LIFE CYCLE SUSTAINABILITY ASSESSMENT FOR SELECTING CONSTRUCTION MATERIALS IN THE PRELIMINARY DESIGN PHASE OF ROAD CONSTRUCTION PROJECTS

Von der Fakultät für Wirtschaftswissenschaften der

Technischen Universität Chemnitz

Dissertation zur Erlangung des akademischen Grades

Doctor rerum politicarum (Dr. rer. pol.)

vorgelegt von

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geboren am 02.08.1989 in Hanoi – Vietnam

eingereicht am:	**14. Nov. 2022**
Gutachter:	**Prof. Dr. Uwe Götze**
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Tag der mündlichen Prüfung:	**26. Jan. 2023**

Online: https://nbn-resolving.org/urn:nbn:de:bsz:ch1-qucosa2-834206

Acknowledgement

The thesis is the result of not only my own effort, but also the assistance of a number of people, whom I would like to thank at this time. Unfortunately, it is hard to include everyone here, but I would stress some names.

Regarding our institution, I'd like to thank my Supervisor, Prof. Dr. Uwe Götze, who has supported me at all times, ever since I applied for the university, and has thus contributed significantly to the creation of this work. Prof. Dr. Uwe Götze was not only a scientific advisor but also a friendly partner for non-academic discussions. It is a joy to convey my most sincere and profound gratitude for his kind supervision, persistent encouragement, valuable lively conversation, and unfailing guidance throughout this effort throughout my most recent year of study in Germany. He assisted in all matters and offered solutions to many issues. Prof. Dr. Uwe Götze supported and assisted me during my study in Germany and thesis writing. I wish to express my sincere appreciation for his support throughout my time in Chemnitz.

Prof. Dr. Silke Hüsing, has kindly agreed to serve as an examiner. I would like to convey my sincere gratitude for her cooperation on the defence and oral examination.

I would like to thank all of the staff members and my colleagues at the Chair of Management Accounting and Control, Faculty of Economics and Business Administration, Chemnitz University of Technology, for their pleasant, kind conversation, insightful talks, and assistance.

I would like to thank the Vietnamese Government, the Ministry of Education and Training, and University of Transport and Communications for their support during my study in German.

Lastly, I would want to appreciate the significant contribution of my family. You all provided me with the crucial assistance and encouragement necessary to have developed this research the way I have been able to, and I dedicate my deepest thanks to you.

To all of you, Thank you very much.

Trong Hung Dinh

Chemnitz, November 2022

Abstract

Road construction project activities cause severe harm to the environment as they consume a tremendous volume of materials and release pollutants into the environment. Besides, an increasing number of researchers is participating in work related to sustainability in the construction industry as well as road construction projects. Similar to other life cycles, a strong influence on sustainability is exerted in the early phases of road construction projects, especially in the preliminary design phase. Especially selecting materials is one of the most critical tasks in this phase because it contributes considerably to the achievement of sustainability targets. For enabling a conscious and systematic selection of materials, a significant evaluation of materials with regard to the three dimensions of sustainability is necessary. However, a well-elaborated and mature instrument supporting such an evaluation has not been developed and presented in literature until now. In the contrary, several studies revealed that the material-dependent activities and the life cycle analysis have been neglected so far. Moreover, selecting materials in the preliminary design phase is mainly based on designers' experience and not on the application of analytic methods. Such selection is highly error-prone. In this thesis, current material selection methods for sustainable development in the preliminary design phase were analyzed. Initially, material selection studies conducted in the early design phase were analyzed to determine the relevant issues. The result emphasized that the integration of sustainability into material selection in the preliminary design phase encountered many obstacles, such as unavailable information and databases. Then, the most important sustainability criteria for selecting road construction materials were identified, covering the economic, environmental, and social dimensions of sustainability. Next, approaches which suggest the application of LCC, LCA, Social LCA, MCDM, and LCSA in road construction material selection are discussed in order to identify their limitations. Accordingly, this thesis developed an instrument based on the LCC, LCA, Social LCA, MCDM methods, and LCSA for assessing the sustainability performance of road construction materials in the preliminary design phase. The instrument is intended to help designers select the most sustainable materials by addressing the issues that emerge in the preliminary design phase. *Firstly,* a procedure model for evaluating the sustainability performance of road construction materials is suggested. It is based on two existing procedure models. One is a decision theory-based procedure model for sustainability-oriented evaluations. The model is divided into two levels, with the overall sustainability performance evaluation at the first level and the evaluation of the economic, environmental, and social performances at the second level. Although this procedure model demonstrates some benefits and has been utilized in some cases, the four-step LCA procedure, according to ISO 14044, appears to be more prevalent and well-established. Therefore, it is suggested here to integrate both approaches. This procedure model contributes to integrating the LCC, LCA, and Social LCA). *Secondly*, this instrument for assessing the sustainable performance of materials is further developed based on the step-by-step models of three pillars of sustainability. This allows for employing numerical methods from the LCC, LCA and Social LCA and thereby reducing the mistakes from the experience-based selection of designers. The proposed instrument also addresses the specific challenges of material selection in the preliminary design phase. The LCC could refine all material-dependent costs incurred during the life cycle and evaluate the material alternatives' total cost. Besides, it defines long-term outcomes by dividing the material life cycle into many consecutive phases and applying the time value of money into the calculation. For the LCA, two scenarios are proposed to solve the problems concerning the lack of available information in the preliminary design phase. Besides, the environmental performance of material-dependent activities, such as the usage of equipment and labor, is also considered in the method. The Social LCA is developed based on the Performance Preference Point (PPR) approach and the Subcategory Assessment Method (SAM) to assess the social performance of road construction materials. The method also shows the potential to support the designers in selecting the most social-friendly material by considering the material-dependent activities and stakeholders. The LCC, LCA, and Social LCA analyses integrated into the LCSA to come up with the general perspective of sustainable level. From the perspective of decision-makers, the importance level of sustainability dimensions might be different. The study suggests applying the AHP method and Likert Scale to evaluate the weightings and then integrating them into the LCSA model to assess the general sustainability performance of road construction materials. After that, a ternary diagram can be drawn to provide a comprehensive picture of the road construction material selection in dependence on these weightings. The assessment of two alternatives, "concrete bricks" and "baked bricks", was conducted as a case study to illustrate and demonstrate the procedure model.

Keywords: road construction material selection, sustainability, preliminary design phase, Life Cycle Costing, Life Cycle Assessment, Social Life Cycle Assessment, Life Cycle Sustainability Assessment.

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AHP	Analytic hierarchy process
ANP	Analytic Network Process
BIM	Building information model
BR(s)	Basic Requirement(s)
CED	Cumulative energy demand
CLT	Cross-laminated timber
CMoC	Cost model of construction
COF	Cash outflows
EMoC	Environmental model of construction
GWP	Global warming potential
ICT	Information and Communications Technology
IP	Impact Pathway
IRR	Internal Rate of Return
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
LEED	Leadership in Energy and Environmental Design
MCDM	Multi-criteria decision-making
NEPA	National environmental policy act
NPV	Net Present Value
PRP(s)	Performance Reference Point(s)
RC	Reinforced concrete
SAM	Subcategory Assessment Method
SFM	Structural Frame Material score
SMoC	Social-impact Model of Construction
Social LCA	Social Life cycle assessment
Social LCI	Social life cycle inventory analysis
Social LCIA	Social life cycle impact assessment
SPS	Social performance score
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UAV	Utility Value Analysis
UN	United Nations

1. Introduction

1.1. Challenges of road construction material selection in the preliminary design phase

The construction industry has a growing interest in sustainability on a global scale. For example, Kiani Mavi et al., (Kiani Mavi et al., 2021) observed a growing interest in researchers to participate in work related to sustainability in the construction industry. The materials which are used in the construction industry and road construction projects have a significant impact on the sustainable development (Li and Guo, 2015; Dinh et al., 2020). Therefore, material selection plays a crucial role in achieving sustainability targets in (road) construction projects (Jalaei et al., 2015; Fazeli et al., 2019).

Construction projects, in general, are divided into six phases, including (1) Initiation, (2) Planning and design, (3) Tender/Bidding, (4) Construction, (5) Handover and operation, and (6) Close-out (Netto and Raju, 2017; Trigunarsyah, 2017; Awng, 2018; Dinh and Dinh, 2021). Road construction projects are specific construction projects, so they follow the general construction project's life cycle (with the six phases mentioned above). The material selection is conducted in the planning and design phase, which includes three main sub-steps: pre-design, preliminary design, and detailed design. *Construction material selection* is a strategy/process to select the most suitable materials according to given requirements and standards. It contains six key steps (Pfeifer, 2009a): (1) Identification of the design requirements; (2) Identification of element design requirements; (3) Identification of candidate materials; (4) Evaluation of materials; (5) Determination of the satisfaction of evaluated materials; (6) Final selection of materials. In general, material selection is a process in which the designers compare material's specifications to given requirements. The selection faces several challenges, involving diverse material alternatives and complex evaluation criteria (Maghsoodi et al., 2020).

As mentioned above, the *preliminary design step* (schematic design/early design step) is a part of the planning and design phase (phase 2) of a road construction project. It clarifies the requirements of the project and its essential documents to execute and manage the project by transferring ideas to plans, drawings, and specifications (Andrade et al., 2012; Bragança et al., 2014; Feria and Amado, 2019). The preliminary design phase significantly impacts project's objectives and their achievement. It puts forth the project idea, which decides the project's feasibility (Cockton, 1992). Erebor et al. (Erebor et al., 2019) recommended that the early design phase gives opportunities for

sustainable development because important decisions influencing the later phases are taken here, such as material selection. As a result, selecting materials performs one of the most critical tasks in this phase because it contributes greatly to the existence of sustainability (Rockizki and Peggy, 2013). According to them, this phase impacts the product's performance by setting up the main structures, materials, budget, and project requirements. Besides, by embracing the triple bottom line of sustainability, the selection can pave the most straightforward way to a sustainable development approach (John et al., 2005).
Road construction materials and sustainability concepts have been central to some authors because road construction projects consume plenty of materials and energy. John et al. (John et al., 2005) pointed out that material selection is the most efficient way to incorporate sustainable development into the construction industry. Shaffi also concluded that sustainability is achieved by considering environmental, socioeconomic, and cultural factors in the selection process (Shafii et al., 2006). In general, sustainability includes three main aspects according to the so-called triple bottom line/ three pillars: (1) economic aspects, (2) environmental aspects, and (3) social aspects (Elkington, 1999; Norouzi et al., 2017).

Life cycle approaches (life cycle costing (LCC), life cycle assessment (LCA), and social life cycle assessment (Social LCA)) are suggested to assess sustainability performance. The LCC is a tool for assessing economic performance by estimating the total cost concerning trade-offs during life cycle phases (Götze et al., 2014), the LCA evaluates alternatives in terms of environmental impacts during life cycle phases (Carvalho et al., 2016), and the Social LCA analysis helps designers and architects assess social performance (UNEP and SLCA, 2020). Babashamsi et al. (Babashamsi et al., 2016a) reviewed most of the sustainability tools and affirmed the importance of the life cycle approach. They also pointed out that the life cycle approach has many advantages, such as equally considering economic, environmental, and social aspects and assessing sustainability performance in the long term. The life cycle approach emerges as a useful tool for evaluating economic, environmental, and social aspects.

Some studies have also attempted to assess sustainability performance in the construction industry by separately utilizing the LCC, LCA, and Social LCA analyses (Rockizki and Peggy, 2013; Bragança et al., 2014; Hosseinijou et al., 2014; Jalaei et al., 2015; Babashamsi et al., 2016b; Hossain et al., 2017; Fazeli et al., 2019; Feria and Amado, 2019; Chen et al., 2020). For *economic aspects*, previous studies pointed out that the economic performances of alternatives should be estimated according to the life cycle cost approach (Andrade et al., 2012; Bragança et al., 2014; Jalaei et al., 2015). However, the LCC analysis encounters problems such as the lack of detailed guidelines and the negligence of cost items in the preliminary design phase (Andrade et al., 2012; Bragança et al., 2014; Jalaei et al., 2015; Fazeli et al., 2019). Besides, previous studies have not considered material-dependent costs such as labor cost and equipment cost. However, for a significant cost assessment, the whole material life cycle and the material-dependent costs should be considered. Moreover, the specific issues of the preliminary design phase (especially lacking information) need to be addressed.

For *environmental dimensions*, Sauer and Calmon (Sauer and Calmon, 2019) reviewed more than 5000 peer-reviewed articles on LCA applications in the construction industry. They identified that the shortage of LCA tools is a primary limitation because most of the current supporting tools are developed for North America and Europe. This paper also claimed that on-site construction data was often neglected, although the LCA results are influenced by different construction methods in the on-site construction area. They also emphasized the deficiencies in clarified data collections and region-specific inventories affecting LCA results' accuracy. In a nutshell, the lack of a database emerges as an explicit problem for applying the LCA analysis to the preliminary design phase. Besides, the material-dependent activities that impact the environmental burden need to be considered because they also impact the environmental burden of each material alternative.

Furthermore, existing studies often neglect the *social assessment* in the preliminary design phase (Hungu, 2013; Bragança et al., 2014; Zhong et al., 2016). Hungu (Hungu, 2013) integrated a social problem (Healthy and Safety of people) into the environmental aspect due to the deficiency of social information in the preliminary design phase. Similarly, Hossain et al. and Zheng et al. (Hossain et al., 2017; Zheng et al., 2020b) emphasized that the current social database is primarily designed for developed countries. As a result, the deficiency of social assessment in the preliminary design phase leads to an imbalance in the sustainability assessment. However, a comprehensive sustainability assessment requires evaluating the social performance during the material life cycle (from material extraction to the close-out phase of road construction projects) involving material-dependent activities as well.

For integrating LCC, LCA and Social LCA, aggregating their results and thereby enabling a comprehensive assessment and selection of objects towards sustainable development, *life cycle* *sustainability assessment* (LCSA) is suggested. Klöpffer (Kloepffer, 2008) affirmed that LCSA is a tool that considers the triple bottom line and evaluates the sustainability of production systems. The LCSA result is computed by summing up the results of life cycle cost analysis (LCC), life cycle assessment analysis (LCA), and social life cycle assessment analysis (Social LCA). Klöpffer also presented the "LCSA equation", in which the total evaluation result is the sum of LCC, LCA, and Social LCA results. The LCSA result is calculated by the following equation (Kloepffer, 2008):

$$\text{LCSA} = \text{LCC} + \text{LCA} + \text{SLCA} \qquad 1.1$$

Equation 1.1 is extremely understandable, and it is capable of being utilized in evaluating and comparing the alternatives. Nevertheless, various contexts coming from the policies of the country and the interest of owners may impact the significance level of economic, environmental, and social aspects. Consequently, designers have distinctive priorities in the three pillars of sustainability; for example, economic factors are commonly prioritized in developing countries, while environmental and social aspects are underestimated (Chang et al., 2016; Banihashemi et al., 2017). Serving as an example, decision-makers in developed countries are likely to reconcile the three pillars of sustainability competently; however, decision-makers in developing countries might have to witness (other) trade-offs among them. Hence, it is essential to cover the importance of LCC, LCA, and Social LCA results when calculating the overall LCSA result. In other words, significant trade-offs between the LCC, LCA, and Social LCA results should be considered for integrating the outcomes to assess the sustainability performance of road construction materials throughout their life cycle. Toosi et al. (Toosi et al., 2020) suggested that considering equal weightings for LCC, LCA, and Social LCA values in Equation 1.1 is a restriction that should be studied more in the future. The designers and architects can determine their own weightings, but the weightings should be derived by an adequate method.

According to the literature review, the material selection towards sustainability in the preliminary design phase shows some problems (see also Section 3.1). Deng and Edwards (Deng and Edwards, 2007) revealed that the research community has not yet focused on the material-dependent activities and life cycle analysis in the preliminary design phase. Braganca et al. (Bragança et al., 2014) suggested critical criteria applied to compare material alternatives in the preliminary design phase, but social dimensions are neglected, similar to (Zhong et al., 2016). Feria and Amado (Feria and Amado, 2019) offered a guideline that covers major contents requiring sustainability. However, the proposed guideline could not effectively assist designers in selecting sustainable materials because it lacked specific instructions. Jalaei et al. and Fazeli et al. (Jalaei et al., 2015; Fazeli et al., 2019) proposed a BIM-integrated TOPSIS-Fuzzy framework for the selection of sustainable components and materials in the preliminary design phase, but this approach demands an extensive database and management system that can only be provided in developed countries (or even not in such countries). Soust-Verdaguer et al. (Soust-Verdaguer et al., 2022) also highlighted the lack of available data in the preliminary design phase. As a result, although this phase strongly impacts the product's performance, few studies involve material selection in the preliminary design phase. Furthermore, the issue of determining weightings for an LCSA is still not solved (Hossaini et al., 2014).

This section outlines the state-of-art of sustainability-oriented material selection in the preliminary design phase and the existing challenges. The crucial problems identified include the lack of database and supporting tools, various environmental profiles, the shortage of detailed guidelines, the lack of case studies, and the abandonment of the research community (more details in section 3.1). Besides, the trade-offs between the LCC, LCA, and Social LCA in the LCSA analysis need to be considered. The given problems raise the demand for proposing a method/model that addresses the issues and enables a significant assessment of the sustainable performance of road construction material in the preliminary design phase. The objectives and structure of the thesis are presented in the section below.

