its carbon and environmental impacts.

Asphalt is a broad term encompassing asphalt binder and asphalt concrete. Asphalt binder, also known as asphalt cement, is a dark brown to black cementitious material in which the predominate component is bitumen. Bitumen is both naturally occurring and can be obtained in petroleum processing. Asphalt concrete, which is used to create pavements, roof shingles, and other surfaces, is a mixture of asphalt binder and aggregates.[49] Aggregate is a collective term for sand, gravel, crushed stone and other minerals in their natural or processed state.[50] In Hot Mix Asphalt, or HMA, aggregates are combined with an asphalt binding medium to form a compound material. By weight, an aggregate generally accounts for between 92 and 96 percent of HMA and makes up about 25 percent of the cost of an HMA pavement structure.[51]

There are several different kinds of asphalt concrete mixtures including hot, warm, and cold mix asphalt. Each of these mixtures can be broken down into further product types. However, HMA and Warm Mix Asphalt (WMA) are the primary focus of this material study. Both hot and warm mix asphalts are primarily used to create asphalt concrete paved surfaces.

Traditionally, HMA has been the process used to create asphalt pavement. HMA is manufactured when high quality aggregate and asphalt binder are heated above 300°F during mixing and kept hot during transportation and construction.[52] WMA is a general term for technologies that reduce the temperature needed to produce and compact asphalt mixtures for the construction of pavements. WMA is produced at temperatures that are 30°- 120°F lower than HMA, while also being maintained at lower temperature than HMA during transport and construction.[53]

Figure 3 below illustrates the typical process map for creating HMA and WMA mixtures. As this material study will discuss, variability for EFs is present in every process step but specifically arises from the amount of energy used in heating and refining aggregate, the differing percentages of recycled content in the mix, and the temperatures used in manufacturing the asphalt mixture. These processes take place during life cycle stages A1 and A3.

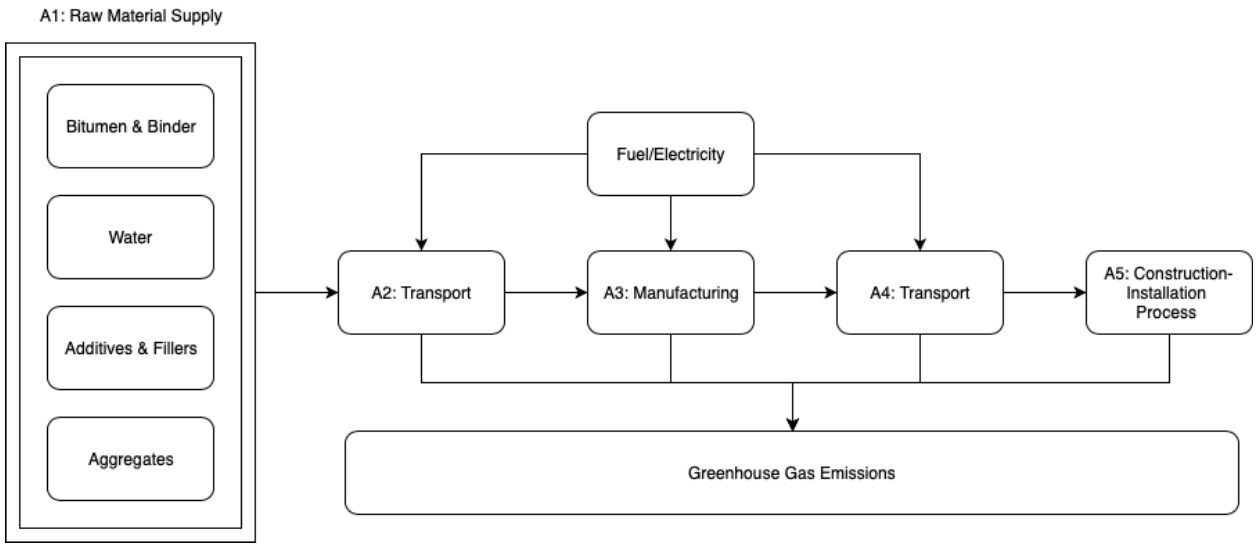


Figure 3: Typical Asphalt Mixture Process Map

Carbon Profile

Asphalt manufacturing requires processes that each have associated amounts of GHG emissions related to material extraction, electricity and fuel usage, and transportation. In 2007, about 1.6 trillion metric tons of asphalt was produced worldwide.[54] The Asphalt Pavement Alliance (APA) is a coalition formed by the Asphalt Institute, the State Asphalt Pavement Associations, and the National Asphalt Pavement Association (NAPA). The mission of the coalition is to establish asphalt pavement guidelines to get the best quality, material performance, and benefits for the environment.[55] According to the APA, an asphalt pavement (at 5 percent asphalt concrete) emits 0.0103 tons of CO_2e per kilometer. In comparison, concrete pavement intended for similar applications emits 0.1073 tons of CO_2e per kilometer.[56]

Sea-Tac Specifications

The Port of Seattle selects and sources asphalt and pavement materials for construction projects in accordance to the Washington State Department of Transportation (WSDOT) requirements and policies. HMA specifications and evaluation standards must be in compliance with the current City of Seattle Standard Specifications for Road, Bridge and Municipal Construction.[57]

State of Emissions Data Variability

The asphalt market in the U.S. is regulated by the National Asphalt Pavement Association, or NAPA, which is a trade organization heavily invested in the application of asphalt. While asphalt is a widely used material, much of the available and disseminated sustainability data in the U.S. is primarily derived from NAPA and other asphalt organizations sharing the same interests, such as the APA and Washington

Asphalt Pavement Association (WAPA). To acquire data for a more holistic and impartial analysis of asphalt, research was expanded to global sources outside of the United States.

The main sources for this material study are EPDs with system boundaries of cradle to gate, or stages A1 through A3. This study also includes asphalt and pavement road LCA studies and inventories which report asphalt information according to ISO 14040 standards, which specify the general framework, principles and requirements for conducting and reporting LCA studies.[58] By gathering data from more diverse sources, the study intends to obtain a more varied sample of EFs with the purpose of reducing any potential biases.

Notably, each EPD and LCA study provided different data depending on the type of mix or percentage of recycled asphalt pavement (RAP), recycled asphalt shingles (RAS), or aggregate used during the asphalt manufacturing process.

Carbon Intensity Life Cycle Phase Analysis

A study by Chang'an University evaluated the carbon emissions associated with HMA used in asphalt pavement construction in China. The study provides information on HMA that is not sponsored by NAPA and therefore can help provide a more objective understanding of the carbon intensity of the different stages of asphalt pavement production. The study specifically evaluates the energy consumption of eight stages in the asphalt life cycle for three different types of fuel combinations used to heat asphalt and aggregate. The three fuel-mix combinations are as follows:

A. asphalt heating with coal and aggregate heating with heavy oil
B. asphalt and aggregate heating process with heavy oil
C. asphalt and aggregate heating process with natural gas

Shown below, Table 2 from the study shows a summarized general analysis of the proportion of carbon emissions per life cycle stage for HMA. The asphalt pavement construction process is divided into eight stages which illustrate the potential for causing variability in an associated emissions factor.[59]

Life Cycle Stage	A (%)	B (%)	C (%)
Aggregate Stocking	1.14	1.23	1.63
Aggregate Supply	0.84	0.77	1.37
Aggregate Heating	65.39	69.00	65.36
Asphalt Heating	15.24	14.93	13.00
Mixture Mixing	12.87	10.33	13.67
Mixture Transport	0.14	0.78	0.12
Mixture Paving	1.52	1.46	1.80
Mixture Rolling	2.63	2.21	3.04

Table 2. Proportion of Carbon Emissions in Asphalt Pavement Life Cycle Stages

The asphalt pavement construction stages from this study are defined in Table 3 as follows:

Life Cycle Stage	Life Cycle Stage Description
Aggregate Stocking	Aggregate is transported and loaded at the mixing station. The main energy source consumed during this phase is the use of diesel oil.[60]
Aggregate Supply	Aggregate is transferred to a cold aggregate bin during the manufacturing process. The main energy source consumed during this phase is the grid power required for production and the use of fuel oil for transportation.[61]
Aggregate Heating	Aggregate is heated at a high temperature generally between 160°C and 190°C. The main energy source consumed is oil and natural gas used during the heating process. This is the most carbon intensive stage of asphalt pavement construction.[62]
Asphalt Heating	The asphalt binder is heated with the aggregate from the previous step. In this stage the main contributor of carbon emissions is the thermal heating fluid used to warm the mixture between 150°C and 170°C.[63]
Mixture Mixing	The mixture developed from the previous steps is blended in a process requiring grid electricity.[64]
Mixture Transport	The asphalt mixture is transported from the mixing site to the pavement site. In transportation, the main energy source consumed is from the diesel fuel used in the transport vehicle.[65] In other cases, the distance from the mixing site to the pavement site is a potential factor.
Mixture Paving	The use of an asphalt paver is the main energy consumption source. [66]
Mixture Rolling	The asphalt mixture is rolled, creating the pavement layers. Diesel oil is the main energy source based on per unit of time and workload.[67]

Table 3: Asphalt Pavement Life Cycle Stage Descriptions as per Chang'an University

The analysis from Table 2 highlights that aggregate heating, followed by asphalt heating, and closely after by mixing are the three most carbon-intensive stages in the asphalt life cycle that together account for more than 90 percent of the carbon emissions from the entire life cycle. Aggregate heating accounts for the maximum proportion of carbon emissions and therefore is a major source of potential variability in emission factors.

A key point to note is that although the fuel-mix used in each step was different for the three sample combinations studied (A, B and C), each step had a similar proportion of carbon emissions across the fuel-mix used. Thus, the asphalt life cycle was less influenced by the energy-mix used and more by the amount of energy used. This signals that while the study was conducted in China, which has a different energy profile than the U.S., the findings should be consistent and able to be replicated in other areas of the world.

The analysis concludes that the type of energy used at each life cycle stage is a source of variability, but the energy intensity in the aggregate heating stage is responsible for the largest proportion of the total carbon emissions followed by the asphalt heating stage. Together, these heating stages and mixture composition had the greatest impact on carbon emissions.[68] As a result, it can be inferred that WMA mixtures require less intensive heating than HMA and therefore will lower the carbon impact.

As aggregate heating requires high levels of energy compared to other asphalt life cycle steps, the most carbon intensive step in asphalt production is A1. The raw material supply stage encompasses the energy required for raw material extraction, refinement, and aggregate heating.[69] To further test these results, EPDs for multiple asphalt mixtures ranging from HMA to WMA and Low Mix Asphalt (LMA) mixtures were analyzed. A one-to-one comparison (e.g. only HMA mixtures of a certain type) is currently not possible due in part to the asphalt industry's lack of standardization across LCAs and EPDs.

Outlining the Results

The National Asphalt Pavement Association has created an EPD verification tool called the Emerald Eco-Label. The goal is to provide the asphalt industry with consistent environmental data so that it can be used more reliably.[70] Table 4 summarizes EPD emission factor data from NAPA's Emerald Eco-Label in addition to European asphalt manufacturers to analyze the state of variability within multiple asphalt EF sources. The functional unit, or declared unit, used in this analysis was one short ton of asphalt.

Source	Emerald Eco-Label	Emerald Eco-Label	Emerald Eco-Label	Emerald Eco-Label	BRE	Eco-Asphalt	Eco-Asphalt
Company - Location	George Reed, Inc. - California	George Reed, Inc. - California	Ajax Paving Industries of Florida - Florida	Payne and Dolan, Inc. - Wisconsin	Tarmac - United Kingdom	ECO-Asfalt - Sweden	ECO-Asfalt- Sweden
Producct description	**2018-TM-004D-VSS-64-10-R15** - Hot Mix Asphalt Mixture	**2018-TM-004D-VSS-64-10-R25** - Hot Mix Asphalt Mixture	**S-1R, a Dense Graded asphalt mixture** - Hot Mix Asphalt Mixture	**801418** - Hot Mix Asphalt Mixture	ULTILOW asphalt - Low Temperature Asphalt Mixture	**ECO-Asfalt® AG 16 4,8%** - Hot Mix Asphalt Mixture	**ECO-Asfalt®** Specific type of asphalt **AG 16 4,8% inluding reused asphalt AG 16 10% RAP** - Hot Mix Asphalt Mixture
Manufacturing temperature range (C/F)	280.0 to 325.0 °F	280.0 to 325.0 °F	300.0 to 325.0 °F	280.0 to 320.0 °F	Typically supplied 40°C lower than a hot equivalent asphalt	Not Provided	Not Provided
Materials (A1) GWP (kg CO2)	30.40	26.00	18.70	20.40	Not Provided	Not Provided	Not Provided
Transport (A2): GWP (kg CO2)	3.59	4.67	57.00	2.75	Not Provided	Not Provided	Not Provided
Production (A3): GWP (kg CO2)	2.70	2.70	15.80	20.90	Not Provided	Not Provided	Not Provided
Merged (A1)-(A2)-(A3): GWP (kg CO2)	Not Provided	Not Provided	Not Provided	Not Provided	64.40	26.20	25.10
Transport to the site (A4): GWP (kg CO2)	out of scope	out of scope	out of scope	out of scope	6.87	out of scope	out of scope
Installation and Construction (A5): GWP (kg CO2)	out of scope	out of scope	out of scope	out of scope	6.04	out of scope	out of scope

Table 4: EPD Analysis for Asphalt Life Cycles A1-A3

Firstly, this data analysis proved problematic because EPDs provided by NAPA included EFs for separate life cycle stages, while EPDs from European sources did not. NAPA provided values for stages A1 to A3 while the European manufacturers provided only an aggregated, merged GWP value for those three stages. This illustrates one instance where the data provided is not a one-to-one comparison due to a lack of standardization.

To better understand this variability across NAPA EPDs, three mixtures from manufacturer George Reed, Inc. that were produced in the same California plant were compared. Only two of the three are shown above in Table 4. Please see Appendix B for more information. Variability was shown to be limited or even nonexistent for the A3 production stage while the A1 raw material supply and extraction stage was interestingly the most variable with it also being the most carbon intensive life cycle stage. Data was relatively consistent from the same EPD provider; however, variability continued to exist in the EFs coming from the same plant depending on the mix type.

Continuing the analysis of the NAPA EPDs, the A1 stage provides moderate variability even among mixes coming from the same plant, as is the case of Jamestown in California. This is partially attributable to the range of energy sources, such oil or renewable energy, used in the extraction of material. This variability can also be due to the different levels of RAP content in a mixture. The first two columns in the table that represent two different mixes from the same company and location illustrate this effect. At their Jamestown, CA plant, George Reed, Inc. uses "R" followed by the numbers 15 and 25 in the mix description to signify the percentage of RAP in the mix. As shown, the EF value decreases as the percentage of recycled content increases in the mixture, declining from approximately 30 kilograms CO_2e to 26 kilograms CO_2e with a 10 percent increase in RAP. While the EPD does not formally disclose this analysis, it can be reasonably inferred that the recycled content in each asphalt mixture play a role in the resulting EF.

There is also high variability occurring at the A2 transport stage and the A3 production stage. Within the A2 stage, this variability is due to different plant locations and methods of transport. However, these EPDs do not provide a detailed breakdown of the A2 stage and thus do not disclose the origin of the raw materials. Therefore, it is gathered that variations must be derived from the distance between the material extraction site to the mixing plant as well as the mode of transportation and fuel type.

As highlighted previously in the study by Chang'an University, the variability, as is illustrated by the remaining two NAPA Emerald Eco-Label EPDs from Florida and Wisconsin, in the A3 production stage can be credited to the temperature used for heating during the manufacturing process or varying mix types. Again, the EPDs only provide incomplete and brief explanations about each stage of the LCA. Since they do not provide enough information to pinpoint exactly where the variability lies among EFs, it is difficult to offer discrete recommendations for limiting this variability.

Lastly, the EPDs from European manufacturers also show a great degree of variability in the merged GWP values for stages A1 through A3. Again, reasons for this could include the amount of recycled content used in each mix. While these EPDs do not have a breakdown of EFs per life cycle stage as the NAPA EPDs, each EPD does show a merged EF that reflects the percentage of RAP or RAS in the mix. For example, for Eco-Asfalt, the mix including the higher RAP percentage reflected the lowest EF. When using any recycled content in the mix, emissions are avoided as there are no emissions associated with the extraction of a virgin material. Emissions coming from material processing and transportation of the stone and asphalt binder are also avoided through the use of RAP or RAS. The production of the asphalt binder is also energy intensive therefore the EFs will be sensitive to the quantity of binder provided by RAP.[71]

Following this analysis, it is advised that EPDs from a standardized program such as NAPA's Emerald Eco-Label program be used for benchmarking purposes and comparison with products that are certified by a specific program or manufacturer. Comparison of absolute value EFs with EPDs from different programs or products using different upstream datasets is not advisable and may lead to erroneous interpretations.

Concrete

Concrete is the most widely used construction material in the world. According to the MIT Concrete Sustainability Hub, more concrete is produced than any other material on Earth.[72] It is a resource intensive material, requiring immense quantities of Portland cement, sand and rock as aggregates, and water for its production worldwide.[73] Concrete construction also regularly requires additional steel, wood, and plastics for tensile reinforcement and formwork.[74] Consequently, there are concerns about the industry's sizeable environmental impacts and carbon footprint.

Concrete is formed by combining water, Portland cement, and aggregates into a slurry which then hardens to form a rock-like substance suitable for use in buildings and infrastructure.[75] Portland cement is a fine powder that is mixed with water to form the paste that binds aggregates together. It is a manufactured substance made with varying combinations of lime, iron, silica, and alumina, depending on the exact raw materials that are readily available to the producer locally.[76] Aggregate can be any form of coarse to medium grained particulate material such as sand and crushed stone, although they may be substituted with waste or recycled materials such as crushed glass and recycled concrete.[77]

Figure 4 illustrates the four potential GHG emission phases during concrete production. It encompasses initial raw material sourcing to final product delivery and installation, or life cycle stages A1 to A5.

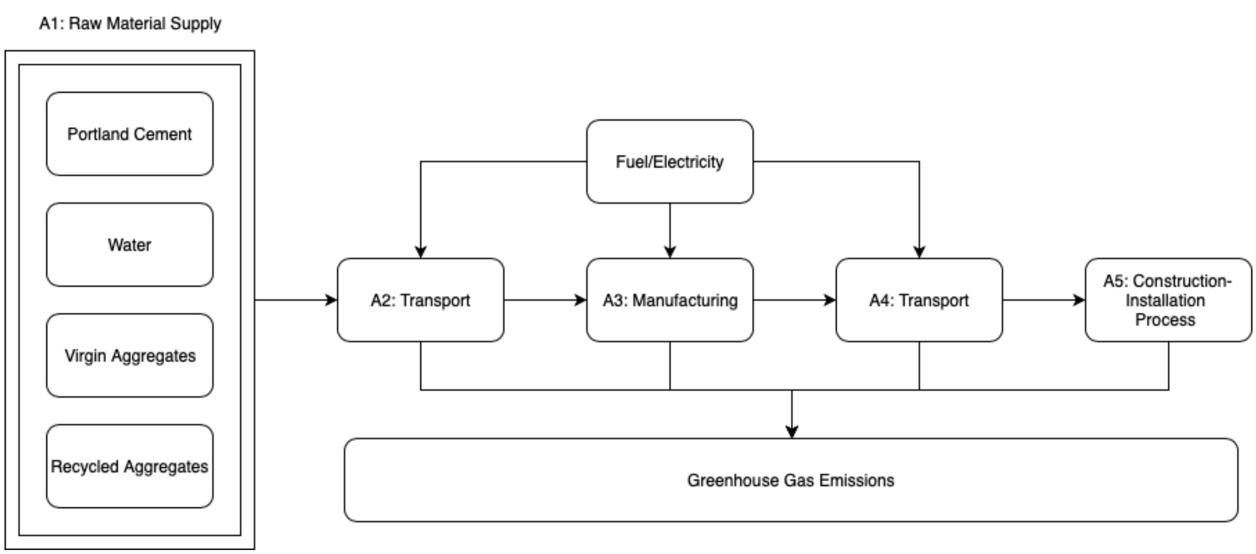


Figure 4: Typical Concrete Mix Process Map

Each one of the above processes involves a different source of primary energy and therefore generates an independent carbon footprint at each process stage. Moreover, each stage is executed differently depending on region and manufacturer. Comparing identical stages between different manufacturers and specific concrete mixes is a complex procedure which requires a deep understanding of all measurable data available from manufacturers for each LCA process.

Carbon Profile

Generally, the typical commercial concrete mix production process consists of two major CO_2 emission sources: the production of Portland cement and coarse aggregates.

- Portland cement was found to be the primary source of emissions, accounting for 74 percent to 81 percent of total CO_2 emissions.[78]
- Coarse aggregates were found responsible for 13 percent to 20 percent of total CO_2 emissions.[79]

Sea-Tac Specifications

Concrete composition for airport runways

To analyze concrete, two specific uses are considered: runways and airport buildings. This is due to two distinct sets of concrete specifications and requirements. For airport runways in the United States, the Federal Aviation Administration (FAA) outlines design specifications for rigid pavement types. Required performance specifications, including surface and base details, are outlined in Item P-501 of the FAA Airport Construction Standards.[80]

Concrete use for airport buildings

Concrete design mixes used in construction at Sea-Tac would comply with local building codes. The Seattle Building Code specifies the minimum cement content to achieve specified design requirements. As each future Sea-Tac building project will have specific concrete mix design requirements based off both aesthetic and performance criteria, a typical concrete mix specification is assumed for the life cycle analysis.[81] These specifications are shown below in Table 5.

Specified 29-Day Compressive Strength in psi (f'_{c_c})	Minimum Permissible Cement Content in lb/cu yd	Minimum Permissible Cement Content in STD. 94-lb Sacks/cu yd
2000	423	4 1/2
2500	470	5
3000	517	5 1/2
4000	611	6 1/2

Table 5: Minimum Permissible Cement Content for Concrete

State of Emissions Data Variability

As a primary building material, concrete has a wealth of published sustainability data that has been verified by third party consultancies. Leading manufacturers such as CalPortland are fairly transparent in their manufacturing processes and have published EPDs that document the environmental impacts of individual concrete mixes from specific plant locations. A major reason for the prevalence of concrete EPDs is the most recent version of the LEED rating system (v4), which awards points for projects that can document having twenty products with third party verified EPDs[82]. For concrete, each distinct mix that serves a specific purpose on a project (foundation, column, pavement, etc.) is considered to be a product, thus creating high demand for published EPDs from all manufacturers.[83] In addition, the National Ready Mixed Concrete Association (NRMCA) has spearheaded the industry's sustainability efforts by hosting a repository of manufacturer EPDs and by publishing industry average studies and reports. There are also many academic reports that analyze LCA studies and impacts. This material study drew from all the aforementioned sources for analysis and conclusions.

Carbon Intensity Life Cycle Phase Analysis

As described in *Life Cycle Inventory of Portland Cement Concrete*, cement is the most energy intensive component in the concrete production process.[84] Since the strength of concrete typically depends on the proportion of cement in its mix, the total embedded energy in concrete varies depending on its specification.[85] Figure 5 from *Life Cycle Inventory* demonstrates how the total embedded energy of various concrete mixes is directly correlated to the amount of cement present in the composition. The study found that replacing one percent of cement with supplementary cementitious materials (SCMs) such as fly ash or slag cement resulted in a one percent reduction in energy consumption per unit of concrete.[86]

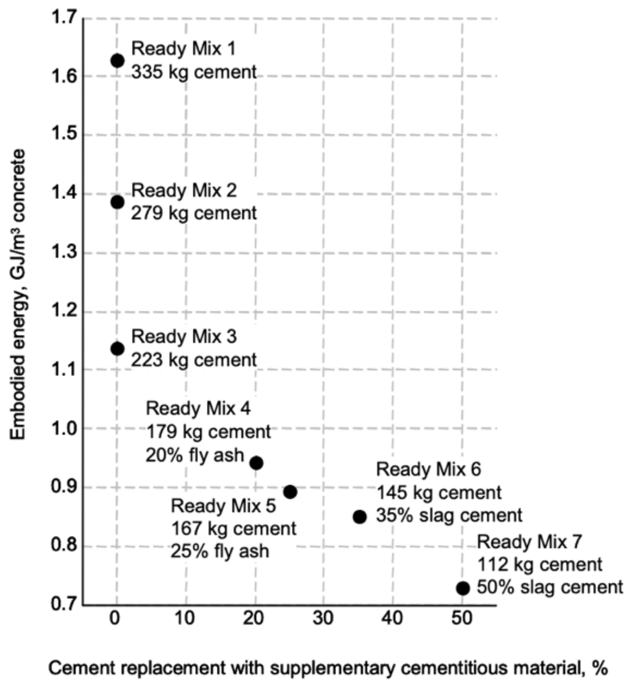


Figure 5: Embodied Energy of Concrete Mixes of Varying Cement Content

The process of manufacturing cement requires significant energy inputs to create the chemical and thermal combustion processes necessary for combining key ingredients.[87] Raw materials are essentially crushed and fed through a rotating kiln heated to temperatures as high as 3000°F to form rock-like substances called clinker. After cooling, the clinker is ground to a fine powder, mixed with additional additives, and packaged for consumption.[88]

Emissions from cement manufacturing has been documented by the Portland Cement Association (PCA) in the form of an industry-wide EPD. The EPD covers the A1-A3 life cycles of cement production using industry average data for each process step. PCA received self-reported data from twenty-two participating manufacturers across the U.S. with varying production technologies and energy sources for their analysis. The EPD, while not third party verified, attempts to process the mixed data to derive meaningful results through a self-developed methodology that created weighed averages of the process inputs. The results of their analysis conclude that 1040 kg of CO_2e is emitted for every metric ton of cement produced, however PCA also states that the data should not be used to assess the environmental performance for specific products.[89]

Outlining the Results

The LCAs for concrete that were reviewed each evaluated their data by a functional unit of one cubic meter of concrete. The functional unit is sometimes referred to as a declared unit, and it represents the amount by which all variables in a concrete mix should be compared. All EPDs that were reviewed, both from industry associations and individual manufacturers, limited their scope of LCA reporting to cradle-to-gate, a partial life cycle analysis that assesses impacts from initial resource extraction to factory ready product status. Therefore, the life cycle stages considered are A1: Raw Material Supply, A2: Transportation, and A3: Manufacturing.

Concrete is by nature a universally consumed product with innate variations due to its localized ingredients and methods of production. At its most basic, a concrete order is a specification for compressive strength, water-to-cement ratio, and aggregate composition.[90] The variables inherent in each specified product include the sourcing of its raw materials, fuel and efficiency of all transportation involved, and the energy source that powers the manufacturing process. To further uncover and assess the variations in emissions reporting, concrete mixes with similar specifications from different manufacturers were evaluated for comparative assumptions.