1.2. Objectives and structure

According to the section above, some practical demands and theoretical research needs are identified. To address them, a detailed model shall be firstly proposed for assessing the sustainable performance of road construction material selection in the preliminary design phase. This method should be developed based on the LCC, LCA, Social LCA, and LCSA. Secondly, the assessment has to include material-dependent activities that impact the economic, environmental, and social aspects, such as using material-dependent equipment. Thirdly, the proposed method has to address the problem emerging due to the information deficiency in the preliminary design phase. Lastly, a case study shall be conducted to demonstrate the proposed method. To reach the objectives, the research questions have to be answered:

- Question 1: What are the specific challenges of life cycle-related road construction material assessment and selection in the preliminary design phase?
- Question 2: What are the state-of-the-art methods that can be applied for sustainability assessment of road construction materials?
- Question 3: Which systematic approach is useful for a significant life cycle-related assessment of materials for road construction projects in the preliminary design phase under consideration of material-related activities and the lack of data in this phase?
  - Question 3a: How can a comprehensive and consistent assessment, including all dimensions of sustainability and the trade-offs between economic, environmental, and social aspects, be achieved?
  - Question 3b: How can a significant life cycle-related economical assessment be conducted?
  - Question 3c: How can a significant life cycle-related environmental assessment be conducted?
  - Question 3d: How can a significant life cycle-related social assessment be conducted?

To demonstrate how the method can be applied, a case study should be conducted. The answers to the research questions require some steps of investigation, which will be systematically presented below:

In **chapter 2**, primary definitions of road construction projects, material selection, and sustainability are introduced. In this chapter, primary terms concerning road construction projects are presented. Besides, the construction material selection is defined in this thesis as a strategy and process of selecting the most suitable materials based on given criteria and standards. According to (WCED, 1987), sustainability is defined as a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Some other terms and concepts are also defined in this chapter. The provided definitions and descriptions establish a foundation for the intended development of a method for assessing the sustainable performance of road construction materials in the preliminary design phase.
Current material selection methods towards sustainable development in the preliminary design phase are presented in **chapter 3** in order to answer the first two research questions. *Firstly*,

material selection studies referring to the early design phase and sustainability are investigated by conducting a literature analysis. The analysis is conducted to show in a systematic way which problems arise, what is already known about the material selection as a whole, and outline the key ideas and theories that help understand the issue. The studies especially refer to the basic methods such as the LCA, LCC, Social LCA, and LCSA. They are reviewed to lay the foundation of the proposed procedure model in three steps: Firstly, their terms and definitions are presented, then their steps are briefly described. Afterwards, the existing applications of the LCA, LCC, Social LCA, and LCSA are researched to find out the challenges, such as the shortage of on-site construction data and material-dependent activities. Besides, the literature analysis also figures out other challenges in the preliminary design phase that impact road construction material selection. The challenges are gathered from previous studies, such as the dominance of the technical aspects and the abandonment of the research community. *Secondly*, the main sustainability criteria that can be applied to select road construction materials are identified. The criteria were gathered from various sources and reviewed in a previous paper of the author (and co-authors) (Dinh et al., 2020). For instance, the economic criteria are divided into (1) Price of materials; (2) Cost in the material transport; (3) Cost in the construction phase; (4) Cost in operation and maintenance phase; (5) Cost in the demolition phase. *Thirdly*, main methods for assessing the economic, environmental, social and sustainable issues are analyzed. The life cycle cost analysis is proposed as an important method for assessing the economic dimension. Accordingly, its terms and steps are described, together with its basic model to estimate the total cost of products during their life cycle. After that, the life cycle assessment is presented as the established instrument to evaluate the environmental dimension. The detailed steps are also described, and their applications in the construction industry and road construction material selection are also analyzed. According to (ISO, 2006b), the social life cycle assessment is applied to evaluate the social burdens and benefits. Its steps are presented as well and several studies concerning the social life cycle assessment method in the construction industry and road construction material selection are also introduced. For a comprehensive sustainability assessment including all three dimensions the life cycle sustainability assessment is suugested. This method integrates the LCA, LCC, and Social LCA into an LCSA equation. Besides, the multi-criteria decision-making methods are also introduced because they show potential as an effective tool supporting decision-making especially with regard to estimate different weightings of dimensions and criteria.

According to the life cycle analysis approach characterized in section 3.1, a procedure model for selecting road construction materials in the preliminary design phase is proposed in **chapter 4** for answering research question 3 and its sub-questions. In the first part, a comprehensive procedure model of road construction material selection in the preliminary design phase is developed. The model is divided into two levels, with the overall sustainability performance evaluation at the first level and the evaluation of the economic, environmental, and social performances at the second level. At the top level, the evaluation activities that refer to all sustainability dimensions are conducted, while the second level uses adequate methods and models to calculate the LCC, LCA, and Social LCA results. The procedure model is developed according to four-step procedure of LCA because it seems to be highly prevalent and understandable. The model includes four steps: (1) Goal and scope definition; (2) Life cycle inventory analysis; (3) Life cycle impact assessment; (4) Interpretation. The system boundary is defined based on the "from cradle to grave" approach, including the extraction, manufacturing, construction, handover and operation, and the close-out phases. In the second part, comprehensive models of LCC, LCA, Social LCA, MCDM methods, and LCSA are built based on the developed procedure model. Noticeably, to address the problem of data availability, two scenarios are suggested. In scenario (1), it is assumed that the amount of materials has already been estimated in the preliminary design phase. For scenario (2), it is assumed that the amount of materials is **not** estimated in the preliminary design phase. After that, detailed guidelines are presented to estimate the economic, environmental, and social performances at the second level and the sustainability performance at the first level. For economic aspects, some LCC models are proposed to estimate the total cost of road construction materials, while their environmental performances are assessed by using the LCA-based guideline. The guideline is specific for the two scenarios, builds models to estimate the environmental performance based on similar projects, and considers the material-dependent activities. Meanwhile, the Social LCA is applied to evaluate the social problems of five main stakeholders, including worker, local community, society, customers, and other actors of the value chain. The Social LCA is modified and developed based on the approach of (Ramirez et al., 2014) with new Basic Requirements, questionnaires and weightings. The importance weightings are estimated by the AHP method to integrate the LCC, LCA, and Social LCA results into the LCSA.

In **chapter 5**, a case study is conducted to demonstrate the procedure model. The case study refers to selecting one of two alternatives: concrete bricks and baked bricks. The two alternatives are used in the project "Provincial road No207 improvement construction project from Quang Uyen to Ha Lang (km 0+00 – km 31+00)". They are compared by applying the procedure model offered in chapter 4. Firstly, the goal, scope, and system boundary of the case study are defined. Secondly, the economic, environmental, and social aspects are assessed by using the LCC, LCA, and Social LCA. Thirdly, the LCC, LCA, and social LCA results are integrated into the LCSA by estimating and applying the weightings of each dimension. Lastly, a sensitivity analysis is conducted by using the ternary diagram.

2. Characteristics of road construction projects, material selection, and sustainability

2.1. Road construction projects

2.1.1. Terms and characteristics

This section explains the terms and definitions of road construction projects. The terms of projects, construction projects, owners, construction material, material selection, and the construction project life cycle are presented below.

A project is a temporary attempt to obtain a particular outcome restricted by a recognized scope and implemented in a certain period (Todorovic et al., 2014; Ma and Fu, 2020). According to A Guide to the Project Management Body of Knowledge (PMI, 2017), a project is defined as a temporary, unique, and progressive effort made to produce many types of tangible or intangible results (a product, service, benefit, and competitive advantage). The effort usually involves a series of interconnected tasks planned for the implementation during a fixed period.

The project *owners* are responsible for establishing the project and ensuring that the project deliveries create benefits to customers (Andersen, 2012). They play an essential role in defining, managing, and delivering project values. The owners also define the benefits, establish a project strategy, identify project requirements, and make critical decisions.

The term "*road*" is defined as a way, a route or land that has been constructed, paved, repaired, or improved to allow travelling by foot, vehicles, or animals. A road often includes one or two roadways along with lanes, sidewalks, or road verges. The term "road" also covers bridges, tunnels, or supporting structures (UNECE, 2009).

A *construction project* is an organized process that constructs, renovates, and refurbishes buildings, structures, or infrastructures. The construction project put a project team, documents, resources, and construction methodologies together to produce specific construction products. A construction project is categorized based on its product types, such as residential, industrial, commercial buildings, and infrastructure projects (Liu et al., 2018). Each construction project type has unique characteristics and requirements. For example, road construction projects do not use elevators, but the buildings need them to move up and down conveniently.

The term "*Road construction project*" has been used to describe a long-term construction process in which construction materials or other resources (e.g., equipment and laborers) are placed, assembled, and transformed until a complete road is obtained and then deconstructed (Barbu and

Sandu, 2020). The road construction project uses materials similar to other construction project types.

The term *stakeholders* is defined as the people, groups, or organizations that could impact or be impacted by the road construction project. The stakeholders have various roles concerning the success of road construction projects (PMI, 2017).

The *life cycle approach* offers a comprehensive framework to structure an extensive view of the whole production process, and it is generally broken down into phases. This approach identifies and emphasizes perspectives that affect every life cycle phase (Biggins et al., 2016). It offers tools, programs, and procedures to support making lifecycle-based decisions.

Project Management Institute (PMI) defined *a project life cycle* as a series of phases that a project passes through from its initiation to its closure. The division of these phases depends on functional or partial objectives, intermediate results, important milestones, or financing supports (PMI, 2017).

Construction materials are defined as physical substances that make up structural components or support the construction works to complete the project. They are important components in a project because their diversities, specifications, and qualities directly impact construction products' applicability, artistry, and durability (Sičáková, 2015). The road construction project uses the same material pool as other construction projects.

Construction material selection is a strategy and process of selecting the most suitable materials based on given criteria and standards. The selection includes six typical steps: (1) Identify the design requirements; (2) Identify element design requirements; (3) Identify candidate materials; (4) Evaluate materials; (5) Determine the satisfaction of evaluated materials; (6) Select materials (Pfeifer, 2009a). The road construction material selection has the same process as building and industrial construction material selections.

Material-dependent activities refer to the activities of laborers and equipment in line with the materials to complete a specific task. Material-dependent substances involve materials, chemicals, and other auxiliary items used together with given material to complete a specific task. The material-dependent activities and substances are determined by construction methods.

There are many technical definitions and terms relating the road construction projects. Several examples of those are presented below according to (FHWA, 2004) and (NCHRP, 2004):

- *A cross-section* is a drawing that illustrates a section of the road that has been sliced across the entire width of the project. It can be used to illustrate a stream, slope, or slide.

- *Ditch/Side Drain* refers to a channel running along the road to collect water from the road and adjacent to a suitable disposal point.
- *Grade/Gradient* is the slope of the road along its alignment. It is expressed as a percentage and the ratio of elevation change compared to the distance travelled.
- *Plan View/Map View* is the view looking from the sky towards the ground (bird's-eye view).
- *Road Center Line* is an imaginary line that runs longitudinally along the middle of the road.
- The paved or unpaved *shoulder* lasts along the edge of the road. An inside shoulder is adjacent to the cut slope, while an outside shoulder is adjacent to an embankment slope.

In general, this section introduces important definitions utilized. The term "project" refers to the effort usually involving a series of related tasks planned for implementation during a fixed period. The project *owners* are responsible for establishing the project and making sure that the project deliveries create benefits to customers. The term "road" is defined as a way or a route that has been constructed, paved, repaired, or improved. The term "road construction project" can be defined as a long-term construction process in which construction resources (e.g., materials, equipment) are placed, assembled, and transformed until a complete road is obtained and then deconstructed. Whereas the "life cycle approach" refers to a comprehensive framework that structures an extensive view of the whole production process, "Project life cycle" is a series of phases that a project passes through from its initiation to its closure. "Construction materials" are defined as physical substances that make up the completed products, and "Construction material selection" is a process of selecting criteria-based materials. In the next section, the road construction project life cycle is clarified.

2.1.2. Introduction to the road construction project life cycle

The road construction project is a specific type of construction project, so it follows the general construction project's life cycle. It is argued that road construction projects should be divided into six phases, including (1) Initiation, (2) Planning and design, (3) Tender/Bidding, (4) Construction, (5) Handover and operation, and (6) Close-out (Figure 2.1) (ASCE, 2012; Eadie et al., 2013; Alroomi et al., 2016; Netto and Raju, 2017; Trigunarsyah, 2017; Awng, 2018). These phases are described below.

In the *Initiation phase*, defining the project scope and requirements is the most important task. The scope includes project targets, technical infrastructure properties, location, infrastructure type, and team members, while project requirements consist of technical, economic, social, and environmental standards (Griffin, 2010).

The primary goals of the *Planning and design phase* are to identify road structure, implementation plan, construction workload, material selection, and necessary budget. This phase includes two main tasks: designing and planning.

- Designing includes three main sub-steps: pre-design, preliminary design, and detailed design.
    - Pre-design step (or conceptual design phase): owners gather project information and establish detailed project design requirements, preliminary budget, and project influences. The criteria govern designers and architects as well as define the project's detailed properties (Klinger et al., 2006).
    - Preliminary design step (schematic design/early design phase): After establishing major criteria and collecting important information, designers complete the preliminary design, and then designers will choose the main materials directly. The content of the preliminary design phase is described in section 2.1.3. Several studies combine the pre-design step and preliminary design step in the preliminary design phase (Alroomi et al., 2016; Trigunarsyah, 2017; Erebor et al., 2019).
    - Detailed design step: The detailed drawings will be completed based on agreed preliminary designs (Pfeifer, 2009b). This phase includes outcomes such as 2D and 3D models, cost estimates, and construction plans. The detailed design will then be sent to specialists for examination and review.
- Planning is concurrently executed with the designing step. In this step, designers give a specific master schedule and budget allocation plan (De Marco, 2011). The schedule contains information about construction time, starting date, work relationships, and work procedure, while the budget allocation plan is a payment schedule for stakeholders.

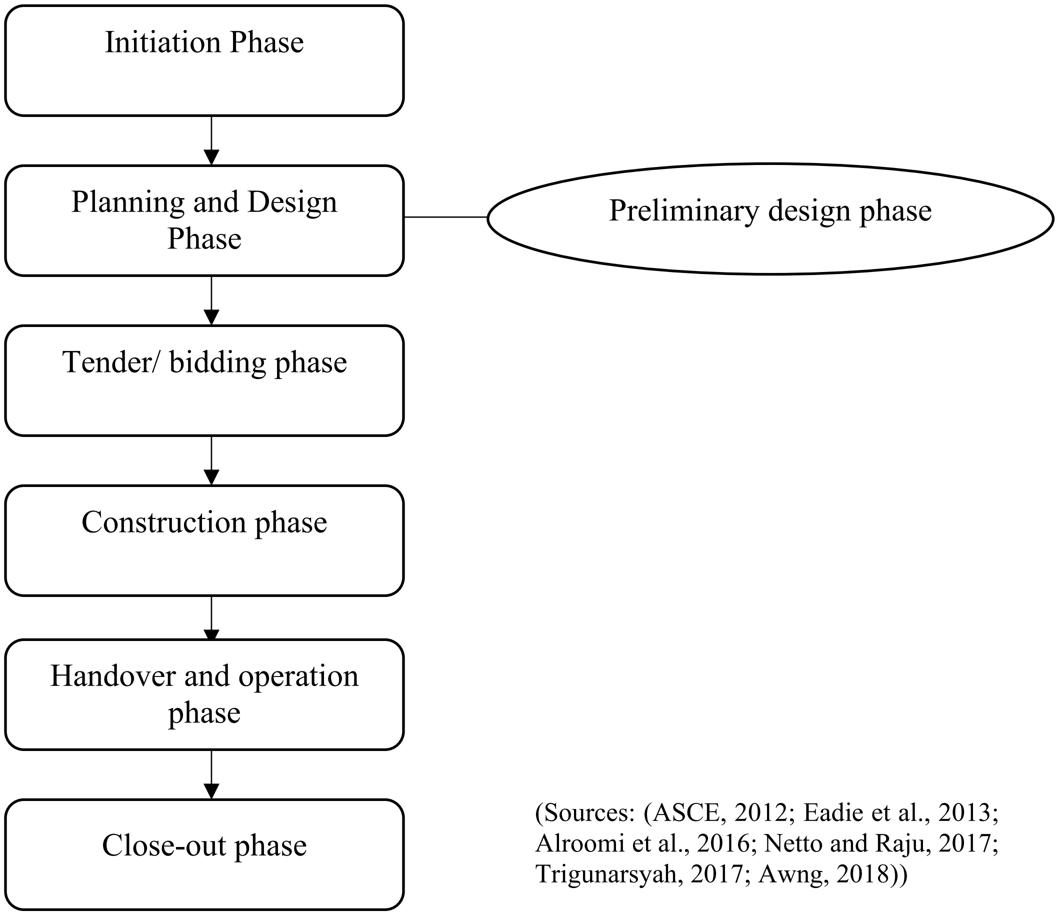
The third phase is the *Tender/ bidding phase*. In this phase, owners choose the most suitable contractors according to contractor selection criteria (e.g., construction method, budget). The criteria require thresholds in tender price, experience of bidders, and qualification of bidders.

The *construction phase* consists of pre-construction, construction, and construction management sub-steps.

- Pre-construction: owners complete legal procedures by getting a construction permit, cleaning the construction site, and preparing the budget. Simultaneously, contractors mobilize laborers, machines, and equipment to the construction area and find material suppliers.
- Construction: the contractor converts construction drawings along with resources such as materials, energies, laborers, and equipment to build the construction product (Harris et al., 2020). The contractor plays an essential role in this phase, while owners, designers, and supervisors govern the contractor's works.
- Construction management: owners manage the schedule, quality, cost, resources, environmental impacts, risks, safety, etc.