Table 6 on the following page catalogs the LCI data sources that are referenced in five different EPDs to calculate the A1 impacts of raw material supply for concrete mixes that meet a 3000 pound per square inch (psi) specification. Each mix design has varying proportions of cement and aggregate, with only a select few that disclose their mix composition. The EPDs are from western U.S. producers, including one from Seattle/Tacoma (CalPortland), several from California (Graniterock, Cemex, Central Concrete), as well as one industry average report (NRMCA).

Producer 3000 psi mix	CalPortland #3110	Graniterock #670297	Cemex #1412543	Central Concrete #330PC901	NRMCA 3000-00-FA/SL
GWP (kg CO_2 per m^3)	306.17	285.51	443.00	324.60	336.20
Cement	WBCSD-CSI tool for EPDs of concrete and cement - Chinese specific clinker factors and kiln fuels assumed	MIT 2014 paper, Update of Portland cement, at plant (USLCI)	USLCI process: "Portland cement, at plant", 2006	USLCI process: "Portland cement, at plant", 2012	Portland Cement Association EPD, 2014
Slag Cement	Slag Cement Association N. American EPD, 2015	LCI Slag Cement Manufacturing, 2003	Ecoinvent process: "Ground granulated blast furnace slag," 2003	Ecoinvent process: "Blast furnace slag cement, at plant," 2007	Slag Cement Association N. America EPD, 2015
Natural Aggregate	Ecoinvent process: "Gravel, round, at mine", ecoinvent 2.02, 2004	Primary data gathered at two of Graniterock's facilities, 2013	Ecoinvent process: "Gravel, round, at mine", ecoinvent v3, 2001	Ecoinvent process: "Gravel, round, at mine", ecoinvent 2.02, 2004	Ecoinvent process: "Gravel, round, at mine", ecoinvent 2.02, 2004
Crushed Aggregate	Ecoinvent process: "Gravel, round, at mine", ecoinvent 2.02, 2004	Primary data gathered at two of Graniterock's aggregate facilities, 2013	Ecoinvent process: "Gravel, crushed, at mine" ecoinvent v3, 2001	Ecoinvent process: "Gravel, crushed, at mine" ecoinvent 2.02, 2004	Ecoinvent process: "Gravel, crushed, at mine" ecoinvent 2.02, 2004
Admixtures	EFCA EcoProfiles (301, 324 and 325)	EFCA EcoProfiles (300, 301, 302, 303, 324 and 325)	EFCA EcoProfiles (300, 301, 302, 303, 324 and 325)	EFCA EcoProfiles (300, 301, 302, 303, 324 and 325)	EFCA EcoProfiles (300, 301, 302, 303, 324 and 325)

Table 6: Upstream Material Life Cycle Impact (LCI) Sources for 5 Concrete LCA Reports

As indicated, there are different GWP outputs from each producer for a basic concrete mix with a compressive strength of 3000 psi. What is most notable are the variations in LCI sources for key raw materials. While there is some consistency, such as the data for admixtures and aggregates, each producer references a different data set for cement, the most energy intensive raw material in concrete production. The reasons for each producer choosing their source is not stated, and the exact proportion of cement in each mix is difficult to determine. Based on the vast impact that cement has on the total emissions of concrete production, this data inconsistency is the core root cause of variability and uncertainty in concrete LCA reporting.

Variability is also present in the LCA data for the transportation and manufacturing stages. CalPortland and Graniterock use assumptions from the USLCI emission factor database for general transportation, while the NRMCA report is careful to separate road transport from others. Cemex and Central Concrete declined to include their source for transportation emissions, even though their reports encompass the A2 LCA stage. In fact, both Cemex and Central also declined to list their data source for emissions during manufacturing. Since their reports cover many concrete mixes from different plant locations with different energy inputs, their omission clouds the accuracy of their LCA results. And while CalPortland and Graniterock do list their emissions data sources for multiple energy inputs, their reports do not attribute them to the specific plant locations that are covered. Therefore, even though they appear to be more transparent than the rest, the total impact of the manufacturing stages in their results remains difficult to assess. The data for these two stages is highlighted in Table 7 and 8 below.

Producer 3000 psi mix	CalPortland #3110	Graniterock #670297	Cemex #1412543	Central Concrete #330PC901	NRMCA 3000-00-FA/SL
GWP (kg CO_2 per m^3)	306.17	285.51	443.00	324.60	336.20
Transportation	USLCI – single unit truck transport, diesel powered; rail transport, diesel powered; ocean freighter, average fuel mix; barge, average fuel mix, 2008.	USLCI – single unit truck transport, diesel powered; rail transport, diesel powered; ocean freighter, average fuel mix; barge, average fuel mix, 2008	None listed	None listed	Road: USLCI 2014 - single unit transport diesel powered, short haul US avg. Rail, ocean freighter and barge: USLCI – rail transport, diesel powered; ocean freighter, average fuel mix; barge, average fuel mix, 2008

Table 7: Transportation LCI Sources for 5 Concrete LCA Reports

Producer 3000 psi mix	CalPortland #3110	Graniterock #670297	Cemex #1412543	Central Concrete #330PC901	NRMCA 3000-00-FA/SL
GWP (kg CO_2 per m^3)	306.17	285.51	443.00	324.60	336.20
Manufacturing	Electricity (kWh) ecoinvent 3.01, 2014 LCI datasets for: Electricity, medium voltage {WECC, US only} USA/Washington Natural Gas (cu. ft.) USLCI, USA, 2008 Liquified Propane Gas (gallon) US LCI: Liquefied petroleum gas, combusted in industrial boiler/US, 2008 Diesel (gallon) USLCI, Diesel, combusted in industrial equipment/US, 2008	Electricity (kWh) ecoinvent 3.01, 2014 LCI datasets for: Electricity, medium voltage {WECC, US only} USA/California Natural Gas (cu. ft.) USLCI, USA, 2008 Diesel (gallon), USA, 2008	None listed	None listed	Electricity (kWh) ecoinvent 3.01 NRMCA purchased electricity grid mix-Electricity, medium voltage, at grid, US USA Natural Gas (cu. ft.) USLCI, USA, 2008 Diesel (gallon) USLCI, Diesel, combusted in industrial equipment/US, 2008 Gasoline (gallon) USLCI, Gasoline, combusted in equipment/US, 2008 Liquified Propane Gas (gallon) US LCI: Liquefied petroleum gas, combusted in industrial boiler/US, 2008

Table 8: Manufacturing LCI Sources for 5 Concrete LCA Reports

The data in Tables 6, 7, and 8 details how the regionality of concrete production contributes to the variability of emission factors from different producers. For instance, CalPortland cites electricity data from EcoInvent specific to Washington State while Graniterock references the EcoInvent California database of electricity emissions to reflect their plant locations. Furthermore, the emission factors from the transportation of raw materials to the manufacturing plant are also contingent on the location of the supplier. In an effort to mitigate these regional variabilities, data from CalPortland was compared with data from Cadman Inc., another concrete producer that serves the Seattle market. The data is shown below in Table 9.

Producer 7000 psi	Global Warming Potential (kg CO_2 per m^3)	Ozone Depletion (kg CFC-11-eq per m^3)	Acidification Potential (kg SO_2-eq per m^3)	Eutrophication Potential (kg N-eq per m^3)	Photochemical Ozone Creation (kg O3-eq per m^3)
CalPortland	335.40	5.88E-6	7.40	0.73	108.05
Cadman Inc.	464.00	1.09E-8	3.08	0.09	0.63

Table 9: Comparison of A1-A3 Environmental Life Cycle Impacts from Concrete Producers in WA

Upon review, comparing manufacturers from the same geographic area did not produce more similar emissions results. Rather, the life cycle impacts between Cadman (Redmond, WA) and CalPortland (Duwamish, WA) are vastly different, despite the close proximity of their mixing plants. As with the comparative analysis in Tables 6, 7, and 8, some of the variability here can be attributed to the different LCI sources for raw materials, transportation, and energy. While CalPortland utilizes a wide range of data sources, Cadman draws all of t heir assumptions from the Boustead (U.K.) LCA database. Above all, the most significant complication is perhaps the lack of transparency for the composition for each specification. Concrete mixes are typically defined by their compressive strength, and while each manufacturer achieves that strength through a proprietary mix of cement, aggregates, and water, not every manufacturer provided detailed composition breakdowns in their EPDs. The uncertainty of key ingredient proportions made it difficult to truly assess comparable concrete mixes to identify meaningful sources of variation.

Steel

Steel is defined as an alloy of iron and carbon which contains less than two percent of carbon, one percent of manganese and small quantities of silicon, sulphur, phosphorus and oxygen.[91] It is an important construction and engineering material which has many uses, including the construction of buildings. According to the World Steel Association, it is the most commonly used metal in the world and can be completely recycled without the loss of its quality.[92] As an essential infrastructure material for many airports, including Sea-Tac, steel has been used for several of its infrastructure projects such as airport terminal buildings, aircraft hangars, cargo buildings, baggage handling system structures, air traffic control towers, and passenger bridge structures.

There are three types of steel that are used specifically for the construction of buildings. These include mild steel, rebar steel and structural steel.[93] For the purposes of evaluating steel emission factors, this study will focus entirely on structural steel. Structural steel is defined as the category of steel shaped for use in construction projects.[94] It is produced in particular cross sections or shapes with a specified value of strength and amount of elemental carbon, which determines the hardness of the steel. The use of steel in the construction of buildings varies largely on the exact shape and size for the specific installation requirement in the building. The analysis further focuses on fabricated structural steel of different types of steel shapes for use in airport building construction.

Generally, the typical structural steel production process consists of two manufacturing methods: Basic Oxygen Furnace and Electric Arc Furnace. The processes are detailed below in relationship to their impact on overall GHG emissions.

1. Basic Oxygen Furnace (BOF): This process accounts for 66 percent of global steel production with 75 percent of all CO_2 emissions stemming from the processing of coke and coal in the initial iron making process. Coke is the byproduct material from heating coal used for iron and steel industry processes.[95] The average total emissions intensity from the BOF process is 2.3 tons CO_2 per ton of steel, almost all of which is generated from fossil fuels. This process is also four times more carbon intensive than the electric furnace process since it requires large amounts of heat and reducing agents.[96]

2. Electric Arc Furnace (EAF): This process accounts for 24 percent of global steel production with an emissions intensity rate of 0.4 tons CO_2 per ton of steel, again primarily generated from electricity.[97]

This material study will focus entirely on the emission factors of the EAF steelmaking method. The BOF steelmaking method remained outside of the research scope as it is a highly complex process and lacks significant data sources for variability research. In addition, approximately 75 percent of steel made in the U.S. uses the EAF method whereas only 25 percent is made using the BOF method.[98] Since the EAF is the most widely used production method in the U.S., data is more readily available.

Figure 6 below illustrates the potential GHG emission phases during the EAF steelmaking and fabrication process. This process expands the typical A1 to A3 life cycle stages to include raw material production, transport of raw materials, manufacturing of structural steel, transport to the fabrication shop, and finally the fabrication of the structural steel shapes. In stages A4 and A5, it is then transported to the construction site and erected.

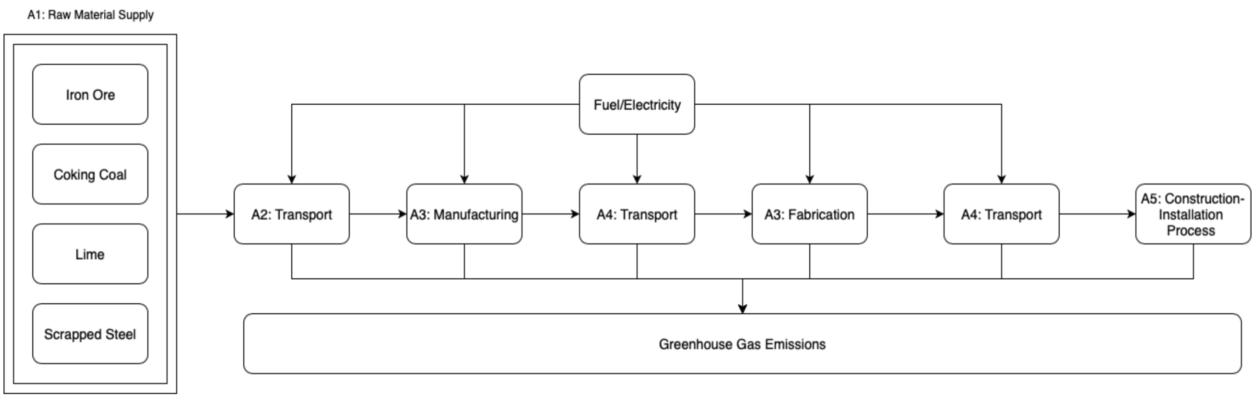


Figure 6: Typical Steel Process Map using an Electric Arc Furnace

Carbon Profile

Steel is a carbon and energy intensive material. In 2017, an average of 1.83 tons of CO_2 were emitted for every ton of steel produced.[99] The industry generates roughly between seven to nine percent of direct emissions from fossil fuel use. The greenhouse gas emissions from the production of steel are primarily caused by the combustion of fossil fuels, electrical energy use, and the use of lime and coal as raw materials.[100]

Sea-Tac Specifications

Steel plays an important role in airport construction as it allows for efficient, long-span structures that are well-suited for busy airports serving multitudes of travelers in addition to aircraft and cargo. Structural steel shapes used in construction at Sea-Tac Airport must comply with local building codes. The Seattle Building Code[101] specifies the design, fabrication and erection of structural steel elements in buildings to be in accordance to the AISC 360 specification.[102] In addition, the American Society for Testing and Materials (ASTM) outlines approved structural steel shapes and the general fabrication criteria of the AISC 360 specification.

State of Emissions Data Variability

As a primary structural and framing building material, steel has a list of published sustainability data which is verified by a number of third-party consultancies. Manufacturers such as Nucor Corporation, Arcelor Mittal, SSAB North America, Gerdau, and Steel Dynamics, Inc. have submitted their LCA data for the combined industry average EPDs. Those EPDs are prepared by industry consortiums such as AISC and ASTM and are verified and registered documents that offer transparent and standardized LCA calculations within the cradle-to-gate boundary.[103]

There are currently no published EPD reports for structural steel by individual mills located in Washington state. Nucor Corporation, with a steel mill in Seattle, does not have a published company-specific EPD report. Arcelor Mittal is the leading manufacturer of steel in the US, but its company specific EPDs are only for mills located in Europe and not for mills situated in the United States.[104] This report drew from all the aforementioned sources for analysis and conclusions following the EAF steelmaking process.

Carbon Intensity Life Cycle Phase Analysis

The life cycle analysis research for the Gerdau EPD of the fabricated structural steel processes as depicted in Table 10 below shows that the raw steel production stage, A1, is the most energy intensive component. In the EAF steel production stage, the scrap steel is melted at 3,000° F, requiring the greatest amount of nonrenewable energy resources. The Gerdau EPD further documented that approximately 15,100 MJ of nonrenewable energy resources are used for the A1 stage of the structural steel production while the nonrenewable energy resources used for the A2 transport and A3 fabrication stages were 276 MJ and 1,700 MJ, respectively.[105] The second most carbon intensive step in the structural steel production process is A3, or the fabrication of structural steel.[106] The fabrication of structural steel shapes includes sewing, cutting, drilling, reinforcing, assembling, welding and shaping for specific construction installations.[107] The least carbon intensive component in the structural steel production process involves stage A2, or the transportation of unformed steel to fabrication centers. However, the industry specific EPDs researched only include an approximate range of transportation distances from the manufacturing sites, making it difficult to ascertain the true impact of this stage.[108]

Product stage	A1. Unfabricated structural steel Manufacturing process	A2. Transportation to Fabrication shop	A3. Fabrication process
GWP (kg CO_2e)	1,120	19.3	116

Table 10: GWP for Product Stages A1-A3 for Structural Steel Produced at Gerdau's Midlothian Mill, TX

Outlining the Results

Generally, all reports, both from industry associations and individual manufacturers, limit the scope of LCA reporting to cradle-to-gate only. Therefore, the life cycle stages considered are A1: Raw Material Supply, A2: Transportation, and A3: Manufacturing and Fabrication. The LCAs for structural steel were reviewed to evaluate their data based on a functional unit of one metric ton of structural steel.

It is important to note that there is variability in defining the stages within the five EPDs which were analyzed for this material study. The three AISC EPDs and the Gerdau EPD define their life cycle stages as

A1: Raw Material Extraction and Manufacturing, A2: Transportation, and A3: Fabrication. This is in contrast to the Commercial Metals Company EPD which defines the life cycle stages as aligned with the scope of this project, specifically that A1 is only referring to the raw material supply and extraction processes, not any manufacturing processes.

From the start, this clearly indicates the variability present in how EPDs from different manufacturers define each life cycle. Therefore, in order to maintain consistency with the scope of this overall project and to ensure comparability with the other two focus materials, this material study continued with the description of life cycle stages A1 through A3 as defined by the Commercial Metals Company EPD. To further uncover and assess the variations in the data reported in these EPDs, fabricated structural steel of different shapes from different manufacturers were evaluated for comparative assumptions.

Table 11 on the following page catalogs the sources that manufacturers and industry consortiums cited to calculate the LCI impacts of the energy use during transportation, manufacturing and fabrication of the production of fabricated structural steel. All EPDs selected for this analysis are from U.S. producers, including two from Texas (Gerdau and Commercial Metals Company) and three industry average EPD reports.[109] All five EPDs use the same process map as described in Figure 6 for the comparison and variability analysis.

Producer	Gerdau (Fabricated structural steel)	Commercial Metals Company (Fabricated heavy structural shapes)	AISC (Fabricated hollow structural steel sections)	AISC (Fabricated hot rolled structural sections)	AISC (Fabricated structural plates)
GWP (A1-A3) (kg CO_2e)	1,255	1,360	2,390	1,160	1,470
Unformed Structural Steel Manufacturing Process	Energy (MJ) - 2014 GaBi 6, Gerdau, Region used: North America Primary and secondary data is available for renewable and nonrenewable energy	2014 GaBi 6 database (uses other geographical region as proxies) Primary data by CMC.	2016 GaBi database, (uses other geographical region as proxies)	2016 GaBi database, (uses other geographical region as proxies)	2016 GaBi database, (uses other geographical region as proxies)
Transportation to Fabrication Center	Energy (MJ) – 2014 GaBi 6, Gerdau, Region used: North America Primary data is available for nonrenewable energy used during the transportation process.	Transportation (Miles) 2014 GaBi 6 database (uses other geographical region as proxies) Primary data by CMC. Primary data is available for the distance of the transportation of steel to CMC's fabrication Centers.	2016 GaBi database, (uses other geographical region as proxies)	2016 GaBi database, (uses other geographical region as proxies)	2016 GaBi database, (uses other geographical region as proxies)
Fabrication Process	Energy (MJ) – 2014 GaBi 6, AISC, Region used: USA Primary and secondary data is available for renewable and nonrenewable energy. Data is aggregated from 288 fabrication centers in the US.	2014 GaBi 6 database (uses other geographical region as proxies) and primary data by CMC.	2016 GaBi database, (uses other geographical region as proxies)	2016 GaBi database, (uses other geographical region as proxies)	2016 GaBi database, (uses other geographical region as proxies)

Table 11: Transportation, Manufacturing and Fabrication LCI Sources for 5 steel LCA Reports

All five EPDs provide the same assumption about the fabrication process, which stated that the data does not differentiate between the fabrication of different shapes of structural steel including structural sections, plates, and hollow structural and non-structural sections as the combined LCI data of the 288 fabrication centers has been used for these EPDs. The Commercial Metals Company EPD provided the raw material transportation assumption which stated that the scraped steel was sourced from within 500 miles of the mill. No further assumptions or LCI input data were documented for the transportation of steel to fabrication shops by any EPD.

As indicated in Table 11, there is a range in GWP output for each EPD as seen by different producers and industry consortiums. Despite the study consistently using the same databases for the LCA sources, variability is present in the GWP values for the five EPDs. The two producers, Gerdau and Commercial Metal Company, used the 2014 version of the GaBi database while the three AISC EPDs used the 2016 version of the GaBi database, noting the time sensitivity of EF data. Furthermore, the Gerdau LCI specifically stated that their LCI sources were specific to the North American region while the Commercial Metal Company and the three AISC EPDs stated that they used global or European proxy data when country-specific data was unavailable. The use of data from different geographical regions creates another source of variability and uncertainty in the provide EF data. Similar to the geographical variability, variability was also present in terms of the lack of consistency with regard to technology used in each EPD. The life cycle inventories of the five EPDs again used proxy data when specific technology data was unavailable.

Uncertainty in the data increased further as the AISC EPD stated that the hot-rolled coil data that formed the basis of the hollow structural steel section production represented a mixture of both EAF and BOF technologies which is inconsistent with the process methodologies in the other EPDs.[110] This could be due to variability of life cycle processes or the lack of knowledge of these stages. The remaining EPDs studied only used EAF technology data which explains the higher GWP value of the AISC EPD compared to the other GWP values from Table 9.

Table 12 below depicts another point of variability as the density of steel for each of the five EPDs is different. The structural steel density used for the functional unit for the AISC EPDs was consistently 7800 kilograms per cubic meter, but the density values for the Gerdau EPD and the Commercial Metals Company EPD was 7850 kilograms per cubic meter and 7833 kilograms per cubic meter, respectively. This presented another difficulty during data analysis as the density value for structural steel was inconsistent and therefore presented higher variability when conducting this study. In addition, the Gerdau EPD stated that the approximate content of structural steel varies slightly from batch to batch. This means that not only does the density per material content for structural steel vary for different EPDs but there is material variability present within each manufacturing plant as well, further discounting the accuracy of the data.

Producer	Gerdau (Fabricated structural steel)	Commercial Metals Company (Fabricated heavy structural shapes)	AISC (Fabricated hollow structural steel sections)	AISC (Fabricated hot rolled structural sections)	AISC (Fabricated structural plates)
Density (kg/m³)	7,850	7,833	7,800	7,800	7,800

Table 12: Approximate Density Values of Fabricated Structural Steel for 5 Steel LCA Reports

Although the EPDs documented their source databases, they did not list their emissions data sources for multiple energy inputs and specific transportation emissions data. The EPDs did not document the transportation distance for the inbound transportation and only the Commercial Metal Company specific EPD documented the average transportation distance to the fabrication centers from third-party steel mills. Further, only the Gerdau specific EPD provided individual GWP values for each product stage. There is a lack of transparency for each EPD as the specific life cycle inventory input values are not properly listed and sourced for each life cycle stage. Furthermore, as the LCA sources are inconsistent and used proxy data, possibly with different assumptions, it indicates that there is a range of variability and lack of comparability for the current LCA data of structural steel.

CONCLUSIONS AND RECOMMENDATIONS

Summary of Results and Conclusions

Following the research and analysis of the three focus materials and their respective EF data, the Capstone team has summarized the results and findings below in Table 13 to illustrate the full detailed uses and alternatives of each material as well as the most carbon intensive life cycle stages.

	Asphalt	Concrete	Steel
Uses at Sea-Tac	Roads, runway surface layer, runway repairs	Building structure, runways, sidewalks	Building structure
Researched Emission Factor Range	25.10-64.40 kilograms CO2e/ton	285.51-443.00 kilograms CO2e/m^3	1160.00-2390.00 kilograms CO2e/m^3
Factors Influencing Variability	Temperature of manufacturing processes and amount of recycled content	Cement content	Pre-fabricated steel manufacturing process and energy source used
Design Alternatives	Implement warm mix asphalts	Maximize structural efficiency to use less	Maximize structural efficiency to use less
Material Alternatives	Utilize higher recycled asphalt content or lower temperature heating methods	Specify low-carbon concrete mixes with fly ash, slag, calcined clays or lower-strength concrete where feasible	Utilize higher recycled steel content

Table 13: Material Results and Variability Summary

Given the high ranges of variability and current uncertainty of information as well as the lack of consistent standardization across industries, the Capstone team has concluded that the researched data is not robust or reliable enough to reasonably compare EFs, and therefore should not be used as a primary source to inform decisions for capital projects at the Seattle-Tacoma International Airport at this point. The Capstone team believes that the collection and analysis of the EPD data in this report is indicative of the current state of embedded carbon data. Specifically, there are currently too many uncontrollable variables and biases in both primary and secondary data that could likely lead to a misinterpretation of results when considering the impacts of embedded carbon. Overall, due to the broad uncertainty in the input data as well as the inherent variabilities in the EFs, the Port of Seattle should not utilize the current data to measure their embedded carbon footprint. Until further advancements are made to standardize calculation methodologies and life cycle assessments, there is no clear way to gauge the accuracy or truth behind any given emission factor.

Nonetheless, the Capstone team has outlined both internal and external first steps that the Port of Seattle can take to begin to limit that variability and uncertainty through the standardization of EPDs and stakeholder engagement. According to a study by Ivanov, et al.,[111] there are thirty main drivers to uncertainty when applying a life cycle assessment to infrastructure projects. The Capstone team has utilized these same thirty variables to construct the below Table 14 which illustrates whether the source of variation is known or unknown to affect the three studied construction materials and respective EPDs that were analyzed in the report. Further, the highlighted rows indicate the sources of variation and uncertainty that the Port of Seattle could reduce through the enactment of the proposed EPD standardization and stakeholder engagement.