The fifth phase is the *handover & operation phase* (or operation and maintenance phase). The construction product achieves its full functions and transfers to the owner (Healey, 2010). During this period, maintenance, repairing and replacement activities are continuously conducted to keep the construction product in good condition.

The last phase is the *Close-out phase*. The road construction project comes to its end and finishes its life cycle. The project is dismantled, and a new one is proposed.



(Sources: (ASCE, 2012; Eadie et al., 2013; Alroomi et al., 2016; Netto and Raju, 2017; Trigunarsyah, 2017; Awng, 2018))

Figure 2.1. Phases of road construction projects

Based on Figure 2.1, the road construction project life cycle is clarified. Accordingly, the preliminary design phase is a component of the planning and design phase, in which *project design criteria,* such as its budget and milestones, are established. Rockizki and Peggy (Rockizki and Peggy, 2013) emphasized that this phase is a foremost part of the project's success because the main requirements and standards are clarified here. Besides, making decisions is an important task in this phase due to it impacts the project's sustainability performance (Erebor et al., 2019; Feria and Amado, 2019). Hence, the preliminary design phase will be dug into in detail below.

2.1.3. Preliminary design phase

The preliminary design phase (schematic design/early design phase) clarifies the requirements of the conceptual design phase (Andrade et al., 2012; Bragança et al., 2014; Feria and Amado, 2019). It involves the beginning of all essential documents to execute and manage the project by transferring ideas and information to plans, drawings, and specifications.

During this phase, the major tasks that all stakeholders should obey were pointed out by Bennett (Bennett, 2003). As argued by him, designers are put in charge of completing designs; engineers develop standards of how various systems conform to the construction product; and other members complete their assigned tasks. Hence, the phase's consequence contains schematics drawings, system configuration, structures, main items, layouts, or expected facilities. Similarly, Feria and Amado (Feria and Amado, 2019) emphasized that the preliminary design phase identifies the main structure, key materials, and required structure elements.

The preliminary design phase contributes significantly to the project’s success. This phase puts forth the project idea, which decides the project's feasibility (Cockton, 1992). Winkler and Chiumento (Winkler and Chiumento, 2009) defined this phase as the most important schematic scheme that is developed to determine the construction site, structure, and expected budget. Likewise, Rockizki and Peggy (Rockizki and Peggy, 2013) concluded that this phase is a foremost part of the project's success since the main demands, such as budget, main structures, and expected performance, are planned here. Besides, Erebor et al. (Erebor et al., 2019) suggested that the preliminary design phase provides massive sustainability opportunities since decisions taken here, such as material selection, influence the later phases. The impacts coming from selecting materials in this phase are presented in section 3.1.

In summary, the preliminary design phase transfers ideas to plans, drawings, and specifications and prepares all essential documents to execute and manage the project. In this phase, the owners seek the expected functions; designers are responsible for completing designs; and engineers develop standards. Its outcomes are dimensioned space layout, primary structures, main materials, utility and specific requirements, and the preliminary budget. Besides, the selection in this phase impacts the later ones of the project. The next section presents the road construction material selection.

2.2. Road construction material selection

Material selection is one of the most crucial tasks designers execute because it directly impacts overall project performance, such as time, cost, and quality (Mehmood et al., 2018). There is a wealth of rare and non-recovery materials used in the construction process (e.g., non-recovery coke and oil). Therefore, the material selection makes a significant contribution to obtaining sustainable development goals (Franzoni, 2011). This section will introduce the materials and their selection in the construction industry, as well as road construction projects.

Construction materials have a pivotal role in the construction industry. Firstly, they are *the most fundamental elements* that allow construction products to meet their requirements. Brick, stone, plaster, mortar, or concrete are arguably indispensable in any road construction project. Concrete products such as slabs, divided concrete, or pavements repeatedly appear in most projects. Secondly, using improper materials leads *to an increase in* project costs and negative environmental and social influences of selected alternatives. Thirdly, the selected materials' characteristics strongly impact the project's performance in *the construction and maintenance phases*. Using suitable materials would likely reduce the construction time, rate of defective materials, as well as repair costs. Besides, the expenditures for running and operating activities could be minimized by improving the quality of material selection.

Horvath (Horvath, 2004) pointed out primary construction materials, such as sand, cement, clay brick, concrete block, paints, etc. As suggested by Sičáková (Sičáková, 2015), construction materials are categorized into groups in respect of their different features. According to Sičáková, *chemical properties*, materials could be inorganic, organic, and combined materials. Based on the *treating level* factor, the divisions contain non-treated natural, waste raw materials, treated raw materials, half-finished materials, composite materials, and final materials. Classification based on the *utilization/function* criteria involves structural and functional materials. From the perspective of *origins,* construction materials are interpreted as natural materials or secondary raw materials. And the general *technical criteria* identify them as ferrous metals, nonferrous metals, plastics, ceramics/diamonds, composite materials, and nano-materials. According to Pandey and Singh, materials are also categorized by six characteristics: mechanical properties, tensile strength, hardness, ductility, impact strength, wear resistance, corrosion resistance, and density (Pandey and Singh, 2017).

Construction material selection is a strategy and process of selecting the most suitable materials based on given criteria and standards. The selection includes five typical steps: (1) Identify the design requirements; (2) Identify element design requirements; (3) Identify candidate materials; (4) Evaluate materials; (5) Determine the satisfaction of evaluated materials; (6) Select materials (Pfeifer, 2009a). In a nutshell, material selection is a process in which the designers compare material's specifications to requirements and criteria, including various material alternatives and complex evaluation criteria (Maghsoodi et al., 2020). According to (Amu et al., 2012; Festus and Adewuyi, 2020), the primary objective of road construction material selection focuses on ensuring the materials' economy and stability. They also confirmed that the knowledge of soil, material properties, and binding materials must be required in selection activities.

Some authors consider that material selection is a component of Multi-criteria decision-making (MCDM method) problems in the construction industry (Mousavi-Nasab and Sotoudeh-Anvari, 2017; Maghsoodi et al., 2019; Maghsoodi et al., 2020). Due to the fact that the MCDM method encompasses numerous criteria, including technical, economic, and environmental considerations. These criteria are normally in conflict with each other because an optimal selection for one criterion could sacrifice others (Lee et al., 2020a).

In contrast, selecting inappropriate materials results in ineffective projects and negatively impacts the economic, environmental, and social dimensions (Florez et al., 2013; Govindan et al., 2015). This thesis assumes that the road construction material selection has the same process as building and industrial construction material selections because the road construction project is a subtype of general construction projects.

Generally, construction materials are the most fundamental elements that allow construction products to meet their requirements and cause the rise in project costs, and negative environmental and social impacts. Construction material selection plays an essential role in obtaining goals of sustainable development. It is a strategy and process of selecting the most suitable materials based on given criteria and standards by comparing material's specifications to requirements and criteria. The following section clarifies the relationship between sustainability and road construction material selection in the preliminary design phase.

2.3. Sustainability and the preliminary design phase

2.3.1. Development of sustainability

The term of *Sustainability/Sustainable Development* suggested by World Summit Sustainable Development and United Nations was defined as: *'we assume a collective responsibility to advance and strengthen the interdependent and mutually reinforcing pillars of sustainable development, economic development, social development, and environmental protection - at the local, national, regional, and global levels' (WSSD and UN, 2002).*

Sustainable development was first mentioned by Carlowitz (von Carlowitz, 1713). After that, an official document covering the fields of primary conservation–oriented and sustainable use was signed by thirty-three African countries in 1969 (Nnadozie, 2003). Subsequently, in 1970, the National environmental policy act (NEPA) published in the USA formed the basis for the first policies on sustainability, including the promotions of harmonious relationships between humans and the environment, avoiding environment destruction, reinforcing the knowledge of ecological system and natural habitat, and establishing a Council on Environmental Quality (Bickford, 2013). In the United Nations Conference on the Human Environment, the majority of participating nations expressed their concerns about environmental protection and sustainable development. As a result, a declaration of 26 principles directly connected with the environment and its development was instituted, followed by an 'Action Plan, the United Nations Environment Program, and Resolutions'.

The World Conservation Strategy report published in 1980 stressed that the development of humanity does not only depend on economic expansion but also the vital maturity of the society and ecological system (IUCN et al., 1980). The first conceptualization of sustainability appeared in 1987 in the Brundtland Report (Our Common Future Report) by the World Commission on Environment and Development. This concept has become the key that helps countries shape their opinions, orientations, and solutions regarding sustainable development.

Because of the urgency of sustainable development, the United Nations Conference on Environment and Development held in Rio de Janeiro *in 1992* witnessed the consensus among member states on the set primary principles as well as the launch of an action plan named Agenda 21 that aims to achieve global sustainable development (United Nations, 1992).

The World Summit on Sustainable Development held in Johannesburg in *2002* reviewed overall performance and achievements over the 10-year period since the Rio Summit. Accordingly, existing issues were altogether touched on, including overpopulation, the gap between developed and developing countries, climate change, and environmental pollution *(WSSD and UN, 2002)*.

The UN Sustainable Development Summit held at the UN headquarters in New York in 2015 introduced a new sustainable development agenda. This newly-proposed agenda consists of seventeen sustainability goals, such as no poverty, zero hunger, good health, and well-being (United Nations, 2015)

The terminology of "*Triple bottom line*" was initiated by Elkington (Elkington, 1999). The author defined it as a framework for measuring and reporting corporate performance against economic, social, and environmental parameters. In essence, the definition is consistent with the aims of sustainability that focus on protecting natural habitats, facilitating economic growth, and ensuring social justice as well as human living conditions. Sustainability could not be reached without considering the three aspects related to the triple bottom line (Norouzi et al., 2017).

The *economic aspect* of sustainability refers to an organization's influences on the economic situation and enhancements to a community's economic growth, competitiveness, and vitality. Moreover, it is essential that economic activities do not lead to a long-term decline in social or ecological capital. The economic aspect refers to balanced growth that does not rely on the loss of resources, as it takes the carrying capacity of the environment and future generations into account. The LCC is a tool for assessing economic performance by estimating the total cost concerning trade-offs during life cycle phases (Götze et al., 2014).

The concept of the *environmental aspect* focuses on the natural environment and the way of maintaining and developing in order to support nature and human life. According to Brodhag & Talière, environmental sustainability includes the ecological integrity and provenance of the natural environment (Brodhag and Talière, 2006). They also recommended that natural resources can be used sustainably by controlling and reducing resource inputs. Natural resources need to be consumed no faster than they can be regenerated, while waste must be generated but no faster than they can be assimilated by the environment (Diesendorf, 2000; Evers, 2018).

Social sustainability is achieved when the official and unofficial processes actively enhance the capacity of current and future generations. The processes generate happy, healthy, and worthwhile communities for people (WACOSS, 2002). It is argued that social sustainability is not easily achieved because the social dimension seems complex and overwhelming (Saner et al., 2020). Unlike economic and environmental systems, where input and output flows are easily observable, the flows in social systems are intangible and cannot be easily modelled (Kolk, 2016; Saner et al., 2020). Figure 2.2 describes the triple bottom line of sustainable development.

(Source: (Diesendorf, 2000))

Figure 2.2. The three-pillar model of sustainable development

Overall, this section briefly introduced the development of sustainability. It can be seen that the perspectives of sustainability should be paid more attention to. The next section conducts the literature review of sustainability in the early design phase.

2.3.2. Sustainability in the preliminary design phase

The preliminary design phase plays an essential role in the achievement of final design's sustainable goals since decisions regarding major project values have to be made in this phase (Bertoni et al., 2015). Besides, the decisions straightly impact the project outcome and success (Pancovska et al., 2017; Feria and Amado, 2019; Moghtadernejad et al., 2020). Hence, the National Institute of Building Sciences (NIBS, 2014) and Li and Guo (Li and Guo, 2015) suggested that sustainability principles should be applied from the preliminary design phase to meet the sustainability requirements. In other words, the concepts and principles of sustainability, coupled with triple bottom lines (economic, social, and environmental dimensions), need to be included in the preliminary design phase.

The integration of sustainability into the preliminary design phase has been researched in several studies. For example, the Information and Communications Technology (ICT) and Leadership in Energy and Environmental Design (LEED) rating system were combined by Andrews et al. (Andrews et al., 2006) to establish healthy and productive working environments for building occupants. The results showed that the LEED system and ICT could be applied in the preliminary design phase to select the buildings. Likewise, four aspects of environmental comfort, including thermal, acoustic, natural lighting, and functionality, were researched by Graca et al. (da Graça et al., 2007). They analyzed 39 existing school designs to present a method for evaluating and optimizing the environmental comforts based on their four proposed aspects.

Other studies from 2010 to 2022 researching the integration of sustainability into the preliminary design phase were shortly briefed in Appendix 8.1.

The current studies mainly focus on building a method to support the designers in assessing the sustainability performance (Gharzeldeen and Beheiry, 2014; Bertoni et al., 2015; Gültekin et al., 2018; Marta et al., 2019). However, some challenges remain in the integration of sustainability into the preliminary design phase of road construction projects. The social aspects are mostly neglected, though they need consideration similar to the others during the preliminary design phase (Nigra et al., 2015). Besides, most case studies have concentrated more on the requirements of building construction projects than road construction projects. For example, the vast majority of studies evaluate the economic and environmental performance of heating, ventilation, and air conditioning system (Lucchini et al., 2012; Stanescu et al., 2013; Dong et al., 2016; Nesticò et al., 2017; Marta et al., 2019).

Summarily, this section focused on the importance of sustainability in the preliminary design phase and reviewed the literature concerning this content. Accordingly, it drew an overall picture of applying sustainability to the preliminary design phase and pointed out its challenges, such as the lack of social performance assessment. Selecting material is an important task in the preliminary design phase. The next section introduces the current studies integrating road construction material selection and sustainability in the early design phase.

3. Current material selection methods towards sustainable development in the preliminary design phase

3.1. Overview of current material selection studies

Long-term issues like resource depletion and environmental pollution are defined as pronounced problems of sustainable development. Road construction project activities cause severe harm to the environment as they consume a tremendous volume of resources and release pollutants into the environment.

The National Institute of Building Sciences (NIBS, 2014) and Li and Guo (Li and Guo, 2015) proposed that sustainability principles should be applied from the preliminary design phase to meet the sustainability requirements. Likewise, according to (Erebor et al., 2019; Feria and Amado, 2019), the selection in the preliminary design phase impacts the later phases, and its decisions straightly affect the project outcome and success (Feria and Amado, 2019; Moghtadernejad et al., 2020). Hence, selecting materials is one of the most significant tasks in the preliminary design phase since it contributes greatly to the existence of sustainability (Rockizki and Peggy, 2013). By embracing the tripartite concepts of sustainability, the selection paves the most straightforward way for sustainability approach (John et al., 2005). This section reviews the literature concerning material selection in the preliminary design phase towards sustainable development.

Deng and Edwards (Deng and Edwards, 2007) clarified the design phase's material selection process. According to them, the preliminary design phase has fewer supporting tools for selecting materials than the later stages. Their study also revealed that the research community has not yet focused on the material-dependent activities and integration of the product life cycle in the early design phase. Selecting materials in the preliminary design phase is mainly based on designers' experience (Weytjens and Verbeeck, 2009). This approach makes more mistakes than employing numerical methods because designers' experience is limited, and available alternatives cannot be compared clearly without specific values or numbers.

Andrade et al. (Andrade et al., 2012) reviewed the previous research to define design phases, emphasized the importance of sustainability, and set out sustainability indicators comparing different construction solutions, including main materials. The indicators are divided into economic, environmental, and social indicators. The environmental indicators cover global warming potential, depletion potential of the stratospheric ozone layer, resource use, waste categories, and energy demand. The economic criteria focus on life cycle costs, while the social aspects include accessibility, functionality, health and comfort, and safety and security. In general, their research pointed out the critical sustainability indicators but did not provide a comprehensive implementation guide.

The importance of material selection in the preliminary design phase was confirmed by Rockizki and Peggy (Rockizki and Peggy, 2013). This phase impacts the product's performance by setting up the main structures, materials, budget, and project requirements. However, they pointed out that the current selection approaches in the schematic design phase were mostly in conformity with the mechanical engineering and economic aspects rather than combining sustainable development. They also attempted to integrate environmental factors into the material selection. Besides, the integration challenges were identified, such as the insufficient database, various environmental profiles, and complex product life cycle. According to them, several authors (Giudice et al., 2005; Bovea and Gallardo, 2006; Ashby et al., 2009) exerted to touch on the combination of environmental aspects in the material selection, but they encountered many obstacles, including unavailable information, different environmental profiles, environmental impact quantification, and complex product life cycle. Besides, the approaches were only general ideas without detailed instructions, and social problems were not included.

Braganca et al. (Bragança et al., 2014) suggested the critical indicators applied to compare material alternatives in the preliminary design phase. It defined environmental impacts, energy, and life cycle costs as indicators to assess the sustainability performance at the preliminary design phase. The environmental indicators include (1) Global warming; (2) Depletion potential of the stratospheric ozone layer: (3) Acidification potential of land and water: (4) Eutrophication potential; (5) Formation potential of tropospheric ozone photochemical oxidants; (6) Abiotic resource depletion potential for elements; (7) Abiotic resource depletion potential of fossil fuels. The energy criterion is the total primary energy demand, and the economic criteria consist of (1) Construction costs; (2) Operation costs; (3) End-of-life costs. Their study also emphasized that the material selection in the preliminary design phase is significant, but the social aspects are neglected.