Different Sources of Variability and Uncertainty	Asphalt		Concrete		Steel	
	Known	Unknown	Known	Unknown	Known	Unknown
Variation/Uncertainties related to the LCA model used and the boundary conditions	x		x		x	
System boundaries, not covering all relecant processes or parameters	x		x		x	
Wrong boundaries, only part of the process is included	x		x		x	
Simplifications of the system and cut-off criteria		x	x		x	
Choice of methods and other technical informaiton	x		x		x	
Allocation assumptions and methods	x		x		x	
Choice of functional unit	x			x	x	
Choice of characterization factors	x		x		x	
Choice of what to analyze in the study	x			x		x
Interpretation of the results		x	x		x	
Normalization of the results (weighting, assessment of environmental impacts)	x		x			x
Variation/Uncertainties related to the input data in the model	x		x		x	
General data quality (specific LCA from an object or general database data)	x		x		x	
Wrong input data		x		x		x
Physical variation in a parameter		x	x		x	
Statistical variation in a parameter	x		x		x	
Measurement uncertainties of parameter data	x		x		x	
Rounding errors in input data obtained from other LCA-results		x	x		x	
Differing manufacturing processes	x		x		x	
Different design of a product with the same function	x		x		x	
Age, operation and maintenance aspects of the studied object		x		x	x	
Geographical placement of project site	x		x		x	
Future or existing infrastructure i.e. is the object already built so data can be available		x		x		x
Assumed service life for construction products and processes	x	x	x		x	
Time relevance, when was the data collected	x		x		x	
Variations/Uncertainties related to actual mistakes or misunderstanding of LCA concepts	x			x	x	
Intential errors - fraud		x		x		x
Calculation errors - random mistakes		x		x		x
Calculation errors - wrong assumptions, lack of knowledge		x		x		x
Misconceptions when collecting data or choosing the appropriate model		x		x		x

Table 14: Sources of Variability and Uncertainty in Infrastructure Project

Recommendations

To address the aforementioned areas of variability and uncertainty, the Capstone team has identified three main recommendations that will allow the Port of Seattle to begin to tackle the data quality and availability issues surrounding EF calculations. These recommended actions will affect both the internal and external policies, processes and people at the Port of Seattle and can be summarized as follows:

1. Policy: commission standardized EPDs
2. Process: create internal data quality rating assessment
3. People: utilize internal and external stakeholder engagement

Commission Standardized EPDs

To influence policy, the Port of Seattle could leverage its purchasing power to encourage manufacturers to provide higher quality LCA data for approval. This approach of sending demand signals to manufacturers from entities with significant building and infrastructure holdings is prevalent in both the public and private sectors. For instance, Google has established a robust safe materials standard for manufacturers to gain product approval for installation in Google's offices around the world.[112] The state of California recently passed the Buy Clean California Act, which established maximum acceptable levels of embedded carbon for a select group of materials for procurement by the state and requires bidders to submit product EPDs in their contractor proposals.[113] This was a momentous legislative endeavor that has influenced similar policy in other states, including Washington (HB 2412) and Oregon (HB 3161).[114]

The Port can emulate this model to influence better documentation of products from manufacturers. Capital project bid contracts can require EPDs for all materials and products used for a specific project. Concurrently, product specifications can be qualified to define an acceptable format for EPDs that manufacturers must follow in order to meet the Port's approval. In particular, it should require manufacturers to submit EPDs that have been produced and reviewed by a select group of Port-approved third-party verifiers to ensure that identical methodologies are used to assess the data, and for the information to be presented in a consistent layout. As illustrated in the material studies, it was much easier and more reliable to compare EPDs from the same verifier. Mimicking this should streamline the information that decision makers must process to better understand emission potentials and compare product proposals. Similar to the approaches by California and Washington State, the Port can pilot this endeavor by defining a list of eligible materials such as concrete, steel, and asphalt to comply with the enhanced EPD requirement.

Create Internal Data Rating and Quality Assessment System for EPDs

To improve processes, the Capstone team recommends that a standardized data rating and quality assessment system should be incorporated by the Port of Seattle to further ensure consistency in the EPD process of tracking embedded carbon. This action will not only support the commissioning of standardized EPDs but will improve the state and validity of data that the Port of Seattle is using. Further, data and quality assessment ratings must be comprehensively developed for each of the life cycle stages, placing priority on stages A1 through A3.

Tables 15, 16, and 17 below provide parameters for how data quality and assessment rating systems can be developed for each stage of the life cycle process in an EPD. The data from these tables was pulled from the CalPortland ready-mixed concrete EPD as previously referenced in this report.[115]

Materials	LCI Data Source	Geography	Year	Data Quality Assessment
General use Cement	Cement Association of Canada EPD of General Use Cement, 2016	Canada	2016	• *Technology*: good Process models Canadian industry average Portland Cement production • *Time*: good Data is within two years • *Completeness*: good • *Reliability*: very good third-party verified EPD
General Use Limestone Cement	Cement Association of Canada EPD of General Use Limestone Cement, 2016	Canada	2016	• *Technology*: good Process models Canadian industry average Portland cement production • *Time*: good Data is within two years • *Geography*: very good • *Completeness*: good • Reliability: very good, third-party verified EPD

Table 15: A1 Raw Material Supply Parameter Rating

Process	LCI data source	Geography	Year	Data Quality Assessment
Rail, ocean, freighter and barge (t*km)	USLCI- rail transport, diesel powered; ocean freighter, average fuel mix; barge, average fuel mix	USA	2008	• *Technology*: very good Processes represents U.S average transportation profiles. • *Time*: fair • *Geography*: good • *Completeness*: good (all data place holders filled) Data is representative of U.S conditions. • *Reliability*: good • Data is from USLCI data base

Table 16: A2 Transportation Parameter Rating

Process	LCI data	Geography	Year	Data Quality Assessment
Electricity (kWh)	CRMCA purchased electricity grid mix Electricity, medium voltage, at grid, (CA- ##) (Ecoinvent v3.01)	US	2008/2015	• *Technology*: very good • *Time*: fair/good Electricity production data is within ten years. Regional production breakdown from 2015. • *Geography*: very good • *Completeness*: good (all data place holders filled) Data representative of Canadian production • *Reliability*: good Ecoinvent has verified the data

Table 17: A3 Manufacturing Parameter Rating

The Capstone team recommends that the Port of Seattle should utilize these five listed parameters as a preliminary foundation in creating the data rating and quality assessment as they comprehensively address the main factors that can contribute to data variability and uncertainty

In addition to including these parameters, it is helpful to incorporate a letter rating system which will help in the documentation and assessment of LCA data quality for Sea-Tac. Table 18 listed below helps provide a description and category for each data quality rating letter.[116]

Test Data Quality Rating Letter	Description
A	Tests are performed by a sound methodology and are reported in enough detail for adequate validation.
B	Test are performed by a generally sound methodology but lacking enough detail for adequate validation.
C	Tests are based on an unproven or new methodology or are lacking a significant amount of background information.
D	Tests are based on a generally unaccepted method, but the method may provide an order-of-magnitude value for the source.

Table 18: Data Quality Letter Rating

Leverage Internal and External Stakeholder Engagement

Finally, the Port of Seattle must address and engage people to enact these recommendations. The success of the standardized EPDs and data rating system will be directly influenced by the amount of stakeholder support that these ideas can gather. First and foremost, the Port of Seattle must communicate to its internal stakeholders the importance and urgency of tracking embedded carbon.

This can be achieved by highlighting the necessity of reducing variability to increase comparability and by providing actionable and comprehensive information to encourage the EPD and data quality rating proposals. Overall, in order to generate internal buy-in for this proposal, the Port must ensure that they speak to their inner stakeholders' interests and also actively engage with them in the decision-making process. For example, the Port needs to clearly communicate the results of this report's material analysis, specifically the life cycle stages with the highest carbon intensity, with the capital project management team and outline new procurement and specification expectations. Active engagement with internal stakeholders such as this will ensure that the questions and concerns raised by these stakeholders are taken into consideration during the decision-making processes and that these recommendations are implemented in a short period of time.

The Port of Seattle also has a responsibility to outwardly communicate these ideas with external stakeholders in order to truly influence new action. While motivating change across industries will require partnership and support from other industry leaders and organizations, the Port of Seattle should first utilize their existing leverage to influence standardization at a local and state level. As seen in California, Washington and Oregon, new policies have either established or started the conversation on maximum levels of embedded carbon in materials that require EPDs during the bidding process. The Port of Seattle should first partner with local and state leaders to further this type of legislation. For example, the Port of Seattle can first work with the Seattle and King County governments to communicate their shared interests on embedded carbon and how the collection of quality data is key to successfully minimizing it. In receiving approval from them, they could band together to commission regional-specific LCA studies that could provide data and results that each party could trust. In partnering with similar businesses and organizations, the potential impacts and reach of these recommendations would go farther, increasing the probability of successful implementation.

Other external partner collaborations include working with industry-leading certification organizations, such as the US Green Building Council, to further advance the inclusion of embedded carbon in the credit/point system that goes into receiving a certification. Finally, the Port of Seattle can communicate with a coalition of other highly sustainable airports. In the US, this includes Boston Logan International Airport and Denver International Airport.[117] Creating a unified force on the topic of embedded carbon will only aid in further influencing policy and action.

Besides actively engaging with external stakeholders, the Port of Seattle can learn from and perfect their processes even further by researching other case studies of capital projects working with embedded carbon. There are a number of informative reports on how to integrate embedded carbon measurements into capital project planning as well as studies on how to limit process variability and data uncertainty. In concluding this report, the Capstone team has prepared a compiled list of resources to provide a starting point on such research.

APPENDICES

Appendices

Appendix A: Additional Graphs

Asphalt Summary Table of EPD Data

Source	Emerald Eco-Label	Emerald Eco-Label	Emerald Eco-Label	Emerald Eco-Label	Emerald Eco-Label
State/country	Jamestown, CA (U.S.)	Jamestown, CA (U.S.)	Jamestown, CA (U.S.)	North Venice, FL (U.S.)	Waukesha, WI (U.S.)
Company	George Reed, Inc. is an asphalt mixture producer. Table Mountain Hot Plant	George Reed, Inc. is an asphalt mixture producer. Table Mountain Hot Plant	George Reed, Inc. is an asphalt mixture producer. Table Mountain Hot Plant	Ajax Paving Industries of Florida, LLC - North Venice - Plant 1; One Ajax Drive	Payne and Dolan, Inc. Control 20 Waukesha Plant N6 W23034 Bluemound Rd
Product Description	This EPD reports the impacts for 2018-TM-004D-VSS-64-10-R0 - Hot Mix Asphalt Mixture	This EPD reports the impacts for 2018-TM-004D-VSS-64-10-R15 - Hot Mix Asphalt Mixture	This EPD reports the impacts for 2018-TM-004D-VSS-64-10-R25 - Hot Mix Asphalt Mixture	This EPD reports the impacts for S-1R, a Dense Graded asphalt mixture - Hot Mix Asphalt Mixture	This EPD reports the impacts for 801418 - Hot Mix Asphalt Mixture
Product Mix	Dense-Graded Superpave 3/4"NMAS Virgin Mix asphalt mixture	Dense Graded Superpave 3/4" NMAS asphalt mixture	Dense-Graded Superpave 3/4" NMAS 25% RAP asphalt mixture	S-1R, an asphalt mix for Dense Graded	Dense-Graded Superpave asphalt mixture
Manufacturing temperature range (C/F)	280.0 to 325.0 °F	280.0 to 325.0 °F	280.0 to 325.0 °F	300.0 to 325.0 °F	280.0 to 320.0 °F
Manufacturing process	Not Provided	Not Provided	Not Provided	Not Provided	Not Provided
Transport Details	Not Provided	Not Provided	Not Provided	Not Provided	Not Provided
Installation and Construction Details	Not Provided	Not Provided	Not Provided	Not Provided	Not Provided
Declared Unit	1 short ton of an asphalt mixture (UNSPSC Code 30111509: Asphalt Based Concrete) as defined as "a plant-produced composite material of aggregates, asphalt binder, and other materials."	1 short ton of an asphalt mixture (UNSPSC Code 30111509: Asphalt Based Concrete) as defined as "a plant-produced composite material of aggregates, asphalt binder, and other materials."	1 short ton of an asphalt mixture (UNSPSC Code 30111509: Asphalt Based Concrete) as defined as "a plant-produced composite material of aggregates, asphalt binder, and other materials."	1 short ton of an asphalt mixture (UNSPSC Code 30111509: Asphalt Based Concrete) as defined as "a plant-produced composite material of aggregates, asphalt binder, and other materials."	1 short ton of an asphalt mixture (UNSPSC Code 30111509: Asphalt Based Concrete) as defined as "a plant-produced composite material of aggregates, asphalt binder, and other materials."
System Boundaries	Cradle-to-gate LCA for asphalt mixtures. This EPD covers the raw material supply, transport, and production life cycle phases (A1-A3). It does not include construction (placement and compaction), use, maintenance, rehabilitation, or the end-of-life life cycle phases (phases A4, A5, B1-7, and C1-4).	Cradle-to-gate LCA for asphalt mixtures. This EPD covers the raw material supply, transport, and production life cycle phases (A1-A3). It does not include construction (placement and compaction), use, maintenance, rehabilitation, or the end-of-life life cycle phases (phases A4, A5, B1-7, and C1-4).	Cradle-to-gate LCA for asphalt mixtures. This EPD covers the raw material supply, transport, and production life cycle phases (A1-A3). It does not include construction (placement and compaction), use, maintenance, rehabilitation, or the end-of-life life cycle phases (phases A4, A5, B1-7, and C1-4).	Cradle-to-gate LCA for asphalt mixtures. This EPD covers the raw material supply, transport, and production life cycle phases (A1-A3). It does not include construction (placement and compaction), use, maintenance, rehabilitation, or the end-of-life life cycle phases (phases A4, A5, B1-7, and C1-4).	Cradle-to-gate LCA for asphalt mixtures. This EPD covers the raw material supply, transport, and production life cycle phases (A1-A3). It does not include construction (placement and compaction), use, maintenance, rehabilitation, or the end-of-life life cycle phases (phases A4, A5, B1-7, and C1-4).
Materials (A1) GWP (kg CO2)	33.70	30.40	26.00	18.70	20.40
Transport (A2): GWP (kg CO2)	2.35	3.59	4.67	57.00	2.75
Production (A3): GWP (kg CO2)	2.70	2.70	2.70	15.80	20.90
Merged (A1)-(A2)-(A3): GWP (kg CO2)	Not Provided	Not Provided	Not Provided	Not Provided	Not Provided
Transport to Site (A4): GWP (kg CO2)	out of scope	out of scope	out of scope	out of scope	out of scope
Installation & Construction (A5): GWP (kg CO2)	out of scope	out of scope	out of scope	out of scope	out of scope
Program Operator	National Asphalt Pavement Association	National Asphalt Pavement Association	National Asphalt Pavement Association	National Asphalt Pavement Association	National Asphalt Pavement Association
LCA and EPD tool developer	Trisight	Trisight	Trisight	Trisight	Trisight

Source	NCC Green Asphalt2	NCC Green Asphalt2	BRE	**Eco-Asphalt** (Environmental impact across all categories varies less than 5% between the asphalt plants.)	**Eco-Asphalt** (Environmental impact across all categories varies less than 5% between the asphalt plants.)
State/country	Arlanda - Sweden	Arlanda - Sweden	Portland House Bickenhill Lane Solihull B37 7BQ	Sweden (different locations)	Sweden (different locations)
Company	Arlanda asphalt plant	Arlanda asphalt plant	Tarmac	The product ECO-Asfalt® was produced at thirteen of Peab Asfalt's stationary asphalt plants in Sweden in 2017	The product ECO-Asfalt® was produced at thirteen of Peab Asfalt's stationary asphalt plants in Sweden in 2017
Product Description	Asphalt type ABb 22 50/70 - Warm Mix Asphalt Mixture	Asphalt type ABS 16 70/100 - Warm Mix Asphalt Mixture	ULTILOW asphalt - Low Temperature Asphalt Mixture	ECO-Asfalt® Specific type of asphalt AG 16 4,8% - Hot Mix Asphalt Mixture	ECO-Asfalt® Specific type of asphalt AG 16 4,8% inluding reused asphalt AG 16 10% RAP - Hot Mix Asphalt Mixture
Product Mix	Mineral rock aggregate 93,4%-95,4% - Bitumen 4,4%-6,2% Water 0,132%-0,186% - Amine 0,026%-0,037% - Fiber pellets 0-0,30%	Mineral rock aggregate 93,4%-95,4% - Bitumen 4,4%-6,2% Water 0,132%-0,186% - Amine 0,026%-0,037% - Fiber pellets 0-0,30%	Aggregate 79.2% , bitumen/Polymer Modified Bitumen (PMB) 4.1% , Additives/fillers 1.7%, RAP 15.0%	Aggregate 95,20 - Bitumen 4,80 - Adhesion material 3,0E-04	Aggregate 95,20 - Bitumen 4,80 - Adhesion material 3,0E-04 - inluding reused asphalt AG 16 10% RAP
Manufacturing temperature range (C/F)	The aggregates are first dried and heated to a temperature of 120°C	The aggregates are first dried and heated to a temperature of 120°C	ULTILOW asphalts are supplied typically 40°C lower than a hot equivalent asphalt	Not Provided	Not Provided
Manufacturing process	The asphalt is produced with the NCC Green Asphalt2 method. The EPD provides 1-page of information about the manufacturing process. For electricity used in the production process (module A3), specific EPD data for green electricity from Vattenfall (100% Water power with EPD) is applied. The emission factor for this electricity is 2,8 g CO2e/MJ.ie. lower production temperature, an increased amount of recycled asphalt. The foamed binder mix is blended into the aggregates and recycled asphalt. Different types of additives such as cement or amine, as well as wax and cellulose fibers might be added for specific desired abilities. Amine is used instead of cement in all of the specific asphalt types declared in this EPD.	The asphalt is produced with the NCC Green Asphalt2 method. The EPD provides 1-page of information about the manufacturing process. For electricity used in the production process (module A3), specific EPD data for green electricity from Vattenfall (100% Water power with EPD) is applied. The emission factor for this electricity is 2,8 g CO2e/MJ.ie. lower production temperature, an increased amount of recycled asphalt. The foamed binder mix is blended into the aggregates and recycled asphalt. Different types of additives such as cement or amine, as well as wax and cellulose fibers might be added for specific desired abilities. Amine is used instead of cement in all of the specific asphalt types declared in this EPD.	In the case of warm mix asphalt, warm mix additive is used to allow for a reduction in the temperature at which the asphalt is supplied. Electricity and fuels are used in the manufacture of asphalt, primarily for heating the asphalt mixture (or maintaining temperature) and mixing/processing constituent materials.	For electricity used in the production process (module A3), data for green electricity (hydro power) is applied, using data from EPD (Vattenfall Vattenkraft AB, 2015).	For electricity used in the production process (module A3), data for green electricity (hydro power) is applied, using data from EPD (Vattenfall Vattenkraft AB, 2015).
Transport Details	A general dataset is used for transport of materials.	A general dataset is used for transport of materials.	Vehicle Type: Lorry Fuel; Consumption (L/km): 0.471; Distance (km): 31.2	Diesel was used as transport fuel, using generic data from the GaBi database. Data includes storage of bitumen at the production site. Site specific data was also used for modelling of production and transport of aggregate	Diesel was used as transport fuel, using generic data from the GaBi database. Data includes storage of bitumen at the production site. Site specific data was also used for modelling of production and transport of aggregate
Installation and Construction Details	Not Provided	Not Provided	Energy Use On-site fuel consumption litres/t 1.78; Waste materials from installation wastage 1%	Not Provided	Not Provided
Declared Unit	1 ton (1000 kg) of specific asphalt types	1 ton (1000 kg) of specific asphalt types	1 tonne (t) of ULTILOW low temperature asphalt.	1 ton (1000 kg) of asphalt at production plant gate. The asphalt type covered in this EPD is AG - Asphalt Concrete Base Courses (hot-mix base)	1 ton (1000 kg) of asphalt at production plant gate. The asphalt type covered in this EPD is AG - Asphalt Concrete Base Courses (hot-mix base)
System Boundaries	The EPD covers the cradle-to-gate stage and the future recycling potential. The geographical scope is the area approximately 100 km around the Arlanda asphalt plant. All foreground data are site specific.	The EPD covers the cradle-to-gate stage and the future recycling potential. The geographical scope is the area approximately 100 km around the Arlanda asphalt plant. All foreground data are site specific.	This is a cradle to gate with all options declared EPD covering all modules from A1 to C4 and includes module D	The LCA covers the cradle-to gate stages, i.e. extraction and transports of raw materials (upstream modules A1-A2) and manufacturing to production plant gate (core module A3)	The LCA covers the cradle-to gate stages, i.e. extraction and transports of raw materials (upstream modules A1-A2) and manufacturing to production plant gate (core module A3)
Materials (A1) GWP (kg CO2)	Not Provided	Not Provided	Not Provided	Not Provided	Not Provided
Transport (A2): GWP (kg CO2)	Not Provided	Not Provided	Not Provided	Not Provided	Not Provided
Production (A3): GWP (kg CO2)	Not Provided	Not Provided	Not Provided	Not Provided	Not Provided
Merged (A1)-(A2)-(A3): GWP (kg CO2)	31.40	49.00	64.40	26.20	25.10
Transport to Site (A4): GWP (kg CO2)	out of scope	out of scope	6.87	out of scope	out of scope
Installation & Construction (A5): GWP (kg CO2)	out of scope	out of scope	6.04	out of scope	out of scope
Program Operator	International EPD® System	International EPD® System	BRE Global, Watford, Herts, WD25 9XX, United Kingdom	The International EPD® System	The International EPD® System
LCA and EPD tool developer	NCC Industry AB	NCC Industry AB	LCA Consultant Verier Alex Hardwick thinkstep Electric Works, Sheffield Digital Ecoinvent (2013) Weidema - GABI ts (2014) thinkstep AG	The PCR Construction products and construction services 2012 v.2.2 (EPD International, 2012) is the basis for the calculation of the life cycle assessment (LCA) from cradle to gate, modelled in GaBi	The PCR Construction products and construction services 2012 v.2.2 (EPD International, 2012) is the basis for the calculation of the life cycle assessment (LCA) from cradle to gate, modelled in GaBi

Appendix B: Regional Manufacturers of Project Materials

Asphalt

Washington Asphalt Pavement Association, or WAPA's, mission is to promote relationships, communication and understanding throughout the HMA paving industry in Washington state. The association provides a current list of their regular members online who are key partners, persons, firms or corporations who own and/or operate Hot Mix Asphalt production facilities within the State of Washington. There are currently 28 total regular members listed:[118]

- Cadman, Inc.
- Central WA Asphalt
- Columbia Asphalt & Ready-Mix – A CRH Company
- Granite Construction – Puget Sound Region
- Granite Construction Company – Eastern Washington Region
- ICON Materials – A CRH Company
- Inland Asphalt Paving Co. – A CRH Company
- Lakeside Industries – Corporate Headquarters
- Lakeside Industries-Aberdeen/Centralia Division
- Lakeside Industries-Anacortes Division
- Lakeside Industries-Greater Seattle/Eastside Division
- Lakeside Industries-Kent Division
- Lakeside Industries-Lacey Division
- Lakeside Industries-Longview Division
- Lakeside Industries-Monroe Division
- Lakeside Industries-Olympic Peninsula Division (Port Angeles, Port Ludlow/Bremerton)
- Lakeside Industries-Vancouver Division
- Miles Resources

- Naselle Rock & Asphalt
- Poe Asphalt Paving, Inc.
- Poe Asphalt Paving, Inc. – Pullman
- Poe Asphalt Paving, Inc.-Post Falls
- Puget Paving & Construction, Inc.
- Pyramid Materials
- Shamrock Paving Inc.
- Tucci & Sons, Inc.
- Watson Asphalt Paving Company, Inc.
- Whatcom Builders

They also count on Associate members who are persons, firms or corporations who don't produce or supply the asphalt as a product but place asphalt mixes. Associate members are also listed on WAPA's website.[119]

Concrete

Concrete is created by mixing water with Portland cement and aggregates. Producers for both those materials and mixes range from small firms to large conglomerates. In major metropolitan areas with significant construction activity, large firms with vertically integrated operations generally have greater influence in controlling supply for the concrete industry. The Seattle and greater Puget Sound market, which has seen tremendous growth in construction in recent years[120], is serviced primarily by two major suppliers: CalPortland and Cadman Inc.

CalPortland

CalPortland is a large producer and supplier of concrete related products that mainly serve the western United States. The firm has operations in cement and aggregate production, as well as concrete mixing, precast concrete, and asphalt. CalPortland has sixteen concrete ready-mix plants in the state of Washington, with ten located around Seattle and Tacoma. In addition, the company has one cement plant terminal in Seattle and three aggregate yards nearby. CalPortland also has service operations that deliver material to construction sites.[121]

Cadman Inc.

Cadman Inc. is a supplier of ready-mix concrete, aggregates, and asphalt that services the major markets in the Pacific Northwest, including Vancouver B.C. The company has numerous aggregate and ready-mix plants in Seattle, Portland, and Vancouver. In addition to its plant locations, Cadman operates a retail distribution center that carries general building products from different vendors and provides delivery services to project sites.[122]

Steel

The United States steel industry includes steel manufacturers, suppliers, and fabricators who produce and fabricate various shapes of structural steel sections. The U.S. steel industry is a world leader in the use of recycled steel.[123] The Seattle and Tacoma areas specifically are serviced by two major steel manufacturers.

Nucor Steel Seattle Inc.

Nucor Steel Corporation is one of the largest steel producers of the United States, headquartered in Charlotte, North Carolina. Nucor Corporation and its subsidiaries operate as a “mini-mill steelmaker” where electric arc furnaces melt scraped steel to produce structural steel. Nucor has operations throughout the U.S. and is one of the largest recyclers of steel in the country. Nucor Steel Seattle, Inc. was founded in 1904 and produces various types of structural steel shapes including angles, beams, channels, etc.[124]

SeaTac Steel Mill and Recycling Services

SeaTac Steel Mill and Recycling Services is a subsidiary of the Edw. C. Levy Co. of Detroit, MI and operates a mini-mill which processes steel scrap. It is located in West Seattle and also provides slag processing and debris handling services.[125]

Appendix C: Evaluation of EPD Third Party Verifiers

Asphalt

Typically, an EPD development process adheres to various international standards such as the leading ISO 14025 standard. ISO 14025 is used by NAPA to define EPDs under its Emerald Eco-label EPD program. The goal of the Emerald Eco-label EPD program is to communicate the environmental impacts of asphalt using Life Cycle Assessment (LCA). The process used to develop an EPD ensures consistent data collection, analysis and reporting requirements, all supported by third party verification. This ensures the reliability of the information communicated through an EPD. Currently, NAPA is the chief source of EPD data cited in various academic and commercial studies involving asphalt LCAs.

All data and declarations produced by NAPA are independently verified in accordance with ISO 14044, ISO 14025, and WAP Sustainability Consulting. Product Category Rules are confirmed by the PCR Review Panel.

WAP Sustainability Consulting

WAP consulting is a privately-owned and managed service, that work with companies lacking an internal sustainability department, or serve as support to the in-house sustainability team. They work with clients to complete LCA services using GaBi, SimaPro or OpenLCA softwares.

The Right Environment Ltd. Co. (PCR Review Panel)

The Right Environment Ltd. Company is a member of the Sustainable Pavement Program Consulting Team and has developed guidance documents for the pavement industry and state agencies on how to advance sustainability in pavement design and operations. They have been involved in publishing the U.S. Department of Transportation's Federal Highway Authority's FHWA Pavement Life Cycle Assessment Framework and are currently developing an LCA tool for pavement design in collaboration with UC-Davis, University of Illinois at Urbana–Champaign and Applied Pavement Technology, Inc. (APTech). In addition, The Right Environment is creating a Pavement LCA Background Database Roadmap and PCR Guidance with Michigan Tech and the Federal LCA Commons.