Zhong et al. (Zhong et al., 2016) offered a model comparing reinforced concrete and structural steel that integrates constructible, economic, and environmental aspects in the preliminary design phase. Firstly, a list of economic sustainability (e.g., material costs, maintenance costs), environmental sustainability (e.g., greenhouse gas, solid wastes), and constructability performance attributes (e.g., construction quality, construction flexibility) was established by reviewing previous studies. Secondly, an interview was carried out to eliminate the attributes that were not significantly important when selecting materials. After that, their research used the Likert scale and analytic hierarchy process (AHP) method to determine the identified crucial attributes' rates and weightings. Lastly, The weightings and rates are aggregated into a single Structural Frame Material score (SFM). The alternative gaining a higher SFM score takes priority over the others. As a whole, the proposed method helps designers select the most sustainable material. Nevertheless, it limits on integrating the social performance, material-dependent activities and the time value of money during the construction project.

Building Information Model (BIM) is an approach to increase collaboration and communication between project stakeholders. The integration between the stakeholders could be facilitated by applying BIM in the preliminary design phase because it offers comprehensive management during the project life cycle (Hungu, 2013). Accordingly, a BIM-integrated TOPSIS-Fuzzy framework was proposed to optimize the selection of sustainable building components and materials in the schematic design phase (Jalaei et al., 2015; Fazeli et al., 2019). The framework includes five phases: (1) create database and parameters; (2) Design BIM model; (3) Extract data to excel and determine weightings; (4) Calculate data; (5) List and rank the alternatives. In general, the proposed framework effectively assesses the sustainability performance of construction materials. However, it is developed based on sustainability criteria of buildings, so it should be modified to apply in road construction projects. Furthermore, this method requires a various database and modern information management systems that only developed countries can perform.

Feria and Amado (Feria and Amado, 2019) published a paper discussing the potential of integrating sustainability into the design phases. According to a survey, their investigation confirmed that the sustainability principles need to be covered at the preliminary design phase, in which the decision influences the whole product life cycle. They also defined a guideline that points out major contents requiring sustainability integrated: (1) Structure and materials; (2) Internal layout; (3) Opening elements; (4) Shading elements; (5) Natural ventilation; (6) Additional energy-efficient strategies. In general, their study emphasized the importance of integrating sustainability into material selection in the early design phase. However, the proposed guideline was unable to support designers in selecting sustainability materials effectively because it is too general without detailed instruction.

Besides, Soust-Verdaguer et al. (Soust-Verdaguer et al., 2022) emphasized the gap in available data between the preliminary design phase and the detailed design phase. In order to assess the sustainability of construction products and materials during the preliminary design phase, they proposed integrating LCSA and Building Information Modelling (BIM). The LCSA can be implemented in the preliminary design phase, while databases taken from the BIM model offer more comprehensive inputs and outputs. Using data extracted from BIM, the LCC, LCA, and S-LCA were performed and incorporated into the LCSA. However, a case study is not conducted, and it is only applicable to developed countries which can apply BIM in the construction industry.

Generally, studies about material selection and sustainability in the preliminary design phase were reviewed in this phase in order to answer the first two research questions (see Appendix 8.2). The current studies are difficult to integrate sustainability into selection in the preliminary design phase due to the shortage of database and supporting tools, the dominance of the technical and physical aspects, various environmental profiles, the shortage of a detailed guideline, the lack of case studies, and the abandonment of the research community. That being the case, it is critical to establish a comprehensive procedure model to evaluate the economic, environmental, and social dimensions altogether for selecting road construction material towards sustainable development in the preliminary design phase. The model should deal with the mentioned challenges. The following sections introduce potential approaches that can be applied to build the model.

3.2. Sustainability criteria in the construction industry

Many authors drilled into the sustainability criteria utilized for assessing sustainability performance. The criteria are established based on the literature review, survey, and historical data. This section reviews the sustainability criteria in the construction industry and points out the main criteria impacting road construction material selection towards sustainable development.

Akadiri and Olomoilaye (Akadiri and Olomolaiye, 2012) identified sustainable assessment criteria and came up with a cluster of 24 sustainability criteria. To establish the criteria, a form of a questionnaire including 24 selected sustainability factors was prepared first and sent to construction stakeholders via email in order to investigate the opinions of designers about the significance of the factors. Second, the results derived from the returned answers were analyzed in order to clarify the interrelationships among criteria and rank them in terms of applicability. Noticeably, these 24 proposed sustainable assessment criteria were all marked as either "high" or "medium-high" when it comes to the significant level, implying that they could be applied in the construction material selection. Besides, Ogunkah and Yang (Ogunkah and Yang, 2012) published their research on factors affecting road construction material selection. They divided these factors into six groups involving (1) general/site factors (location, distance, scale), (2) environment/health factors (safety, waste prevention), (3) cost/economic factors (life cycle cost, labor cost), (4) sensorial factors (appearance, texture, color), (5) social/cultural factors (compatibility, aesthetics traditions), and (6) technical factors (reusability, demonstrability). Similarly, by reviewing other studies, a list of primary sustainability criteria for selecting materials in the construction industry is established (Table 3.1).

Table 3.1. The list of sustainability criteria

ID	Sustainability criteria	References	Interpretation
A	**Economic criteria**		
A1	Price of materials	(Zhou et al., 2009; Akadiri and Olomolaiye, 2012; Ogunkah and Yang, 2012; Bragança et al., 2014; Govindan et al., 2015; Khoshnava et al., 2018; Mahmoudkelaye et al., 2018; Roy et al., 2019)	"Price of material" is the price when the contractors or owners order from the suppliers. This thesis assumes that the material price covers the costs of the material extraction and manufacturing phases.
A2	Cost of the material transport	(Zhou et al., 2009; Bragança et al., 2014; Pancovska et al., 2017; Mahmoudkelaye et al., 2018; Falqi et al., 2019)	"Cost of the material transport" covers the costs of vehicles during the material transportation process.

A3	Cost in the construction phase	(Zhou et al., 2009; Bragança et al., 2014; Govindan et al., 2015; Mahmoudkelaye et al., 2018; Roy et al., 2019)	"Cost in the construction phase" refers to the costs of construction activities (such as, costs of labor and equipment) in the construction area.
A4	Cost in the operation and maintenance phase	(Akadiri and Olomolaiye, 2012; Govindan et al., 2015; Mahmoudkelaye et al., 2018; Falqi et al., 2019; Roy et al., 2019)	"Cost in operation and maintenance phase" includes the costs of fixing or replacing materials.
A5	Cost in the demolition phase	(Zhou et al., 2009; Akadiri and Olomolaiye, 2012; Govindan et al., 2015; Mahmoudkelaye et al., 2018; Roy et al., 2019)	"Cost in the demolition phase" covers the costs of road deconstruction.
B	**Environmental criteria**		
B1	Energy consumption	(Zhou et al., 2009; Akadiri and Olomolaiye, 2012; Ogunkah and Yang, 2012; Govindan et al., 2015; Park et al., 2017; Khoshnava et al., 2018; Mahmoudkelaye et al., 2018; Falqi et al., 2019)	"Energy consumption" represents electricity or fuel consumed by construction equipment. The construction equipment needs gas or electricity in operation.
B2	Water consumption	(Dusart et al., 2011; Bragança et al., 2014; Govindan et al., 2015;	"Water consumption" criterion represents the amount of water consumed by laborers or construction equipment.

		Park et al., 2017; Mahmoudkelaye et al., 2018)	
B3	Global warming	(Ogunkah and Yang, 2012; Bragança et al., 2014; Govindan et al., 2015; Žitný et al., 2016; Khoshnava et al., 2018; Mahmoudkelaye et al., 2018; Arukala et al., 2019)	"Global warming" refers to the increase of the earth's temperature, which causes climate change. This criterion is represented by greenhouse gases emission (e.g., CO_2)
B4	Waste production management	(Zhou et al., 2009; Govindan et al., 2015; Park et al., 2017; Falqi et al., 2019)	"Waste production management" is the management of waste production. The number of recycling scraps represents this criterion.
B5	Toxic emission	(Zhou et al., 2009; Akadiri and Olomolaiye, 2012; Bragança et al., 2014; Park et al., 2017; Mahmoudkelaye et al., 2018; Arukala et al., 2019)	"Toxic emission" is the emission of poisons to the environment when using the construction material. Construction materials have many volatile organic compounds and poison chemicals.
B6	Natural resources depletion	(Zhou et al., 2009; Bragança et al., 2014; Mahmoudkelaye et al., 2018)	Construction materials are natural resources such as steel, wood, or oil. It makes the number of natural resources decrease.
B7	Acidification of land and water	(Bragança et al., 2014; Žitný et al., 2016;	Construction material emit chemical poison (e.g., SO_2, NO_x, H_2S,..) into land or water.

		Mahmoudkelaye et al., 2018)	
B8	Potential in recycling and reuse materials	(Akadiri and Olomolaiye, 2012; Govindan et al., 2015; Mahmoudkelaye et al., 2018; Arukala et al., 2019)	"Potential in recycling and reuse materials" refers to the construction material recyclability.
C	**Social criteria**		
C1	Safety in construction and operation	(Akadiri and Olomolaiye, 2012; Ogunkah and Yang, 2012; Govindan et al., 2015; Mahmoudkelaye et al., 2018; Arukala et al., 2019)	In the construction site, safety is the priority, and it must be ensured for workers, residents, and clients.
C2	The health of laborers and residents	(Akadiri and Olomolaiye, 2012; Ogunkah and Yang, 2012; Govindan et al., 2015; Khoshnava et al., 2018; Mahmoudkelaye et al., 2018; Arukala et al., 2019; Falqi et al., 2019)	Some materials emit chemical poisons, which harm the health of laborers and residents.
C3	Labor availability	(Akadiri and Olomolaiye, 2012; Govindan et al., 2015; Roy et al., 2019)	The construction works use many local laborers.

(Source: a previous paper from author and co-authors (Dinh et al., 2020))

According to Table 3.1, the list of sustainability criteria includes economic, environmental, and social criteria. The table presents the primary criteria, their references and interpretations. The economic criteria are divided into (1) Price of materials; (2) Cost in the material transport; (3) Cost in the construction phase; (4) Cost in the operation and maintenance phase; (5) Cost in the demolition phase. The environmental criteria are categorized into (1) Energy consumption; (2) Water consumption; (3) Global warming; (4) Waste production management; (5) Toxic emission; (6) Natural resources depletion; (7) Acidification of land and water; (8) Potential in recycling and reuse materials. The social criteria fall under categories such as (1) Safety in construction and operation; (2) The health of laborers and residents; (3) Labor availability. All criteria are gathered from previous studies, along with their interpretations.

The life cycle approach is able to support designers in selecting construction materials in the preliminary design phase by offering a comprehensive framework to structure an extensive view of the whole road construction process that is generally broken down into stages (Biggins et al., 2016). Babashamsi et al. (Babashamsi et al., 2016a) reviewed most of the sustainability tools and affirmed the importance of the life cycle approach. They also pointed out that the life cycle approach has many advantages, such as considering economic, environmental, and social aspects equally and assessing sustainability performance in the long term. The life cycle approach, including the life cycle cost, life cycle assessment, and social life cycle assessment, emerges as a tool for evaluating the economic, environmental, and social faces, respectively. The LCC is a tool for assessing economic performance by estimating the total cost concerning trade-offs during life cycle phases (Götze et al., 2014), while the LCA evaluates alternatives in terms of environmental impacts during life cycle phases (Carvalho et al., 2016). The Social LCA analysis helps designers and architects assess social performance (UNEP and SLCA, 2020). Many other studies have also attempted to assess sustainability performance by separately utilizing the LCC, LCA, and Social LCA analyses (Rockizki and Peggy, 2013; Bragança et al., 2014; Hosseinijou et al., 2014; Jalaei et al., 2015; Babashamsi et al., 2016b; Hossain et al., 2017; Fazeli et al., 2019; Feria and Amado, 2019; Chen et al., 2020). Besides, the LCC, LCA, and Social LCA analyses may cover sustainability criteria listed in Table 3.1.

Summarily, many authors exerted to establish criteria to assess the sustainability performance in the construction industry. Accordingly, a list of principal sustainability criteria covering economic, environmental, and social dimensions was proposed to determine the sustainability performance of road construction material selection in the early design phase. The following section summarizes the main contents of LCC, LCA, Social LCA, and LCSA for assessing the sustainability performance of construction.

3.3. Methods for economic evaluation

The economic aspect is one of the top priorities in comparing and selecting construction materials, along with technical, environmental, and social dimensions (Adams, 2006; Gundes, 2016; Trigaux et al., 2017; Li et al., 2019). *The life cycle costing/life cycle cost (LCC)* method is applied widely in assessing the economic performance of alternatives. This method serves as an effective tool to differentiate between and compare the economic performance of alternatives. It also provides a meaningful supporting tool that allows all costs incurred through the product life cycle to be tallied. The below sections introduce this method and its application in road construction material selection.

3.3.1. Terms and definitions in the life cycle cost method

This section presents the terms and definitions used in the LCC. Main definitions, such as life cycle cost, the cash flow, and the time value of money, are interpreted according to previous studies.

Through an academic lens, the term *of life cycle costing/ life cycle cost (LCC)* method has been persistently explicated by scholars. According to Dhillon (Dhillon, 2009), the LCC analysis adds all costs incurred throughout the life cycle of an item or service. Likewise, the LCC is a tool for evaluating economic performance by estimating the total cost concerning trade-offs during life cycle phases (Götze et al., 2014). In recap, the LCC analysis is conceived as a system tracking and cumulating all costs correlated with a particular item from its idea to its abandonment phase. For the construction industry, this method calculates the total costs incurred in initiation, planning and design, tender/bidding, construction, handover & operation, and close-out phases.

The cash flow is the movement of money from one individual/group to another one. It is also defined as the expected cash inflows and outflows of an investment alternative (Mussatti and Vatavuk, 2002). According to Mussatti and Vatavuk, cash inflows are revenues generated from the sale of goods or services, while cash outflows stem from paying products’ expenses. According to Götze et al. (Götze et al., 2015), an investment project is a course of cash in- and outflows, normally beginning with a cash outflow followed by cash inflows.

The term *“Total life cycle cost”* is the total cost of a product or service incurred during its life cycle. Accordingly, the total life cycle cost could be presented as an equation below (DSN, 2005; Mearig et al., 2018):

$$\text{Total life cycle cost} = \begin{array}{c}\text{capital cost + operating and maintenance cost + replacement}\\ \text{cost + repair cost + disposal cost – savage value}\end{array} \qquad 3.1$$

The term “*Time value of money”* is used to consider the fact that the current value of a specific amount of money would likely be dissimilar compared to its value in the future. As suggested by Götze et al. (Götze et al., 2015), the time value of money refers to the treatment of how time impacts the value of future returns achieved from undertaking an investment project. According to them, it is incorporated to compare cash flows from different periods, and the values depend on the time at which they take place. Hence, discounting or compounding cash flows are used to convert the values at different points in time (Götze et al., 2015). Using discounting approach, all future cash flows are transformed into their equivalent figures at the beginning of the project. Conversely, the cash flows are converted to their equivalent value at the end of the investment project by using compounding. *Discount rate is* a figure reflecting the time value of money. This rate is used to convert future cash flow to the present value (normally year 0) (ISO, 2017).

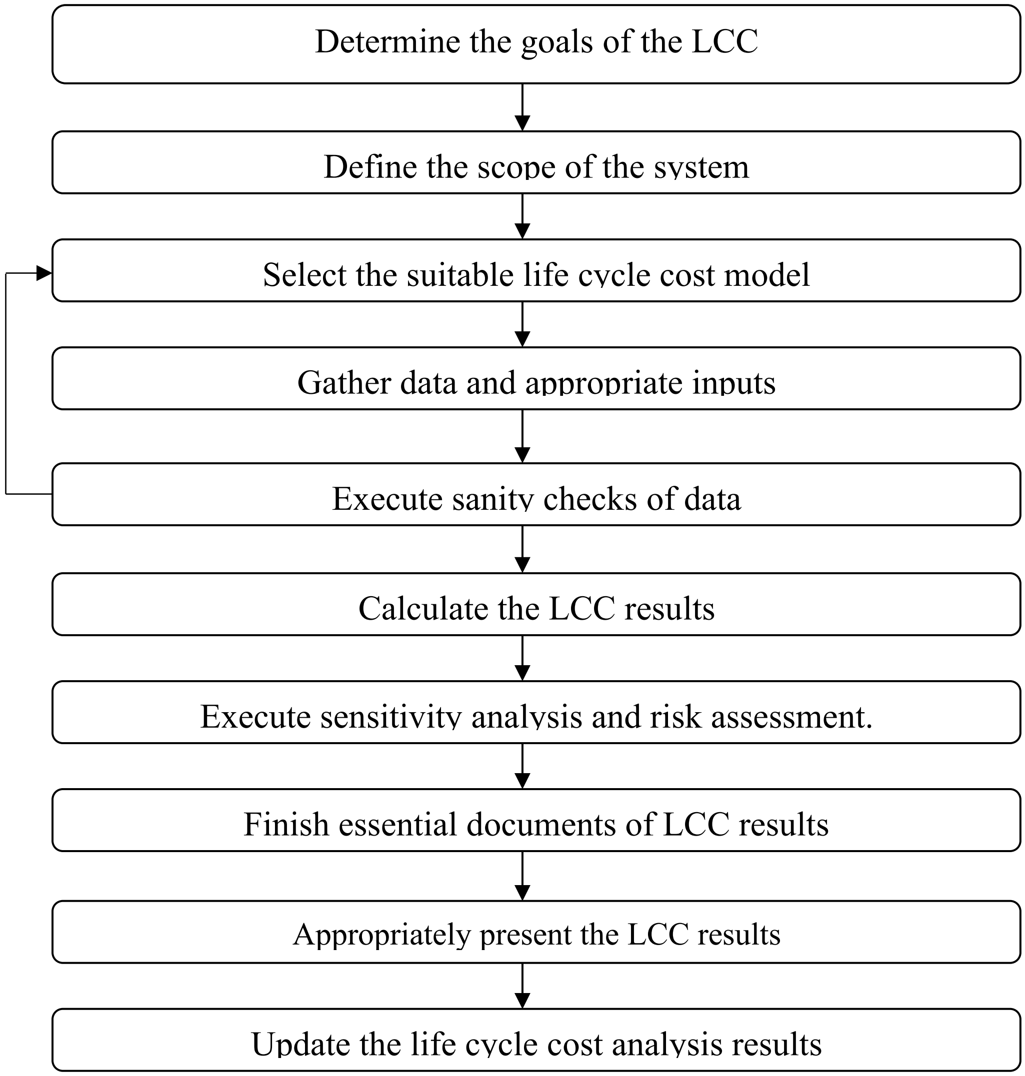
Net present value method is a method focusing on selecting projects that maximize the Net Present Value (NPV) generated from their implementation. NPV is the net monetary gain (or loss) from a project, reckoned by discounting all present and future cash inflows and outflows related to the project (Götze et al., 2015). By using the method, all future cash flows from the project will be discounted back to time 0 (discounting).

Material-dependent costs refer to the costs of laborers and equipment incurred in line with the materials to complete a specific task. According to Ehrlenspiel et al. (Ehrlenspiel et al., 2007a), the material-dependent costs should be estimated in the early design phase to increase the accuracy.

Terms and definitions in the LCC are introduced in this section. For example, the LCC is defined as a method for assessing economic performance by evaluating the total cost concerning relevant trade-offs during the project life cycle (Götze et al., 2014). The definitions fundamentally provide general knowledge for the LCC, and the next section briefly describes the LCC steps.

3.3.2. Life cycle cost analysis steps

Numerous authors conduct research on life cycle cost analysis. Barringer (Barringer, 2003) offered a process to estimate the LCC value. According to him, designers define the requirements of the project and prepare the cost breakdown structure first. Then the analytical chart and cost models are chosen to gather the data. Next, the cost profiles for each year are established to estimate the LCC value for alternatives. The sensitivity analysis and risk assessment of the high costs are then conducted to select the most cost-efficient alternative. This process gave detailed steps on how to apply the LCC analysis to select alternatives. However, the discount rate was not involved in the model. The basic steps of the LCC analysis are also suggested by Ho and Rahman (Ho and Rahman, 2004). They carried out the LCC analysis in six steps: (1) Define project name and alternatives; (2) Define project elements; (3) Define classifying and quantifying dimensions; (4) Estimate costs; (5) Compute life cycle costs; (6) Compare LCC result and select the most cost-effective alternative. In general, according to (Greene and Shaw, 1990; Barringer, 2003; Ho and Rahman, 2004), the life cycle cost analysis steps are presented below.



(Sources: (Greene and Shaw, 1990; Barringer, 2003; Ho and Rahman, 2004))

Figure 3.1. Life cycle cost analysis steps

According to the previous studies, the flowchart shown in Figure 3.1 illustrates ten steps of an LCC analysis session. The suggested process highlights the relationship between the steps and the gathered data.

Step 1: *Determine the goals of the LCC*: The goals of the LCC analysis need to be pointed out explicitly. The goals are dependent on the expected results received from the analysis. In some cases, these goals are pre-determined nevertheless do not reach the required degree of clarity, so they must be re-determine later.

Step 2: *Define the scope of the system*: In this phase, the system boundary is identified. This step specifies the activities and potential cost items that appear in the selected life cycle phases. Greene and Shaw (Greene and Shaw, 1990) confirmed that this step is extremely difficult because the system definition and scope are vague at the beginning of the project.

Step 3: *Select the suitable life cycle cost model:* In this step, experts identify and select cost items in order to build the LCC model. This selection is driven by the specified objective, its characteristics, or expected results.

Step 4: *Gather data and appropriate inputs:* the data gathered from diverse resources need to be clear, transparent, and reliable. Accordingly, the resources should be peer-reviewed articles, books, authority documents (regulations, policies), and internal sources. Several criteria could be used to estimate the reliability of a source, including (1) Accuracy (e.g., double-checking the information, looking for the disclaimer); (2) Authority (e.g., written by a trustworthy author and institution); (3) Update (e.g., Release time); (4) Coverage (e.g., identifying its relevancy) (Wette, 2020).

Step 5: *Execute sanity checks of data*: Within this step, the data need to be checked and appraised on the basis of consistency, accuracy, validity, and completeness. The consistency check is carried out to find out if the data have any conflicts. The accuracy check points out whether the data values inputted are the correct values. The validation check is conducted to confirm and provide evidence that the requirements of data are fulfilled. The completeness check determines whether the information from phases is sufficient for making conclusions regarding the goal and scope defined (ISO, 2006b). If the data do not meet the requirements, the model in step 3 will be revised and modified.

Step 6: *Calculate the LCC results*: In this step, experts calculate the LCC results based on the input data and the LCC model.

Step 7: *Execute sensitivity analysis and risk assessment*: Because the LCC analysis calls for a wide range of data from different sources, the sensitivity analysis and risk assessment should be carried out. The sensitivity analysis is performed to deal with data uncertainty. According to (Götze et al., 2015), the sensitivity analysis investigates the relationships between the various data and the outcomes to examine the influence of uncertain data and assumptions on the model's results.

Step 8*: Finish essential documents of the LCC results*: After choosing a suitable alternative, experts finalize the documents required to support and interpret the results. The documents should involve the system description, methodology description, analyzed results, proposed conclusions, and recommendations.

Step 9: *Appropriately present the LCC results*: the results are distributed to diverse groups of audiences. Hence, it is mandatory to ensure the clarity and understandability of the presentation with the help of suitable supporting tools, such as PowerPoint Presentation, Google Slides, and Prezi.

Step 10: *Update the life cycle cost analysis results*: The present inputs would unpredictably alter in the future due to the changes in cash flow or time parameters. Hence, the results would not be constantly accurate and therefore require timely updates. The updates can be conducted by tracking the actual costs of the project and comparing them to the estimated cost result. Accordingly, the experts can determine the odds, find out the reasons, and manage the budget.

The section presents the main LCC steps that experts should follow to evaluate the total cost of products or services during the life cycle. The next section introduces an LCC model that incorporates the discount rate.

3.3.3. Life cycle cost model

The LCC result is the sum of *cost elements* and revenues covering trade-offs through the product's life cycle. This section introduces a life cycle cost model normally utilized to estimate the total cost of products or services.

Dhillon (Dhillon, 2009) divided total cost into separate cost items, including recurring costs, nonrecurring costs, and costs in dissimilar phases. Accordingly, Dhillon also established a set of formulas that are applied to the construction industry. Because the project schedule often lasts for a significant period, the time value of the money factor needs to be taken into account continuously for the formulas to be viable and generate significant results. Likewise, the material decisions in road construction projects implicate long-term period investments, and the LCC models based on discounted cash flow methods, especially the net present value method, are suggested. The integration of the NPV method and the LCC addresses the long-term matter. Hence, the equation below serves as an essential presentation of this collaborative attempt (Biolek et al., 2017):

$$LCC = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \quad 3.2$$

Where:

- LCC is the life cycle cost from year 0 to year t;
- $C_{t:}$ is cost flows in year t
- t denotes year being analyzed (with t = 0,1,2,3,…,T)
- T is the project time
- r denotes the discount rate.

Essentially, the LCC value is calculated by summing all the costs incurred from year 0 to year T. The alternative selection depends on the LCC results, by which the most noteworthy alternative holds the lowest LCC value.

In general, for evaluating the total life cycle costs, the selected mathematical LCC model plays an important role. It is recommended to apply the method with its target value - "net present value", due to it is the most widely accepted method for estimating the economic performance in long-term projects. The next section introduces the NPV method that can be integrated into the LCC models to evaluate the total live cycle cost.

3.3.4. Net present value method

Because construction projects last many years, major methods of investment appraisal and their target values are useful for LCC. This part presents several main methods applied to assess the economic efficiency of construction projects. Next, the *Net Present Value (NPV)* is introduced as a potential method for comparing the total costs of road construction materials.

Dynamic methods such as *Static Payback Period, Internal Rate of Return (IRR), and Net Present Value (NPV)* are reviewed. The Static Payback Period is the period after which the budget invested is recouped from the average cash flow surpluses calculated from the project (Götze et al., 2015). This method should not be regarded as the decision criterion on its own because it is unable to incorporate profits and cash flows generated after the payback period. *Internal Rate of Return* (IRR) is the rate that prompts the NPV result of zero when applying it as a uniform discount rate (Götze et al., 2015). The IRR method and NPV method require the same data and underlying assumptions, but the IRR calculation is slightly more difficult than the NPV's. The *NPV method* is a potent tool that performs the task of evaluating and singling out the most valuable investment alternative (Krigsvoll, 2007; Schade, 2007). Substantially, NPV is the net monetary gain (or loss) from a project computed by discounting all future cash inflows and outflows related to the project (Götze et al., 2015). In other words, the NPV represents the present value of all future cash inflows (CIF) diminished by the cash outflows (COF) (Götze et al., 2014). Accordingly, the NPV calculation could be expressed as below:

$$\begin{aligned} NPV &= PB - PC \\ &= \sum_{t=0}^{T} (CIF_t - COF_t) \cdot q^{-t} \qquad 3.3 \\ &= \sum_{t=0}^{T} (CIF_t) \cdot q^{-t} - \sum_{t=0}^{T} (COF_t) \cdot q^{-t} \end{aligned}$$

Where

- PB: the present value of cash inflows
- PC: the present value of cash outflows.
- t: time index;
- T: the economic life;
- CIF_t: cash inflow at time t;
- COF_t: cash outflow at time t;
- q^{-t} : discounting factor at time t (with $q^{-t} = \frac{1}{(1+r)^t}$);
- r: discount rate

The most valuable investment alternative is selected based on the positive, zero, or negative NPV's result. An investment project enjoys profits if its NPV value is greater than zero. If the NPV result equals zero, the project or alternative is in need of additional criteria to be reflected upon. Finally, when the present value of cash inflow is lower than the present value of cash outflow, the NPV is negative; and as a result, the whole project or relevant alternatives are repudiated (Götze et al., 2015). In case of identifying sufficient potential alternatives, experts compare alternatives in line with their NPV values. The most favorable investment project is the one with the highest NPV among all projects (Götze et al., 2015).

The NPV model requires the forecasts of initial investment outlay, future cash flows, liquidation value, and relevant discount rate (Götze et al., 2015). *The initial investment outlay* incurred at the beginning of the first period (t=0) is the amount of cash outflow incurred in the acquisition phase of a project. Cash inflows and outflows are the cores of *the cash flows,* and they have to be forecasted explicitly for the whole project life (or the relevant parts of it). However, this prediction is again gruelling, as cash flows rely on numerous variables such as various elements of cash flows, influence factors (climate, qualification of workers), high uncertainty, or economic policies. In the construction industry, Al–Issa and Zayed (Al-Issa and Zayed, 2007) indicated that the factors affecting cash inflow and outflow forecast consist of financial management, construction conditions, subcontractors, and suppliers. *Liquidation values* are the cash inflows in the close-out phase. These values are controlled by the future prices that buyers are able to pay for the remaining assets. In fact, they are calculated by assuming that the planning period is shorter than the expected project life, and they are the amount receivables when reselling the investment project, less any additional costs such as demolition costs (Götze et al., 2015). *The discount rate* takes into account compatibility and representation. Firstly, differing from cash flows, economic life, or initial investment, this rate permits compatibility between alternatives. Secondly, this rate transforms other opportunities in the current and future context into opportunity costs. Various authors have proposed their own means of calculating the discount rate so far (Öberg, 2005; Götze et al., 2015; Schultz, 2016).

As mentioned before, the NPV method is an effective tool to compare alternatives. The most outstanding advantage of this method is its association with the time value of money and discount rate. Furthermore, the NPV method requires low computational efforts and makes more realistic assumptions in comparison with the static models (Götze et al., 2015). However, this method also faces several problems, such as predicting the initial investment outlay, future cash flows, economic life, liquidation value and the relevant discount rate. For combining the LCC and the NPV, the LCC divides total cost into separate cost items that can be estimated in present values. The next section introduces the application of the LCC and the NPV in material selection.

3.3.5. Application of the life cycle cost analysis in the construction industry and road construction material selection

The life cycle cost analysis has many benefits in estimating the economic burdens of road construction projects. Firstly, it could be utilized in the early phase to refine all costs spent over the life cycle and compare material alternatives. For example, Robati et al. (Robati et al., 2018) proposed an LCC model to select structural materials over the project life cycle. Other studies also apply the LCC analysis to compare costs between material alternatives (Babashamsi et al., 2016b; Coleri et al., 2018; Fantozzi et al., 2019; Feria and Amado, 2019; Gao et al., 2019; Kumar et al., 2019; Moins et al., 2020). Secondly, the LCC analysis defines long-term value by dividing the product life cycle into many consecutive phases and considering the time value of money. Accordingly, the cost items (e.g., construction costs, maintenance cost, and disposal cost) can be estimated separately as a part of the LCC equation (Gurum, 2018; Li et al., 2020; He et al., 2021). *Discount rate* reflecting the time value of money *is* one of the most critical advantages of the LCC analysis. This rate is used to convert future cash flow to the present value (normally year 0) (RICS, 2014; ISO, 2017). Many studies gave equations to estimate the material life cycle costs utilizing the discount rate (Wolthuis, 2014; Metwally and Abouhamad, 2019; Potkány et al., 2019). Thirdly, the LCC analysis could help reduce the total cost by identifying the costs dominating the total product cost. For example, Todor et al. (Todor et al., 2017) used the LCC analysis to estimate the construction phase's cost. Their study helped stakeholders identify cost proportion in the construction phase and determine which types of cost must be kept and which types could be eliminated.

The LCC is widely applied to reckon the total cost of materials in construction projects. In this spirit, Ehlen (Ehlen, 1997) recommended that the LCC analysis creates a platform for designers to assess new materials and make decisions on their application. The author also concluded that the LCC analysis could be put in use as a tool to evaluate those materials which have satisfied the technical performance requirements. Alshamrani et al. (Ashraf et al., 2015) broke down the life cycle cost of material into cost items, including initial costs, operating costs, maintenance costs, and salvage values. However, they neither provided detailed equations to calculate these costs nor covered cost items such as material-dependent costs, storage, and waste material freight cost. From another viewpoint, Babashamsi et al. (Babashamsi et al., 2016b) introduced a methodology to calculate total material cost based on the LCC analysis. They defined the costs of a construction project as the aggregate amount of initial costs, maintenance and rehabilitation costs, and salvage values. Their research also considered discount rate in the calculation; nevertheless, cost items such as maintenance costs or salvage value were only worked out ambiguously. In recap, the above studies have not yet touched on material-dependent costs, storage cost, and shipping costs, although they have considerable influences on the total cost.

For the preliminary design phase, Ferial and Amado (Feria and Amado, 2019) recognized the feasibility of applying the LCC analysis and consequently noted that this method might be applicable for calculating material costs in this earliest design phase. A study by Rockizki and Peggy (Rockizki and Peggy, 2013) pointed out that the current material selection approaches in the preliminary design phase were mostly in conformity with the mechanical engineering and economic aspects rather than combining sustainability. According to Rockizki and Peggy, designers convert project requirements into technical and economic criteria and compare them with properties of existing material databases for selecting materials in the preliminary design phase. They also suggested that the economic performances of alternatives should be estimated according to the life cycle approach. Meanwhile, Andrade et al. (Andrade et al., 2012) and Bragança et al. (Bragança et al., 2014) set out sustainability indicators that should be estimated in comparing different construction solutions proposed. The economic indicators developed based on LCC include construction costs, operation costs, and end-of-life costs. However, their study only identified the crucial economic indicators, but it does not give a detailed guideline for the indicators' calculation. Jalaei et al. (Jalaei et al., 2015) suggested a method combining Building Information Modeling (BIM) and LCC to analyze the total costs in the preliminary design phase, especially energy costs in the handover and operation phase. The LCC analysis started by evaluating initial costs in the construction phase and then estimated the total annual energy costs (electricity costs and fuel costs) through an LCC module using inputs from BIM's database. In general, their research focused on energy costs, so the calculation of initial costs and disposal costs were not specifically described. Fazeli et al. (Fazeli et al., 2019) developed a new method from the study conducted by Jalaei et al. (Jalaei et al., 2015). They compared the economic performance of sustainable building components by using Matlab and BIM, and the result is validated by using the LCC analysis. However, the LCC analysis solely focused on the initial construction costs and energy costs, while disposal costs were omitted. Conclusively, the authors affirmed that the LCC analysis encounters problems such as the lack of detailed guidelines and cost items neglected in the preliminary design phase.