Concrete

Concrete and cement research have relied primarily on academic literature and common private company EPDs. In order to confirm there is no bias or interest conflicts, those EPDs were verified by three independent verifiers; the Athena Sustainable Materials Institute (ASMI), Eco Form, and Sustainable Research Group (SRG). Summarized below is an overview of each verifier as described on their current respective websites.

Athena Sustainable Materials Institute (ASMI)

ASMI's reputation as a credible, objective organization is built on its science-based, transparent collaboration and clear, robust information. It ensures claims are supported by facts to achieve verification for the highest sustainability objectives. The construction sector and its product suppliers are moving rapidly towards life cycle assessment (LCA)—the Institute was formed to help them get there.

Accredited by:

- US Dept of Agriculture/US Forest Service
- Cement Association of Canada
- BC Forestry Innovation Investment
- BC Housing

Ecoform

Ecoform is a technical analysis company in the United States that focuses on the environmental performance of companies and their products and processes. Ecoform was founded in 2006 but benefits from the combined 50-year history of its practitioners whose experience includes working with a variety of corporate and university organizations such as The University of Tennessee's Center for Clean Products. Ecoform takes pride in its ability to work confidentially with leading corporations across multiple industry sectors to provide critical information that can be used to shape corporate policy.

Sustainable Research Group (SRG)

Sustainable Research Group (SRG) is an organization of experienced industry professionals dedicated to identifying, documenting and improving business performance by using principles that move their clients toward environmentally healthy and socially responsible practices. SRG's clients include manufactures, service companies, governmental and institutional organizations that recognize the value of sustainable business practices to maximize resource efficiency and stakeholder reputation.

Steel

The steel research has relied primarily on academic research reports and private company EPDs. In order to ensure no bias or conflict of interest, these five EPDs have been verified by third-party consultants such as:

SCS Global Services

Founded in 1984, SCS Global Services is a private third-party verifier which focuses on environmental, sustainability and food certification practices. It also provides auditing, testing and standard development practices. The main vision of this organization is to promote sustainable decision-making strategies and policies in every economic sector so as to protect the environment, safeguard communities and raise the overall standard of living.

Industry Ecology Consultants

Industry Ecology Consultants is a privately-owned consultancy which focuses on the sustainable combination of business, environment and technology. It provides sustainability services to small, medium and large enterprises which includes services in the areas of sustainability and industrial ecology. Its services include Life Cycle Assessment and capacity building, green marketing and communication advisement, enterprise and product carbon management and design for environment capacity building.

ISO 14025

ISO 14025 is the environmental labels and declarations standard. This ISO standard helps establish principles and procedures for Type III environmental declaration programs and declarations. These Type III environmental declarations are primarily intended for business to business interaction. The data and declarations produced by the Steel Tube Institute EPDs have been independently verified in accordance with ISO 14025 by Underwriters Laboratories and the PCR assessed by the PCR Review Panel.

Endnotes

[1] Connaughton, et al. "Cutting embodies carbon in construction projects." *WRAP:* 1-2. Accessed April 21, 2019. http://www.wrap.org.uk/sites/files/wrap/FINAL%20PRO095-009%20Embodied%20Carbon%20Annex.pdf

[2] EPA. 2011. "Uncertainty and Variability." Accessed May 1, 2019. https://www.epa.gov/expobox/uncertainty-and-variability

[3] Frey, H.C. 2019. "Quantification of Uncertainty in Emission Factors and Inventories." *EPA.* Accessed May 1, 2019. https://www3.epa.gov/ttn/chief/conference/ei16/session5/frey.pdf

[4] Frey, H.C. 2019. "Quantification of Uncertainty in Emission Factors and Inventories." *EPA.* Accessed May 1, 2019. https://www3.epa.gov/ttn/chief/conference/ei16/session5/frey.pdf

[5] EPA. 2011. "Uncertainty and Variability." Accessed May 1, 2019. https://www.epa.gov/expobox/uncertainty-and-variability

[6] Frey, H.C. 2019. "Quantification of Uncertainty in Emission Factors and Inventories." *EPA.* Accessed May 1, 2019. https://www3.epa.gov/ttn/chief/conference/ei16/session5/frey.pdf

[7] EPA. 2011. "Uncertainty and Variability." Accessed May 1, 2019. https://www.epa.gov/expobox/uncertainty-and-variability

[8] Port of Seattle. 2017. "Century Agenda: Strategic Objectives." *Port of Seattle.* Accessed April 19, 2019. https://www.portseattle.org/page/century-agenda-strategic-objectives

[9] EPA. "Basic Information of Air Emissions Factors and Quantification." *EPA.* Accessed April 14, 2019. https://www.epa.gov/air-emissions-factors-and-quantification/basic-information-air-emissions-factors-and-quantification

[10] Sharf, Samantha. 2018. "Full List: America's Fastest Growing Cities 2018." *Forbes.* (February 28). Accessed April 28, 2019. https://www.forbes.com/sites/samanthasharf/2018/02/28/full-list-americas-fastest-growing-cities-2018/#2091873d7feb

[11] Ibid.

[12] Visit Seattle. 2019. "Seattle Facts." *Visit Seattle.* Accessed March 24, 2019. https://www.visitseattle.org/press/press-kit/seattle-facts/

[13] King County. 2018. "Statistical Profile of: King County." *King County.* Accessed March 24, 2019. https://www.kingcounty.gov/~/media/depts/executive/performance-strategy-budget/regional-planning/Demographics/Dec-2018-Update/KC-Profile2018.ashx?la=en

[14] Port of Seattle. 2017. "Commission." *Port of Seattle.* Accessed March 24, 2019. https://www.portseattle.org/about/commission

[15] Port of Seattle. 2017. "Our Mission." *Port of Seattle.* Accessed March 24, 2019. https://www.portseattle.org/about/our-mission#

[16] Port of Seattle. 2018. "Sustainable Airport Master Plan (SAMP) Update." *Port of Seattle.* May 30. Accessed April 28, 2019. https://www.portseattle.org/sites/default/files/2018-06/180530-SAMP-Presentation-Public-Meeting.pdf

[17] Port of Seattle. 2017. "Century Agenda: Strategic Objectives." *Port of Seattle.* Accessed April 19, 2019. https://www.portseattle.org/page/century-agenda-strategic-objectives

[18] Leigh Fisher. 2018. "Sustainability Planning and Management Strategy: Seattle-Tacoma International Airport." *Leigh Fisher* (May): 2-7–2-10. Accessed April 28, 2019. https://www.portseattle.org/sites/default/files/2018-05/TM-No-09-Sustainability-Plan-and-Management.pdf

[19] Port of Seattle. 2017. "Airport Basics." *Port of Seattle.* Accessed March 24, 2019. https://www.portseattle.org/page/airport-basics

[20] Port of Seattle. 2018. "Sustainable Airport Master Plan (SAMP) Update." *Port of Seattle* (May): 4. Accessed March 24, 2019. https://www.portseattle.org/sites/default/files/2018-06/180530-SAMP-Presentation-Public-Meeting.pdf

[21] Port of Seattle. 2017. "Sustainable Airport Master Plan (SAMP)." *Port of Seattle.* Accessed March 24, 2019. https://www.portseattle.org/plans/sustainable-airport-master-plan-samp

[22] Moncaster, Alice and J. Y. Song. 2012. "A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings." *International Journal of Sustainable Building Technology and Urban Development* 3, no. 1: 26-36, DOI: 10.1080/2093761X.2012.673915

[23] The International Organization of Standardization. 2006. "ISO 14044: 2006 (en)." *ISO.* Accessed April 30, 2019. https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en

[24] Sustainable Minds. 2013. "Learn about SM Single Score results." *Sustainable Minds.* Accessed April 1, 2019. https://www.sustainableminds.com/showroom/shared/learn-single-score.html#

[25] United Nations Department of Economic and Social Affairs. 2017. "World Population Prospects: The 2017 Revision." *United Nations.* (June 21). Accessed April 1, 2019. https://www.un.org/development/desa/publications/world-population-prospects-the-2017-revision.html

[26] Betts, M., et al. *Global Construction 2030: A global forecast for the construction industry to 2030* 4, no. 1 (Oct 2015): 3, Rep. London, UK: Global Construction Perspectives and Oxford Economics.

[27] IATA. 2018. "IATA Forecast Predicts 8.2 billion Air Travelers in 2037." *IATA.* October 24. Accessed April 13, 2019. https://www.iata.org/pressroom/pr/Pages/2018-10-24-02.aspx

[28] EPA. 2019. "Overview of Greenhouse Gases." *EPA.* Accessed April 13, 2019. https://www.epa.gov/ghgemissions/overview-greenhouse-gases

[29] Connaughton, et al. "Cutting embodies carbon in construction projects." *WRAP:* 1-2. Accessed April 21, 2019. http://www.wrap.org.uk/sites/files/wrap/FINAL%20PRO095-009%20Embodied%20Carbon%20Annex.pdf

[30] Ibid.

[31] De Wolf, C., K. Simonen, and J. Ochsendorf. "Chapter 21 Initiatives to Report and Reduce Embodied Carbon in North American Buildings" in *Embodied Carbon in Buildings Measurement, Management, and Mitigation* (Springer International Publishing, 2018), 463-482. https://doi.org/10.1007/978-3-319-72796-7_21

[32] Victoria, M. and S. Perera. "Chapter 11 Carbon and Cost Hotspots: An Embodied Carbon Management Approach During Early Stages of Design" in *Embodied Carbon in Buildings Measurement, Management, and Mitigation* (Springer International Publishing, 2018), 247-262. doi: https://doi.org/10.1007/978-3-319-72796-7_21

[33] Graham, Peter. 2015. "Building the path to 1.5°C: What the Paris Agreement Means for Buildings & Construction." *GBPN.* December 13. Accessed February 18, 2019. http://www.gbpn.org/our-blog/building-path-15°c-what-paris-agreement-means-buildings-construction

[34] Perroud, S. 2018. "Accurately measuring embodied carbon in buildings." *EPFL.* December 3. Accessed February 18, 2019. https://actu.epfl.ch/news/accurately-measuring-embodied-carbon-in-buildings/

[35] Kaethner, S.C. and J. A. Burridge. 2012. "Embodied CO_2 of structural frames." *Structural Engineer 90,* no. 5. 33-40.

[36] De Wolf, C., K. Simonen, and J. Ochsendorf. "Chapter 21 Initiatives to Report and Reduce Embodied Carbon in North American Buildings" in *Embodied Carbon in Buildings Measurement, Management, and Mitigation* (Springer International Publishing, 2018), 463-482. https://doi.org/10.1007/978-3-319-72796-7_21

[37] UK Green Building Council. 2017. "Embodied Carbon: Developing a Client Brief" *UKGBC*. (March). Accessed April 30, 2019. https://www.ukgbc.org/sites/default/files/UK-GBC%20EC%20Developing%20Client%20Brief.pdf

[38] EPA. 2016. "Basic Information of Air Emission Factors and Quantification." *EPA.* (September 27). Accessed April 30, 2019. https://www.epa.gov/air-emissions-factors-and-quantification/basic-information-air-emissions-factors-and-quantification

[39] Ibid.

[40] EPA. 1995. "A.P. 42 Vol. 1 Introduction." *EPA.* Accessed March 16, 2019. https://www3.epa.gov/ttnchie1/ap42/c00s00.pdf

[41] GHG Protocol. "Quantitative Inventory Uncertainty." *GHG Protocol.* Accessed March 16, 2019. https://ghgprotocol.org/sites/default/files/Quantitative%20Uncertainty%20Guidance.pdf

[42] Schneider, David. 2018. "Cement, Steel, and Natural Gas Are Major Greenhouse Gas Emitters, Too." *IEEE Spectrum.* (June 4). Accessed April 1, 2019. https://spectrum.ieee.org/energy/environment/cement-steel-and-natural-gas-are-major-greenhouse-gas-emitters-too

[43] National Asphalt Pavement Association. 2019. "History of Asphalt." *NAPA*. Accessed April 19, 2019. https://www.asphaltpavement.org/index.php?option=com_content&view=article&id=21

[44] Carbon Smart Materials Palette. "Concrete." Accessed March 24, 2019. https://materialspalette.org/concrete/

[45] Carbon Smart Materials Palette. "Steel." Accessed March 24, 2019. https://materialspalette.org/steel/

[46] Port of Seattle. 2018. "Seattle-Tacoma International Airport Design Guidelines and Standards." *Port of Seattle.* Accessed March 19, 2019. https://www.portseattle.org/sites/default/files/2019-02/Architecture_Guidelines_Standards_2018.pdf

[47] Port of Seattle. 2018. "Seattle-Tacoma International Airport Rules for Airport Construction." *Port of Seattle.* (February 16). Accessed March 19, 2019. https://www.portseattle.org/sites/default/files/2018-03/rules_airport_constr.pdf

[48] National Asphalt Pavement Association & European Asphalt Pavement Association. 2011. *The Asphalt Paving Industry A Global Perspective Third Edition.* (August). Accessed March 19, 2019. https://www.asphaltpavement.org/images/stories/GL_101_Edition_3.pdf

[49] Asphalt Institute. 2019. "Glossary of Terms." *Asphalt Institute*. Accessed March 19, 2019. http://www.asphaltinstitute.org/engineering/glossary-of-terms/.