Multiple software and tools have been developed with the purpose of working out the total cost of a construction project based on the LCC, for example, SAP 200 and APA. Notwithstanding, their path towards effectiveness stills encounters hindrances in case of applying the LCC to the preliminary design phase. Firstly, the tools are designed to look at the project as a whole; therefore, with their inflexible nature, they are difficult to perform the tasks like calculating the total cost of a specific material along with its material-dependent costs in the early design phase. To apply the tools to the preliminary design phase, they should be modified to calculate with historical project data (expected annual replacement cost, expected material-dependent cost rate). Secondly, the input data require heavily detail-oriented approaches that struggle with the lack of available information in the preliminary design phase. Furthermore, each material comes along with diverse labor or equipment, so the input data are mined from a wide assortment of resources that the software and tools do not cover.

In general, the up-to-date studies have solely focused on establishing the general LCC equations in the preliminary design phase. Meanwhile, measures evaluating cost items and material-dependent costs have arguably been neglected or have exposed themselves due to the lack of illustrative formulas in this phase. These have resulted in creating inadequacy in case of calculating the cost items and total cost. The fact that each material alternative is imposed upon by different types of material-dependent costs urges the formation of a more thorough approach to the total cost.

This part aims to review the LCC and its application in the construction industry to produce applicable equations estimating the total cost of each specific material in the preliminary design phase. The equations are expected to spread over all stages of the project life cycle, provide detailed guidelines, and take into thorough consideration the material-dependent costs. With the intention of reaching this ultimate goal, there are four objectives pursued by this thesis. Firstly, a list of potential costs in each phase and material-dependent costs are established to help figure out the cost items. Secondly, models of the total cost and cost items are constructed on the basis of the LCC analysis, present value, and discount rate. Thirdly, a case study is presented in conformity with the proposed equations. Lastly, the shortage of information in the preliminary design phase needs to be considered. The next section describes the method applied to assess the environmental performance.

3.4. Methods for environmental evaluation

The life cycle assessment analysis is widely applied to estimate the environmental burden throughout the life cycle (Meex et al., 2018; Nizam et al., 2018; Seyis, 2020). It puts forth an insight into environmental performance in the construction industry (Simonen, 2014; Wang et al.,

2019) and can assess the environmental benefits of new materials (Liu et al., 2020). Many studies defined it as decision support in selecting construction materials (Simonen, 2014; Hauschild et al., 2018). This section presents the main definitions of the LCA and its current application in material selection.

3.4.1. Terms and definitions in the life cycle assessment method

This part introduced the terms and definitions used in the LCA. Main definitions, such as the life cycle assessment, functional unit, and system boundary, are interpreted according to current studies.

The *life cycle assessment (LCA)* is the compilation and evaluation of the inputs, outputs, and potential environmental impacts of products, processes, and services during their life cycle (ISO, 2006a). Overall, the LCA analysis is a comprehensive and systematic approach for evaluating the environmental impacts of a product, process, and service during its life cycle. It included four steps: (1) Goal and scope definition; (2) Life cycle inventory analysis; (3) Life cycle impact assessment; (4) Interpretation.

The *life cycle inventory analysis (LCI)* phase is the second phase in the LCA analysis, including collecting and quantifying inputs and outputs for products, processes, and services throughout their life cycle (ISO, 2006a). Its outcome catalogues the flows crossing the system boundary and provides the starting point (input and output flow) for the next phases.

The *life cycle impact assessment (LCIA) phase* - the third phase of the LCA - focuses on calculating, evaluating, and comparing the magnitude and significance of the environmental impacts throughout the life cycle of products, processes, and services (ISO, 2006a). In this phase, the environmental burdens are assigned to selected impact categories (e.g., climate change, human toxicity) (Bierer et al., 2013).

The *life cycle interpretation phase (or interpretation phase*) is the last phase of the LCA analysis when the outcomes of the LCI and LCIA phases are interpreted regarding the defined goal and scope in order to reach conclusions and recommendations (ISO, 2006a). In other words, this phase aims at concluding the environmental performance of services, processes, and products according to the defined goal, scope, and findings derived from LCI and LCIA phases.

The term *"functional unit"* is described as a measure of the studied system's function, which is responsible for ensuring that all alternatives being compared provide an equivalent level of function and service (Bayer et al., 2010). The functional unit denotes the primary functions. For example, Brattebø suggested that the functional unit for a road construction project in LCA should take the form of 'Road infrastructure enabling annual traffic between "A" and "B" over an analysis time horizon of a defined number of years' (Brattebø et al., 2013).

The *system boundary* is a set of criteria identifying which unit processes are included (ISO, 2006a). It determines the activities and systems being included or excluded in each of the LCA's phases. The detailed guidance from European Commission et al. (EC et al., 2010) suggested that the system boundary should be illustrated in diagram forms (e.g., flow chart) to clarify which life cycle phases have been included in the system model.

The *life cycle inventory databases,* comprehending raw materials, energy data, production processes, and wastes, are systematically set up by organizations and LCA tool developers. In other words, the databases involve elementary flows (inputs and outputs) circulating during the whole life cycle. These databases vary depending on the differences in specific countries and regions.

The *reference flows* are the processes' outputs and satisfy the function's requirements. According to ISO (ISO, 2006a), the reference flow measures the process outputs required to fulfil the functional unit. According to (EC et al., 2012), the reference flows are the flows to which all other input and output flows quantitatively relate to the function unit. The calculation of reference flows estimates the input and output database being referenced to the selected functional unit.

According to ISO, *impact category indicator* is a quantifiable representation of an impact category. The category indicator result is obtained through multiplying LCI inputs and outputs to their respective characterization factors (ISO, 2006b).

The *characterization factor* is derived from a characterization model converting an assigned LCI result to the common unit of the category indicators (ISO, 2006b). The characterization factors can be drawn from the international life cycle data system (EC et al., 2012), ReCiPe database (RIVM, 2020), published sources, or software databases (e.g., Simapro, Gabi, Ecoinvent).

Midpoint indicators focus on single environmental problems like climate change or acidification. *Endpoint indicators* show the ecological impact on three higher aggregations, including human health, ecosystem quality and resource scarcity.

This section briefly defined the definitions of the LCA. The main contents, such as LCI, LCIA, and system boundary, are introduced to form a basis for reviewing life cycle assessment analysis steps in the following part.

3.4.2. Life cycle assessment steps

The LCA analysis is a tool for calculating and evaluating the total environmental impact. Four main steps involved in carrying out the LCA analysis comprise (1) Goal and scope definition; (2) Life cycle inventory analysis; (3) Life cycle impact assessment; (4) Interpretation (ISO, 2006b).

Step 1: Goal and scope definition

This step determines the working plan of the LCA analysis. In this step, the designers and experts define the whole life cycle's goals, scopes, functions, functional units, and reference flows. The significance of the goal and scope definition was emphasized by many authors. Babaizadeh et al. (Babaizadeh et al., 2015) stressed the importance of defining system boundary because it identifies and justifies which aspects of the product life cycle are covered. Similarly, according to Rebitzer (Rebitzer et al., 2004) and Albertí et al. (Albertí et al., 2019), defining the functional unit is an important task because it enables products, processes, or services to be compared and analyzed.

Step 2: Inventory analysis (life cycle inventory analysis)

The inventory analysis phase (or life cycle inventory analysis – LCI) handles the *collection, categorization, and calculation* of physical material characteristics and inventory flows (ISO, 2006b; Cabeza et al., 2014). To collect the data, experts gather all the data given in the unit processes and quantify all flows linked to the unit processes. Then the categorization step is conducted by specifying the main data categories and assigning the inputs and outputs to selected categories. Last, the quantity of environmental category indicators is calculated to quantify relevant input and output flows. All activities, relevant unit processes and their flows (e.g., energy, materials, products, waste, emissions, etc.) are modelled to quantitative data (for example, the number of input and output) and qualitative data (e.g., conditions of emission measurement, etc.) (Bierer et al., 2013). In more detail, the LCI examines system boundary, designs the flow diagram, assembles data, and calculates quantities of inputs and outputs (Baumann and Tillman, 2004; Simonen, 2014). In addition, defining cut-off criteria and conducting allocation can be conducted in this phase.

Step 3: Impact assessment (life cycle impact assessment phase)

For the *life cycle impact assessment phase (LCIA)*, the significance of the quantified environmental burdens defined in the LCI is determined. LCIA phases involve the mandatory elements (selection, classification, and characterization) and optional elements (normalization, grouping, weighting, and data quality analysis), as suggested by (Guinée, 2002; ISO, 2006b; EC et al., 2010). First, experts *review impact categories, category indicators, and characterization models* to select the most suitable ones (*selection*). Second, the LCI results are assigned to the corresponding impact categories (*classification*). Third, category indicator results are calculated (*characterization*) by converting LCI results to standard units and aggregating the converted results within the same impact category (ISO, 2006b). The LCIA results are estimated by multiplying the individual inventory data in the LCI results with the defined characterization factors and then aggregating the results of these multiplications for each impact category (Guinée, 2002; EC et al., 2010). The LCIA value is estimated by the following equation:

$$LCIA_c = \sum_i (CF_i \cdot E_i) \tag{3.4}$$

Where:

- $LCIA_c$ is the LCIA value of impact category c
- CF_i is the characterization factor of LCI inputs and outputs type i.
- E_i is the individual inventory data of LCI inputs and outputs type i.

For example, indicator "climate change" can be calculated in a formula such as:

$$LCIA_{CC} = \sum_i (GWP_i \cdot E1_i) \tag{3.5}$$

Where

- GWP_i is the characterization factor of LCI inputs and outputs type i concerning climate change (for example, CO_2)
- $E1_i$ is the amount of LCI inputs and outputs type i concerning climate change.

For optional elements, the *normalization* step is implemented to shed light on the relative importance and make the results understandable. This step concerns the inconsistencies, provides interpretation, and lays the groundwork for the next activities. Guinée (Guinée, 2002) pointed out that *weighting* factors for each impact category should be determined before being assigned to the normalized result. Then the weighted results are summed up to estimate a single score. Before presenting the result of this step, experts may apply *the sensitivity analysis* method to forecast potential alterations in the results in case input information changes. This step adds a lot of information to the LCA procedure.

Step 4: Interpretation (life cycle interpretation)

In the life cycle interpretation steps, the findings of an LCI and LCIA are compiled and discussed in accordance with the purpose and scope specification in order to derive conclusions and provide a basis for suggestions and decision-making. This step should include significant contents according to the results of LCI and LCIA phases, such as CO_2 emission, climate change, and acidification. It also needs to consider completeness, sensitivity, and consistency checks before making conclusions (ISO, 2006b). According to Guinée (Guinée, 2002), the three main activities in this phase include (1) an evaluation of results, (2) an analysis of results, and (3) the formulation of the conclusions and recommendations.

To summarize, the LCA analysis is carried out to evaluate the total environmental impact through the product life cycle. It consists of four main steps: (1) Goal and scope definition; (2) Life cycle inventory analysis; (3) Life cycle impact assessment; (4) Interpretation. In step 1, the goals and scopes are determined, such as functions, functional units, and reference flows. Step 2 is conducted by completing the flow diagram, collecting and validating data, relating data to the functional unit and reference flow, and calculating the LCI results. The main activities in step 3 are selection, classification, and characterization, while the last step conducts consistency and uncertainty analysis and makes conclusions. The following section introduces the application of the LCA in road construction material selection.

3.4.3. Application of life cycle assessment method in the construction industry and road construction material selection

The life cycle assessment analysis is a comprehensive way of estimating the environmental burden throughout the life cycle (Meex et al., 2018; Nizam et al., 2018; Seyis, 2020). This method performs many advantages in estimating environmental burdens. *First*, the LCA analysis offers an insight into environmental performance in the construction industry (Simonen, 2014). For example, Wang et al. (Wang et al., 2019) attempted to apply the LCA analysis to the project life cycle to evaluate the environmental performance of urban green infrastructures in China. Their study breaks down infrastructure projects into phases, including extraction and construction, use and maintenance, end-of-life, and transportation, and investigated their impact categories, such as global warming potential, acidification potential, and water use. *Second*, the LCA analysis is served as decision support in selecting construction materials (Simonen, 2014; Hauschild et al., 2018). For instance, Hafner and Storck (Hafner and Storck, 2019) proposed an LCA procedure to assess the environmental performance of vertical building extensions and select their primary material. The given materials, including brick, reinforced concrete, wood, and steel, were compared based on the global warming potential (GWP). The result showed that vertical building extension made of wood performs the lowest CO_2 equivalent. *Third*, the LCA analysis can assess the environmental benefits of new materials (Hauschild et al., 2018). This argument was agreed upon by Liu et al. (Liu et al., 2020), who reviewed the LCA studies of building materials in recent years and figured out that the LCA analysis can lead to the research and development of new materials.

Numerous authors researched on life cycle assessment analysis in the construction industry. Wang et al. (Wang et al., 2019) exerted to apply the LCA analysis to assess environmental performance during the project life cycle in China. The research categorized infrastructure projects into phases and drilled into their impact categories, such as global warming potential, acidification potential, and water use. They determined the most significant impact category in each phase and pointed out the potential environmental improvement. As a result, they concluded that using materials in the construction phase accounted for dominant environmental impacts. Meanwhile, the impacts enveloping construction with thermal performance were evaluated under two operational patterns using the LCA (Monteiro et al., 2020). According to them, the environmental burdens were identified for each project phase, and the cumulative energy demand (CED) method and the CML 2001 method were used to assess the environmental loads. The CED method estimates the total non-renewable primary energy consumed, while the CML 2001 assesses the other environmental impacts, such as abiotic depletion, global warming potential, and acidification. Besides, Sauer and Calmon (Sauer and Calmon, 2019) reviewed 5,149 peer-reviewed articles on LCA application in the construction industry and building projects from 2013 to 2018 to describe LCA's development and point out the knowledge gaps in this field. They identified that the shortage of LCA tools is a primary limitation because most of the current supporting tools are developed for North America and Europe. They also emphasized the deficiencies in clarified data collections and region-specific inventories.

The LCA analysis is qualified as a framework for assessing the environmental impacts of material alternatives. Gustavsson and Sathre (Gustavsson and Sathre, 2006) used the LCA analysis to research factors affecting the balance of energy consumption and CO_2 emission in utilizing concrete and wood products. They indicated that the application of wood and wood by-products effectively reduces fossil fuel and net CO_2 emission. Hafner and Storck (Hafner and Storck, 2019) offered a procedure based on the LCA to assess vertical building extensions' environmental performance and select major materials. In addition, the LCA is applied to assess the environmental burden of distinguishing asphalt and concrete alternatives for road construction projects by Heidari et al. (Heidari et al., 2020). In their study, carbon emissions and energy consumption are involved. Accordingly, they estimated the number of CO_2 (tons) emitted to the environment to analyze the carbon emissions, and the amount of energy (unit: MJ) was used to analyze the energy consumption. Lastly, they used the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to choose the most valuable alternative. Chen et al. (Chen et al., 2020) also applied the LCA analysis to the construction material selection. They compared LCA results of two alternatives, including cross-laminated timber (CLT) and reinforced concrete (RC). The cross-laminated timber is a wood structural product made from timber board and built up of layers of planks with adjacent layers, while the reinforced concrete is made from concrete and steel. The paper estimated the environmental influences (resource efficiency and global warming) of alternatives. The results indicated that the total mass of the resource consumed for the CLT building was 33.2% less than the RC building alternative, and a 20.6% reduction in embodied carbon was achieved for the CLT alternative, compared to the RC building.

A search of the literature reviewed studies that assess the environmental performance to compare construction materials in the preliminary design phase. Andrade et al. (Andrade et al., 2012) and Bragança et al. (Bragança et al., 2014) set out sustainability indicators that should be estimated in comparing different construction solutions proposed. The environmental indicators based on the LCA analysis contain global warming potential, acidification potential, resource use, and recycling materials. However, their study only identified the environmental indicators and did not give a detailed guideline for the estimation. Rockizki and Peggy (Rockizki and Peggy, 2013) concluded that the current material selection approaches in the preliminary design phase are mainly based on the mechanical engineering and economic aspects rather than combining sustainability. Accordingly, they recommended applying the LCA to evaluate the environmental performance of material alternatives, and the application's challenges were also pointed out, such as the unavailable information and different environmental profiles. The authors also did not offer a detailed guideline for applying the LCA analysis in the early design phase.

Many LCA software has been developed to help designers evaluate the environmental performance of construction materials. Bayer et al. (Bayer et al., 2010) classified the LCA tools based on four levels: "material level, product level, building level, and industry level". The "material level" refers to the tools evaluating the environmental performances of building materials. These material-focused supporting tools are integrated into software packages such as Gabi and Simapro. Eco-Invent, one of the most ideal suitable for building materials, is a typical example of such a tool. (Martínez-Rocamora et al., 2016; Stafford et al., 2016). After a few years, 45 LCA software tools were reviewed by Olagunju and Olanrewaju (Olagunju and Olanrewaju, 2020), and they suggested that GaBi, OpenLCA, SimaPro, and Umberto are four prominent software packages. Gabi was developed by IKP and PE Product Engineering GmBH in Germany. Open LCA is a free package that allows customers to evaluate environmental burdens throughout the LCA's four main steps. SimaPro developed by PRé Consultants has been widely used around the world, and Ifu Hamburg created Umberto 25 years ago. Table 3.2 illustrates the comparison of GaBi, OpenLCA, SimaPro, and Umberto.

Table 3.2. A comparison of Gabi, OpenLCA, SimaPro, and Umberto

Content	Gabi	OpenLCA	SimaPro	Umberto
Database	Gabi datasets, Ecoinvent, US LCA (NREL)	No	Ecoinvent, US input/output, US LCI, Dutch input/output, Swiss input/output, LCA food,	Gabi database, Ecoinvent

			industry data, Japanese input/output, IVAM	
ISO 14040 guidelines	YES	YES	YES	YES
Statistical analysis	YES	YES	YES	YES
Reports of results	Self-editor for reports Exports to Word/Excel	Graphical Report presentation, custom tables Exports to Word/ Excel	Graphical Report presentation with list of impacts Exports to Word/ Excel	Graphical Report presentation Exports to Word/ Excel
Comparison of results	YES	YES	YES	YES

(Source: (Olagunju and Olanrewaju, 2020))

According to Table 3.2, OpenLCA has several specific characteristics. It does not have a database because it works with OpenLCA Nexus (an online repository) supported by the Ecoinvent, European Platform for life cycle assessment, and GaBi databases. However, the LCA sources (e.g., unit processes, and environmental factors) are not free for customers. In summary, these software packages are able to compare different alternatives so they can be used in selecting construction materials. However, their database is built mainly for developed countries, so the specific-region data for other countries are insufficient (Zuo and Zhao, 2014; Sauer and Calmon, 2019). Furthermore, material-dependent activities are not involved, and there is not any study on applying the software packages to the preliminary design phase.

Generally, the LCA analysis has been applied in the material selection due to its advantages and its potential applications. However, few studies used the LCA for road construction material selection in the early design phase. The proposed LCA is expected to cover all phases of the project life cycle, provide detailed guidelines, and consider the material-dependent activities. Accordingly, there are four goals that this proposed method follows. Firstly, a list of potential material-dependent activities in each phase is identified to help determine the environmental impacts. Secondly, the method is developed according to the LCA described in (ISO, 2006b; ISO, 2006a). Thirdly, a case study is presented in conformity with the proposed method. Lastly, the shortage of information in the preliminary design phase needs to be considered. The next section describes the method applied to assess social performance.

3.5. Methods for social evaluation

The social dimension is one of the three pillars of sustainability. The social life cycle assessment (Social LCA) method performs potentials in assessing social performance throughout the project life cycle (Jørgensen, 2013; Dong and Ng, 2015; Zheng et al., 2020b). This section introduces primary definitions, steps, and applications of the Social LCA.

3.5.1. Terms and definitions in social life cycle assessment method

This part introduced the definitions of the Social LCA and its applications. The main definitions of social life cycle assessment, social impacts, and others were drawn from current studies.

The social life cycle assessment (Social LCA) method is a social impact evaluation method focusing on addressing the social aspects of products and services. This method also offers information on social aspects of decision-making that improves organisations' performance and stakeholders' well-being (UNEP and SETAC, 2009; UNEP and SLCA, 2020). The Social LCA analysis was developed based on the ISO 14040 framework for the LCA, so it also includes four main steps: (1) Goal and scope definition; (2) Social life cycle inventory analysis; (3) Social life cycle impact assessment; (4) Interpretation (UNEP and SETAC, 2009; UNEP and SLCA, 2020).

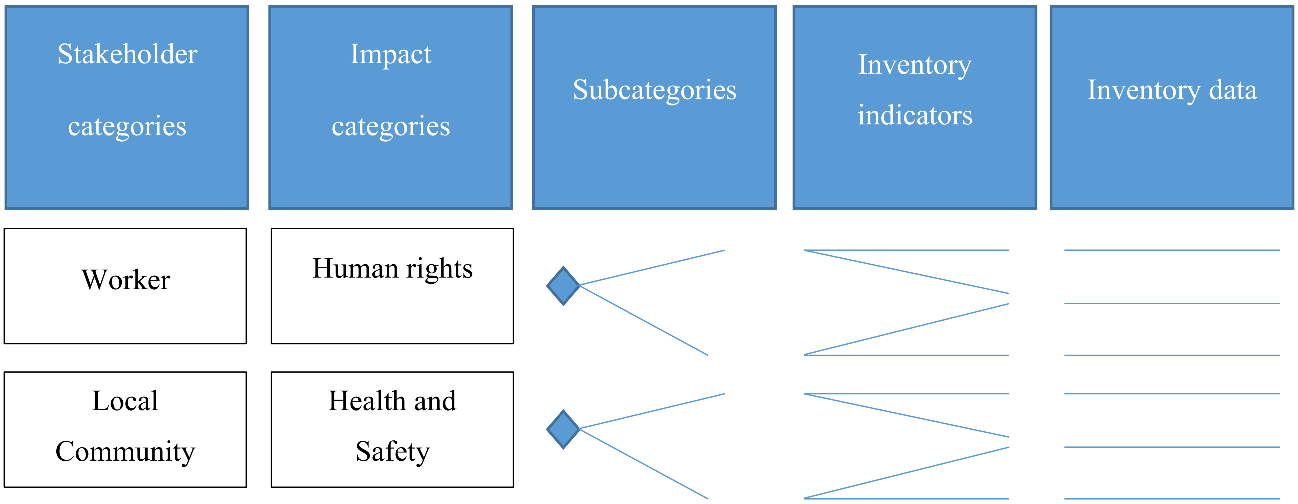
The term *stakeholder* is used to indicate diverse groups of people that are potentially impacted by manufacturing activities (Siebert et al., 2018). Wu and Su (Wu and Su, 2020) also defined a stakeholder category as a group of individuals who are anticipated to have shared interests in the products or services. There are five main stakeholder categories, including (1) worker, (2) local community, (3) society, (4) consumer, and (5) other actors in the value chain (UNEP and SLCA, 2020).

Social impacts are the positive and negative influences that a particular item has on society. *Social impact categories* are logical groupings of LCIA results (e.g., human rights, health and safety, and working conditions) related to the interest of stakeholders or decision-makers. In other words, they are classes that cover specific social issues concerned by stakeholders and decision-makers (UNEP and SETAC, 2009; UNEP and SLCA, 2020). There are two types of social impact categories. Specifically, the first type (Type 1) implies the social issues of interest to stakeholders, such as health and safety, human rights, working conditions, socio-economic repercussions, cultural heritage, and governance. The second type (Type 2) comprises the elements corresponding to endpoints, including human capital, cultural heritage, and human well-being. The two types' definitions were also researched by (Wu et al., 2014; Bonilla-Alicea and Fu, 2019). They pointed out that the characterization model of type 1 does not incorporate causal relationships between the input inventory data, while inventory indicators are converted to quantitative values by comparing the inventory data to a Performance Reference Point (PRP) – a reference value. The indicator results will be aggregated into a total score. In contrast, the type 2 model is linked with midpoint and endpoint impact categories through causal relationships.

Subcategories are socially relevant characteristics or attributes that serve as representations of social impacts within the impact categories. In short, they are representations and constituents of the impact categories (UNEP and SETAC, 2009). As suggested by Wu and Su (Wu and Su, 2020), the subcategories are categorized based on stakeholder and impact categories and are judged by utilizing inventory indicators.

The *inventory indicators* refer to the extent of social impact categories/subcategories. They are quantitative, semi-quantitative, or qualitative indicators varying depending on the goal of the study. The quantitative indicators use numbers to evaluate the social impact categories/subcategories; the qualitative indices are demonstrated by words/sentences; and the semi-quantitative ones make use of the yes/no form or certain scoring systems (UNEP and SETAC, 2009). For example, working hours per week is a quantitative indicator assessing the working hour issue of employees. The relationships between stakeholder categories, impact categories, subcategories, and inventory indicators are depicted in Figure 3.2.

Figure 3.2. The relationship between stakeholder categories, impact categories, subcategories, and inventory indicators



(Source: (UNEP and SLCA, 2020))

This section briefly defined the definitions of the Social LCA. The main contents, such as stakeholder categories, impact categories, subcategories, and inventory indicators, are introduced to form a basis for researching social life cycle assessment analysis steps in the following part.

3.5.2. Social life cycle assessment analysis steps

The Social LCA analysis is built based on the traditional LCA analysis; hence, it displays the same framework as the LCA. The main steps employed in this method contain (1) Goal and scope definitions, (2) Inventory analysis, (3) Impact assessment, and (4) Interpretation (UNEP and SETAC, 2009; UNEP and SLCA, 2020).

a. Goal and Scope definition

The Social LCA goals include the study's objectives, the application of the results, reasons for carrying out the study, the stakeholders, and the target audiences. The scope should be determined clearly so that the detail of the study is feasible and compatible with the given goals. For defining scope, the system boundary is established in a way akin to the LCA analysis. It aims to appoint unit processes involved in the Social LCA (Martínez-Blanco et al., 2015; UNEP and SLCA, 2020). Other contents, such as functions, functional unit, reference flow, data resources, social indicators, stakeholders, impact assessment method, type of impact categories and subcategories, and data quality requirements, are determined in this phase as the LCA analysis.

b. Social life cycle inventory analysis

After defining the goal and scope, the social life cycle inventory analysis (Social LCI) is conducted to collect and analyze the data from all unit processes. The Social LCI is the second step of the Social LCA, and it is divided into sub-steps.

- *Completing the flow diagram from system boundary:* According to the goals and scope instituted in the previous phase, the structure of all unit processes and their relationships are illustrated in flow diagrams. Similar to the LCA, a flow diagram of the Social LCA executed at the aggregated processes should be illustrated by boxes and arrows. The boxes denote unit processes, and the arrows represent the flows and connections. After that, the stakeholders for each unit process are also identified. For example, the stakeholders of the transportation process are workers (represented by drivers) and the local community.
- *Preparing for data collection*: experts are obliged to have a good understanding of social problems, necessary data, required subjects, and data collection methods. Although the stakeholder, impact categories, subcategories and inventory indicators are identified in the goal and scope definition, they also need to be meticulously re-identified after completing the flow diagram. According to the UNEP/SETAC initiative, 31 subcategories and indicators are available to be selected for evaluation and assessment (Hosseinijou et al., 2014). To ensure the validity, the sources must be reliable documents, such as published studies and reports.
- *Collecting the data* is the most challenging exercise by reason of the shortage of information and databases. Data collected from sources is quantitative (numbers), semi-quantitative (yes/no or rating scale responses), or qualitative (feelings) (Subramanian and Yung, 2018). The unit processes characteristics (e.g., relevant stakeholders, activities), impact categories, sub-categories, category indicators and the used sources should be referenced in the final report. Regarding the data level, UNEP (UNEP and SLCA, 2020) proposed two specific levels of comprehending generic data and site-specific data. The generic data are available in government, intergovernmental and multilateral websites, while site-specific data are gathered from organization-specific reports, interviews, or surveys (UNEP and SETAC, 2013). After collecting the data, the flows for each unit process are determined.
- *Validating data* should be conducted during the data collection to demonstrate that the data meet the requirements. This step is similar to that of the traditional LCA analysis.

- *Relating data to the functional unit and unit processes:* This phase is also identical to the corresponding one from traditional LCA analysis. The social LCI inputs and outputs are calculated for each unit process. After that, all of them are related to the functional unit. For example, two worker-hours are needed for building a wall, so eight worker-hours are needed when four walls are required. However, Dreyer et al. (Dreyer et al., 2006) indicated that it might be arduous to link quantifiable data with the functional unit and unit processes due to the difficulty in quantifying qualitative data (UNEP and SETAC, 2009). To solve this problem, Hosseiniju et al. (Hosseinijou et al., 2014) put forth a pathway that includes the AHP method, characterization, inconsistency analysis, hierarchical additive weightings, and sensitivity analysis. Particularly, they combined the AHP method, material flow analysis, and hierarchical additive weightings to reckon the qualitative data in the Social LCA analysis.
- After that, the social LCI result is estimated. It is an aggregation of all Social LCI inputs and outputs over unit processes in relation to the reference flow and functional unit.

$$I_c = \sum_s I_{c,s} \tag{3.6}$$

Where:

- I_c denotes the Social LCI result of Social LCI inputs and outputs type c;
- $I_{c,s}$ represents the Social LCI result of Social LCI inputs and outputs type c in phase s.

After getting the Social LCI results, the social life cycle impact assessment step is conducted to estimate the social performance.

c. Social life cycle impact assessment

Social life cycle impact assessment (Social LCIA) is a phase estimating the magnitude of the selected social impact categories and subcategories. According to the UNEP/SETAC (UNEP and SETAC, 2009), the Social LCIA phase includes three primary sub-steps below.

- Step 1: *Selecting*: Based on the Social LCI results, experts are compelled to make informed decisions on the selection of impact categories, stakeholders, impact category indicators, characterization methods, and models. In other words, experts review social impact categories, subcategories, category indicators, and characterization models based on the actual Social LCI results to select the most suitable ones.

- Step 2: *Classification*: The gathered category indicators are assigned to the corresponding stakeholders, impact categories, and subcategories (Grießhammer et al., 2006; UNEP and SETAC, 2009; UNEP and SLCA, 2020).
- Step 3: *Characterization*: In this step, the subcategory results are estimated by characterization models. The characterization model is not always presented itself as a mathematical operation; instead, it is an aggregation step gathering texts or qualitative information and converting them into a single score. For the Social LCIA method, some studies suggested applying the "Reference Scale Assessment/ Performance Reference Point" (PRP) approach and "Impact Pathway" (IP) approach to social performance estimation (Ramirez et al., 2014; Siebert et al., 2018; Sureau et al., 2019; Huertas-Valdivia et al., 2020; UNEP and SLCA, 2020).
- The Social LCA also subsumes *optional steps, including normalization and weighting*. The normalization segment calculates quantitative indicators by rescaling the characterization results into comparable values (for example, a range from 0 to 1). The weighting part helps modify the normalization results based on the importance of subcategories and impact categories. The weightings can be obtained by conducting questionnaire surveys, the Likert scale and the AHP method. The normalization results are then multiplied by the weighting factors to advance to the figures which represent the social impacts.

The social LCIA outcomes evaluate the social performance value of each social impact category or a single score. The outcomes will be moved to step 4 - Social life cycle interpretation.

d. Social life cycle interpretation

This phase assesses the results to make conclusions. The phases include the identification of significant issues, consideration of consistency and completeness, participation of stakeholders, recommendations, and reporting documents. According to the UNEP/SETAC (UNEP and SETAC, 2009), 'significant issues' implies limitations, assumptions, hotspots, notable beneficial social impacts, or crucial infringements. 'The consistency' touches on the suitability aspect of the data and methodology. 'The completeness' focuses on whether the relevant issues are being resolved. Meanwhile, the conclusion, recommendations, and relevant documents are being given concerning the goal and scope of the study.

The Social life cycle assessment framework is developed from the environmental LCA framework to assess the social performance of products, processes, and services. It offers an insight into social performance in the construction industry. Otherwise, the Social LCA has potentials to support the designers in selecting the most social-friendly material. The following section reviews the current application of the Social LCA analysis in the construction industry and road construction material selection.

3.5.3. Application of the social life cycle assessment method in the construction industry and road construction material selection

In the construction industry, the social life cycle assessment has many potential applications. *First*, the Social LCA analysis provides an understanding of social performance in the construction industry. Dong and Ng (Dong and Ng, 2015) proposed a Social LCA model called the Social-impact Model of Construction (SMoC) to assess building construction projects' social performance. By analyzing the social impacts of subcategories, such as child labor and fair salary, the model pointed out the most important social aspect, positive and negative impacts, and the potential of improving social performance. Also, Zheng et al. (Zheng et al., 2020b) developed a social life cycle assessment (Social LCA) framework for pavement based on the UNEP/SETAC guidelines. This framework covers four stakeholders, 12 subcategories, and 16 social indicators. *Second*, the Social LCA analysis is defined as decision support in selecting construction materials. Hosseinijou et al. (Hosseinijou et al., 2014) presented a method based on UNEP/SETAC guidelines, including four steps: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) life cycle interpretation. This method is demonstrated by comparing the social performance of materials “steel/iron” and “concrete/cement”. *Third*, the Social LCA can integrate with the LCC and LCA to estimate the sustainable performance in the construction industry (Dinh et al., 2020). Several studies about Social LCA in the construction industry are presented below.

Dong and Ng (Dong and Ng, 2015) came up with a Social LCA model named SMoC to assess the social performance of building construction projects. The proposed model is made up of three main activities. The first step was to establish the Social LCA analysis framework based on the UNEP guidelines. The second action was to build the SMoC model by collecting the weighting factors of the social impacts of on-site construction activities. The third one reflects upon integrating the UNEP/SETAC guidelines and SMoC results to realize the Social LCA analysis. In this step, data from the national worksheet giving the normalized national social indicator results of the building industry in Hong Kong are integrated with the weightings into the SMoC model to assess the social performance. However, this method witnesses the lack of normalization methods and does not consider the qualitative data. Besides, the application in the information deficiency condition needs more reviews.

Liu and Qian (Liu and Qian, 2019b) came up with a methodological framework for the Social LCA through a stakeholder-based perspective. This framework includes four contents: (1) a proposed assessment framework, (2) indicators for each subcategory, (3) weights of impact subcategories, (4) application of the method. Firstly, the framework was established to estimate the social performance score (SPS), then social indicators were identified according to the study's objectives and data availability. Next, the selected indicators need to be scored and normalized from -2 to +2, and the weightings of subcategories and indicators are obtained through questionnaire surveys. The SPS is received by aggregating the product of normalized scores of subcategories and their corresponding weightings. For demonstration, a case study was carried out using the proposed method to compare the life-cycle social performance of two buildings. Generally, the method exerted to offer a framework supporting designers to assess the social performance of buildings. However, the indicator scores are assigned mainly based on the authors' opinions instead of providing a detailed guideline.