[50] Pavement Interactive. "Aggregate." *Pavement Tools Consortium.* Accessed May 1, 2019. https://www.pavementinteractive.org/reference-desk/materials/aggregate/

[51] Washington Asphalt Pavement Association. 2010. "Aggregate." *WAPA.* Accessed May 1, 2019. www.asphaltwa.com/materials-aggregate/

[52] U.S. Department of Transportation. 2016. "Warm Mix Asphalt FAQs." *USDOT FHWA.* (November 21). Accessed May 1, 2019. https://www.fhwa.dot.gov/innovation/everydaycounts/edc-1/wma-faqs.cfm#trad.

[53] Ibid

[54] National Asphalt Pavement Association & European Asphalt Pavement Association. 2011. *The Asphalt Paving Industry A Global Perspective Third Edition.* (August): 3. Accessed March 19, 2019. https://www.asphaltpavement.org/images/stories/GL_101_Edition_3.pdf

[55] Asphalt Pavement Alliance. 2019. "About Us." *APA.* Accessed May 1, 2019. http://www.asphaltroads.org/about-us/

[56] Asphalt Pavement Alliance. 2010. *Carbon Footprint - How Does Asphalt Stack Up?* Accessed May 1, 2019. http://www.asphaltroads.org/assets/_control/content/files/carbon_footprint_web.pdf

[57] City of Seattle. 2017. "Standard Specifications for Road, Bridge and Municipal Construction." *City of Seattle.* Accessed May 1, 2019. http://www.seattle.gov/util/cs/groups/public/@spu/@engineering/documents/webcontent/2_035032.pdf

[58] International Organization for Standardization. 1997. "International Standard IS0 14040" *ISO*. (June 15). Accessed May 1, 2019. https://web.stanford.edu/class/cee214/Readings/ISOLCA.pdf

[59] Peng, Bo, et al. 2015. “Evaluation system for CO2 emission of hot asphalt mixture.” *Journal of Traffic and Transportation Engineering* 2, no 2: 116-124. Accessed May 1, 2019. https://www.sciencedirect.com/science/article/pii/S2095756415000124

[60] Ibid.

[61] Ibid . Peng, Bo, et al. 2015. “Evaluation system for CO2 emission of hot asphalt mixture.” *Journal of Traffic and Transportation Engineering* 2, no 2: 116-124. Accessed May 1, 2019. https://www.sciencedirect.com/science/article/pii/S2095756415000124

[62] Ibid.

[63] Ibid.

[64] Ibid.

[65] Ibid.

[66] Ibid.

[67] Ibid.

[68] Ibid . Peng, Bo, et al. 2015. “Evaluation system for CO2 emission of hot asphalt mixture.” *Journal of Traffic and Transportation Engineering* 2, no 2: 116-124. Accessed May 1, 2019. https://www.sciencedirect.com/science/article/pii/S2095756415000124

[69] Emerald Eco-Label. 2019. “An Environmental Product Declaration for Asphalt Mixtures.” *George Reed, Inc.* (March 27). Accessed May 1, 2019. https://asphaltepd.org/published/epd/52/

[70] NAPA. 2019. “NAPA EPD Program.” *NAPA.* Accessed March 27, 2019. http://www.asphaltpavement.org/EPD

[71] RAP Technologies. 2015. “NAPA’s Greenhouse Gas Calculator.” *RAP Technologies.* Accessed May 1, 2019. https://raptech.us/greenhouse-gas-dashboard/

[72] MIT Concrete Sustainability Hub. “Why Concrete?” *MIT.* Accessed March 15, 2019. http://cshub.mit.edu/why-concrete

[73] Allen, E., & Iano, J. 2013. “Fundamentals of building construction: Materials and methods.” Accessed May 1, 2019. https://ebookcentral.proquest.com

[74] Ibid.

[75] Portland Cement Association. 2018. “Cement & Concrete Basics.” *PCA.* Accessed May 1, 2019. https://www.cement.org/cement-concrete-applications

[76] Allen, E., & Iano, J. 2013. "Fundamentals of building construction: Materials and methods." Accessed May 1, 2019. https://ebookcentral.proquest.com

[77] Ibid.

[78] Flower, David & Jay Sanjayan. 2007. "Green house gas emissions due to concrete manufacture." *The International Journal of Life Cycle Assessment* (July) 12: 282. https://doi.org/10.1065/lca2007.05.327

[79] Ibid.

[80] Federal Aviation Administration. 2018. "Advisory Circular: Standard Specifications for Construction of Airports." *FAA.* (December 21). Accessed May 1, 2019. https://www.faa.gov/documentLibrary/media/Advisory_Circular/150-5370-10H.pdf

[81] Seattle Department of Construction & Inspections. 2015. *Seattle Building Code,* Chapter 19. Accessed May 1, 2019. http://www.seattle.gov/documents/Departments/SDCI/Codes/SeattleBuildingCode/2015SBCChapter19.pdf

[82] U.S. Green Building Council. "Building project disclosure and optimization – environmental product declarations." *USGBC.* Accessed May 1, 2019. https://www.usgbc.org/credits/new-construction-core-and-shell-schools-new-construction-retail-new-construction-healthca-22

[83] National Ready Mixed Concrete Association. "NRMCA EPD Program." *NRMCA.* Accessed May 1, 2019. https://www.nrmca.org/sustainability/EPDProgram/

[84] Marceau, Medgar, Michael Nisbet, & Martha VanGeem. 2007. "Life Cycle Inventory of Portland Cement Concrete." *Portland Cement Association.* Accessed May 1, 2019. http://www.nrmca.org/taskforce/item_2_talkingpoints/sustainability/sustainability/sn3011%5B1%5D.pdf

[85] Allen, E., & Iano, J. 2013. "Fundamentals of building construction: Materials and methods." Accessed May 1, 2019. https://ebookcentral.proquest.com

[86] Marceau, Medgar, Michael Nisbet, & Martha VanGeem. 2007. "Life Cycle Inventory of Portland Cement Concrete." *Portland Cement Association.* Accessed May 1, 2019. http://www.nrmca.org/taskforce/item_2_talkingpoints/sustainability/sustainability/sn3011%5B1%5D.pdf

[87] Allen, E., & Iano, J. 2013. "Fundamentals of building construction: Materials and methods." Accessed May 1, 2019. https://ebookcentral.proquest.com

[88] Ibid.

[89] Portland Cement Association. 2014. "Environmental Product Declaration: Portland Cements." *PCA.* (September 2). Accessed May 1, 2019. https://www.cement.org/docs/default-source/sustainabilty2/pca-portland-cement-epd-062716.pdf?sfvrsn=2

[90] Allen, E., & Iano, J. 2013. "Fundamentals of building construction: Materials and methods." Accessed May 1, 2019. https://ebookcentral.proquest.com

[91] *The World Steel Association. 2018* "About Steel." Accessed May 1, 2019. *https://www.worldsteel.org/about-steel.html*

[92] Ibid.

[93] Northern Weldarc, LTD. 2016. "Common Types of Steel Building Constructions." *NWL.* (November 4). Accessed May 1, 2019. http://northern-weldarc.com/common-types-steel-building-constructions/

[94] Benchmark Fabricated Steel. 2017. "What is Structural Steel?" *Benchmark Fabricated Steel.* (August 7). Accessed May 1, 2019. https://benchmarksteel.com/2017/08/what-is-structural-steel/

[95] Environmental Protection Agency. 1995. "Coke Production." *EPA.* Accessed May 1, 2019. https://www3.epa.gov/ttn/chief/old/ap42/ch12/s02/final/c12s02_1995.pdf

[96] Turner, Michael. "The Global Networks for Climate Solutions Factsheet: Mitigating Iron and Steel Emissions." Columbia Climate Center. Accessed May 1, 2019. http://climate.columbia.edu/files/2012/04/GNCS-Iron-Steel.pdf

[97] Ibid.

[98] Thompson, Robbie. 2018. "Steelmaking 101." *Metal Conklin Industries.* (July 12). Accessed May 1, 2019. https://www.conklinmetal.com/steelmaking-101/

[99] World Steel Association. 2019. "Steel's Contribution to a Low Carbon Future*." World Steel Association.* Accessed May 1, 2019. https://www.worldsteel.org/publications/position-papers/steel-s-contribution-to-a-low-carbon-future.html

[100] Turner, Michael. "The Global Networks for Climate Solutions Factsheet: Mitigating Iron and Steel Emissions." Columbia Climate Center. Accessed May 1, 2019. http://climate.columbia.edu/files/2012/04/GNCS-Iron-Steel.pdf

[101] Seattle Department of Construction & Inspections. 2015. *Seattle Building Code,* Chapter 19. Accessed May 1, 2019. http://www.seattle.gov/documents/Departments/SDCI/Codes/SeattleBuildingCode/2015SBCChapter19.pdf

[102] ASTM. 2015. "Steel Standards." *ASTM.* Accessed May 1, 2019. https://www.astm.org/Standards/steel-standards.html

[103] Moncaster, A. M. & Song, J-Y. (2012). A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings, *International Journal of Sustainable Building Technology and Urban Development*, 3:1, 26-36, DOI: 10.1080/2093761X.2012.673915

[104] Arcelor Mittal. 2011. "Sustainability of Steel." *Arcelor Mittal.* (January). Accessed March 19, 2019. http://www.usa.arcelormittal.com/~/media/Files/A/Arcelormittal-USA-V2/what-we-do/steel-products/201101_sustainability-of-steel.pdf

[105] Gerdau. 2016. “Environmental Product Declaration: Structural Steel, Midlothian Steel Mill.” *Gerdau.* (December 15). Accessed May 1, 2019. https://www.scscertified.com/products/cert_pdfs/SCS-EPD-04281_Gerdau_Structural_Steel_Midlothian_121516.pdf

[106] Gerdau. 2016. “Environmental Product Declaration: Structural Steel, Midlothian Steel Mill.” *Gerdau.* (December 15). Accessed May 1, 2019. https://www.scscertified.com/products/cert_pdfs/SCS-EPD-04281_Gerdau_Structural_Steel_Midlothian_121516.pdf

[107] Commercial Metals Company. 2016. “Environmental Product Declaration: Fabricated Heavy Structural Shapes.” *CMC.* Accessed May 1, 2019. https://www.cmc.com/en/files/pdfs/cmc-global-pdfs/leed-pdfs/leedv4-cmc-epd-fabricated-heavy-structural-shapes.aspx

[108] Steel Tube Institute. 2016. “Environmental Product Declaration: Hollow Structural Sections.” American Institute Steel Construction. (September 22). Accessed May 1, 2019. https://steeltubeinstitute.org/wp-content/uploads/2016/09/101.1_STI_EPD_hollow-sections.pdf

[109] American Institute of Steel Construction. 2016. “Environmental Product Declaration: Fabricated Hot-Rolled Structural Sections.” *American Institute of Steel Construction*. (March 31). Accessed May 1, 2019. https://www.aisc.org/globalassets/why-steel/102.1_aisc_epd_-fab-sections_20160331.pdf

[110] Steel Tube Institute. 2016. “Environmental Product Declaration: Hollow Structural Sections.” American Institute Steel Construction. (September 22). Accessed May 1, 2019. https://steeltubeinstitute.org/wp-content/uploads/2016/09/101.1_STI_EPD_hollow-sections.pdf

[111] Ivanov, Oskar Larsson, et al. “Consideration of uncertainties in LCA for infrastructure using probabilistic methods.” *Structure and Infrastructure Engineering* (2019): 3-4, https://www.tandfonline.com/doi/full/10.1080/15732479.2019.1572200

[112] Google. “2018 Environmental Report.” Accessed April 24, 2019. https://storage.googleapis.com/gweb-sustainability.appspot.com/pdf/Google_2018-Environmental-Report.pdf

[113] “Buy Clean California Act, Cal. Ch. 816, Sec. 3. 2017.” Accessed April 23, 2019. https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?division=2.&chapter=3.&part=1.&lawCode=PCC&article=5

[114] University of Washington College of Built Environments. “Buy Clean Washington.” Accessed April 23, 2019. http://www.carbonleadershipforum.org/resources/buy-clean-washington/

[115] Canadian Ready Mixed Concrete Association. “Environmental Product Declaration: CRMCA ready-mixed concrete. Accessed April 23, 2019. https://info.nsf.org/Certified/Sustain/ProdCert/EPD10092.pdf

[116] George Pouliot, et al. “Quantification of Emission Factor Uncertainty.” *EPA.* Accessed April 24, 2019. PDF.

[117] Airport Technology. 2018. “The world’s most environmentally friendly airports.” *Airport Technology.* (April 26). Accessed April 24, 2019. http://www.airport-technology.com/features/worlds-environmentally-friendly-airports/

[118] Washington Asphalt Pavement Association. 2019. “Regular Members.” *WAPA.* Accessed May 1, 2019. http://www.asphaltwa.com/regular-members/

[119] Washington Asphalt Pavement Association. 2019. “Associate Members.” *WAPA.* Accessed May 1, 2019. http://www.asphaltwa.com/associate-members/

[120] Rosenberg, Mike. 2019. “Seattle construction still booming and won’t end anytime soon.” *The Seattle Times.* (February 19). Accessed May 1, 2019. https://www.seattletimes.com/business/real-estate/seattle-construction-still-booming-and-wont-end-anytime-soon/

[121] CalPortland. 2019. Homepage. Accessed May 1, 2019. https://www.calportland.com

[122] Cadman Heidelberg Cement Group. 2019. Homepage. Accessed May 1, 2019. https://cadman.com

[123] World Steel Association. 2019. Homepage. Accessed May 1, 2019. https://www.worldsteel.org

[124] Nucor. 2019. Homepage. Accessed May 1, 2019. https://nucor.com

[125] Edw. C. Levy & Co. 2019. Homepage. Accessed May 1, 2019. http://edwclevy.com