Meanwhile, Zheng et al. (Zheng et al., 2020b) developed a social life-cycle assessment (Social LCA) framework based on the UNEP/SETAC guidelines. This framework covers four stakeholders (worker, local community, consumer, and society), 12 subcategories (e.g., Working hours, Health and safety, and Equal opportunities), and 16 social indicators (e.g., Average working hours per month). In particular, the method followed the UNEP/SETAC guidelines (UNEP and SETAC, 2009), so it started with defining the goal and scope. Next, the social life cycle inventory phase is conducted using site-specific data rather than generic data. After that, for the social life cycle assessment, the scores are assigned to assess the inventory data, then aggregated into a single score after considering the weights estimated based on the AHP method. Lastly, interpretation is the last step to report and discuss the results in order to draw conclusions. This method used site-specific data to increase the social LCA analysis precision, but it is not suitable for developing countries limiting site-specific data.

Venkatesh (Venkatesh, 2019) drilled into a total of 213 publications on applying the Social LCA from 1996 to April 2018 and concluded that the volume of Social LCA publications had been remarkably increased over time. This tendency implies the growing attention towards this method in practice. Venkatesh also categorized the publications into different research fields: agriculture, chemical, fuel, or food. Notwithstanding, there had been only four studies showing its interest in the construction industry. Similarly, Bonilla-Alicea and Fu (Bonilla-Alicea and Fu, 2019) also reviewed the current social impact assessment methodology. They concluded that the Social LCA used in the construction industry only accounted for 9% of 81 articles published between 2009 and 2019. The method is mainly applied to European countries – developed countries.

Several authors have applied the Social LCA analysis in construction material selection. Hosseinijou et al. (Hosseinijou et al., 2014) presented a method based on UNEP/SETAC guidelines, including four steps: (1) Goal and scope definition, (2) Life cycle inventory analysis, (3) Life cycle impact assessment, and (4) Life cycle interpretation. Accordingly, the goal and scope definition phase determines the study's goal, system boundary, functional unit. In the life cycle inventory analysis, the mainstream of the product life cycle is defined based on the material flow analysis to identify its most important stages. Next, the interview is carried out to build the database and assign scores. In the next phase - life cycle impact assessment, the analytic hierarchy process method is used to convert the decision-makers intuition into a number/single score. For the last phase, the conclusions, recommendations, and reports are provided. The developed method was applied to evaluate the social performance of concrete and steel as building materials in Iran. The results showed that “steel/iron” in the north of Iran generally has better social performance than “concrete/cement”. However, the scores are not assigned by standard thresholds. Therefore, the problems of accuracy and consistency are particularly pronounced.

Meanwhile, Hossain et al. (Hossain et al., 2017) presented a single score-based social life cycle assessment methodology to assess and compare the social performance of recycled and natural construction materials. Their method was developed based on UNEP/SETAC guidelines, Global Reporting Initiative, and the Hong Kong Business Environment Council Limited data. This method included two main parts: (1) the qualitative research based on expert’s interviews for identifying subcategories and indicators, (2) the data analysis and case-specific survey for collecting required data. Their study pointed out four crucial subcategories in construction material assessment, including the materials' safety issues, workers' health and safety, the company’s commitment to sustainability, and its policies. The developed method was demonstrated by applying it to assess the social performance of natural and recycled aggregates. This method was generally developed according to the Athena LCI database developed for Vancouver, so it is limited to apply to other regions, such as developing countries.

The Social LCA analysis has not yet been applied to road construction material selection in the preliminary design phase. Notably, it is only assigned as an environmental impact category (Healthy and Safety of people) in the schematic design phase (Hungu, 2013). It is due to that the deficiency of information in the preliminary design phase restricts the data collection in the Social LCA. Besides, the current social database is mainly developed for developed countries (Hossain et al., 2017; Zheng et al., 2020b). These problems induce the increasing need to develop a Social LCA-based method for material selection in the preliminary design phase. The current studies often neglect the social assessment in the preliminary design phase (Giudice et al., 2005; Bovea and Gallardo, 2006; Ashby et al., 2009; Bragança et al., 2014; Zhong et al., 2016). Andrade et al. (Andrade et al., 2012) reviewed the previous research, emphasized the importance of sustainability, and set out sustainability indicators. The indicators are categorized into economic, environmental, and social indicators. Their study pointed out the critical social indicators, but it did not give a detailed guideline for the application.

Generally, the Social LCA application into the construction industry has not been yet paid attention to by the research community, as mentioned above. However, it also reveals the great potential in the construction field due to the increasing number of studies in recent years. There are several studies about the Social LCA for material selection, but they faced major challenges concerning location-specific data, information deficiency, and the shortage of case studies. Hence, the proposed Social LCA needs to solve the problems and integrate with the LCC and LCA into the LCSA. Besides, material-dependent activities should be involved. The next section introduces some potential methods that can help designers assess the sustainability performance regarding the LCC, LCA, and Social LCA results.

3.6. Methods for sustainability evaluation

3.6.1. Life cycle sustainability assessment method

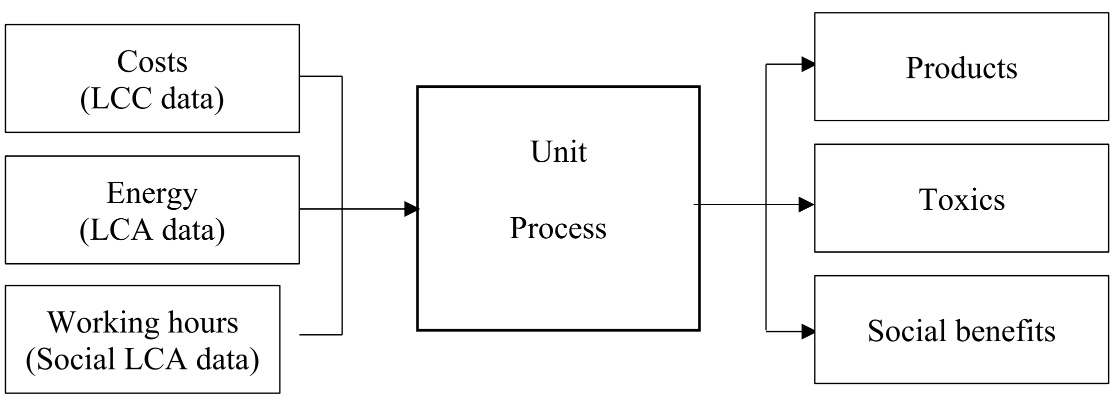
Economic, environmental, and social dimensions are only separate parts of sustainability, so the LCC, LCA, and Social LCA results perform an incomplete picture of sustainable development. Integrating LCC, LCA, and Social LCA is essential for assessing sustainability performance by conducting trade-offs between the results of LCC, LCA, and Social LCA. Life cycle sustainability assessment (LCSA) is suggested as a comprehensive method for estimating and selecting objects towards sustainable development (Kloepffer, 2008). Otherwise, Benedict (Benedict, 2017) also pointed out that the LCSA considers the full range of impacts (economic, environmental, and social impacts) in sustainable development. Besides, the relevant data are organized, and the results are generated in a structured form. Fauzi et al. conducted a literature review of 124 papers from 2007 to October 2018. They concluded that the LCSA had been applied in some areas, such as energy, manufacturing, and waste treatment. Besides, the increasing of LCSA publications shows a significant potential to accept it as an effective method for assessing sustainability performance and making decisions (Fauzi et al., 2019). This section analyzes the life cycle-related methods in order to answer the first two research questeions and question 3a.

The term of life cycle sustainability assessment (LCSA) was first mentioned by Zhou et al. (Zhou et al., 2007). The LCSA, with some disciplinary models, was defined as a transdisciplinary integration framework (Guinée et al., 2011). As suggested by the UNEP and SETAC guideline (UNEP and SETAC, 2011), the LCSA is a framework for evaluating economic, environmental, and social impacts in the context of decision-making processes towards more sustainable products throughout their life cycle. As pointed out by Zamagni (Zamagni, 2012), the life cycle analyses should not be used separately to estimate the sustainability impacts. The author also provided three main contents that should be considered in the sustainability assessment: (1) the increasing concern of sustainability assessment; (2) the relevance of life cycle approaches; (3) the importance of interdisciplinary integration. Accordingly, it is suggested that major future works can focus on the application of the LCSA framework. The LCSA framework follows the ISO standard 14040 of the LCA, meaning that the LCSA includes four main steps: (1) Goal and scope definition, (2) Life cycle inventory analysis, (3) Life cycle impact assessment, and (4) Life cycle interpretation.

The step *"Goal and scope definition"* introduces the purpose, delimitation, and target audiences of the study. It must be careful that the LCA, LCC and Social LCA have different aims and results, so mutual goals and scopes are forcefully recommended to undertake a combined LCSA. The functional unit, unit processes, impact categories and system boundary also need to be identified in this phase (UNEP and SETAC, 2011). Stefanova et al. (Stefanova et al., 2014) emphasized the importance of the step "Goal and scope definition". Due to the fact that the sustainability impacts are defined, research questions are posed, and the system boundary is represented in a structured manner, this step strongly impacts the subsequent steps and establishes direct links with the later ones. Zanni et all., (Zanni et al., 2020) proposed that the LCSA system boundaries can be defined according to 5 approaches: (1) “from cradle to gate” approach; (2) “from cradle to grave” approach; (3) From a "gate to gate" perspective; (4) “from gate to grave “; (5) "from cradle to cradle".

“*Life cycle inventory analysis*” is the second step of the LCSA. Like the traditional LCA, it deals with the *collection, categorization, and calculation*. This step includes the same sub-steps as the LCA, such as completing the flow diagram, preparing data collection, and collecting the data. Besides, the data should be collected at the unit process level, including input and output from the LCC, LCA, and Social LCA. As a result, all three LCC, LCA, and Social LCA data types are collected during the life cycle (UNEP and SETAC, 2011). There is a shortage of Social LCA data compared to the LCC and LCA data, and the Social LCA database is still under development (Dong and Ng, 2016; Zheng et al., 2020a). Figure 3.3 depicts unit process form in the LCSA. The inflows cover LCC, LCA, and Social LCA data, while the outflows contain products, toxins, and social benefits.

Figure 3.3. A form of the unit process in the LCSA



(Source: (UNEP and SETAC, 2011))

Costa et al. (Costa et al., 2019) remarked that the input-output data are collected and calculated during this phase. By reviewing previous studies, they figured out that a single inventory integrating the environmental, social, and economic indicators has been widely applied. Besides, the importance of primary and secondary data is also emphasized in this paper. The primary data are collected directly through observation, laboratory analysis results, and interviews, while secondary data consist of other authors' commercial databases, scientific literature, and commissioned reports.

The data collected are then related to the functional unit and unit processes. This step is also identical to the corresponding one from the LCA. However, LCC data and LCA data are quantitative values, while the Social LCA data are quantitative, semi-quantitative, and qualitative values. So, the qualitative data need to be converted to quantitative figures by using converting methods, as suggested by Hosseinijou et al. (Hosseinijou et al., 2014).

The LCI results are moved to the next phase – *life cycle impact assessment*. The classification and characterization are conducted as the compulsory steps in this phase. For the classification, the inventory results are assigned to the selected impact categories. The characterization converts LCI results to common units, and then the converted results are aggregated in the relevant impact categories. It is also suggested that the LCIA results are estimated by multiplying the individual inventory data in the LCI results with the defined characterization factors and then aggregating the multiplication results (Guinée, 2002; EC et al., 2010). For aggregating the LCC, LCA, and Social LCA results, Kloepffer (Kloepffer, 2008) proposed a conceptual equation based on the three life cycle approaches to estimate the LCSA value. The figure is calculated by summing up the LCC, LCA, and Social LCA results as below:

$$LCSA = LCC + LCA + SLCA \tag{3.7}$$

This equation requires the identical system boundary between the LCC, LCA, and Social LCA. In other words, it means that one identical system boundary for all three components is used. Besides, the different units between the LCC, LCA, and Social LCA results should be considered, so the LCC, LCA, and Social LCA should be normalized before calculating.

Life cycle interpretation is the last phase of the LCSA, offering conclusions, recommendations, and reports based on objectives defined in step "goal and scope definition" (UNEP and SETAC, 2011). Experts are suggested to carry out essential checking activities like consistency, completeness, contribution, sensitivity, and uncertainty analysis.

Several authors have applied the LCSA method to the construction industry. Dong and Ng (Dong and Ng, 2016) proposed an LCSA framework to assess the sustainability performance of construction projects. However, the developed framework did not engage with the costs incurred in the handover and operation and close-out phases. Besides, the weightings were not included, and LCI data were only drawn from the generic database. Meanwhile, Liu and Qian (Liu and Qian, 2019b) provided an integrated building-specific sustainability assessment framework with respect to the LCSA approach and weighting calculation. The framework includes four main parts: (1) defining alternatives and hierarchical structure of the LCSA model; (2) evaluating the performance of each alternative; (3) estimating and assigning weightings based on the AHP method; (4) ranking alternatives. The proposed framework is illustrated by applying to rank the sustainability performance of three building designs. Notwithstanding, this method did not evaluate the close-out phase's costs, and the weightings were only determined based on the authors' opinions. Visentin et al. (Visentin et al., 2020) carried out a bibliometric and systematic literature review to assess the application of the LCSA in the central scientific data. Particularly, they reviewed 105 publications corresponding to the period 2008–2019. The results figured out that the developed countries predominate the number of publications. Besides, they also found out that the LCSA has been already applied widely in the construction field to assess the sustainability performance of projects (Hossaini et al., 2014; Gencturk et al., 2016; Janjua et al., 2019a; Liu and Qian, 2019a). However, the LCSA application in other fields, such as energy and agriculture, is paid more attention than the construction area.

For selecting construction materials, several studies tried to apply the LCSA to compare material alternatives. Hossaini et al. (Hossaini et al., 2014) introduced an AHP-based LCSA framework that appraises building materials' environmental and socioeconomic impacts. The framework was developed from the UNEP guidelines, including four main steps mentioned above. Firstly, the goals and scope of the study were defined. Secondly, the inventory analysis was conducted to estimate the input-output flows. Thirdly, the impact assessment was carried out, including two sub-steps: (1) data analysis and (2) sustainability assessment. This step also established a list of 18 sustainability criteria and used the AHP method to convert the triple bottom line criteria into a sustainability index. Lastly, the interpretation step drew conclusions and recommendations. A case study of material comparison – concrete and wood- of two six-storey buildings is conducted to illustrate the developed method. The proposed framework helped designers assess the sustainability performance of materials. However, their data gathered from Canada – a developed country, the shortage of material-dependent activities and the AHP-based weightings were solely determined according to the authors' perspectives. Balasbaneh et al. (Balasbaneh et al., 2018) compared the sustainability impacts of five types of hybrid timber structures by applying the LCSA. According to them, life cycle analysis results should first be calculated. Next, the results were analyzed independently rather than combining or aggregating. It can be seen that this makes the conclusion ambiguous because the LCC, LCA, and Social LCA results are not aggregated into a single score. Zheng et al. (Zheng et al., 2019) put forth an LCSA method including four main steps: (1) defining system, (2) modelling, (3) unifying, and (4) interpreting. Firstly, the alternatives, goals and scope are defined. Secondly, the LCC, LCA, and Social LCA results are estimated based on the inventory analysis and impact assessment models. Thirdly, a multi-criteria decision-making model was applied to aggregate the three sustainability performances. Lastly, the results are highlighted and discussed together with a sensitivity analysis. The proposed method is used to assess the level of the sustainability performance of pavement structures in practice. Basically, this method offered an effective way to determine the sustainability performances of construction items and materials. However, this method remains several limitations, such as the omission of material-dependent costs and social performance in the close-out phase.

However, the LCSA remains some challenges. The obstacles were identified by the below studies.

By reviewing several case studies, Benedict (Benedict, 2017) proposed future works that should be done to reach more effective utilization. Whereby it is necessary to investigate results changed by weightings and how stakeholders estimate them. It is due to that various contexts coming from the country's policies and the interest of owners impact the significance level of economic, environmental, and social aspects. Consequently, experts have distinctive priorities in the three pillars of sustainability; for example, economic factors are commonly prioritized in developing countries, while environmental and social aspects are underestimated (Bachmann, 2013; Chang et al., 2016; Banihashemi et al., 2017; Dinh et al., 2020). Hence, Toosi et al. (Toosi et al., 2020) suggested that considering plain weightings for LCC, LCA, and Social LCA values in the LCSA model is a restriction that should be researched more. Several authors tried to determine the importance weightings and assign them to the LCSA model (Hossaini et al., 2014; Sou et al., 2016; De Luca et al., 2018; Reddy et al., 2018; Costa et al., 2019). However, the issues of determining importance weightings in LCSA are still not addressed. It is due to that the weightings were mostly determined by the authors' opinions or perspectives of developed countries (Hossaini et al., 2014).

Meanwhile, Costa et al. (Costa et al., 2019) discussed the challenges of the LCSA. By reviewing 71 articles regarding the system boundary, they figured out that many types of system boundaries are applied in the LCSA case studies. Moreover, the LCC, LCA, and Social LCA system boundaries are not always identical because they could relate to different economic, environmental, and social performances. They result in inconsistent system boundaries, unavailable inventory data, and difficulties in developing an accepted LCSA analysis.

Schramm et al. (Schramm et al., 2020) reviewed previous studies to overview the state-of-the-art of LCSA for sustainable development. They analyzed current case studies and found out that not many studies consider economic, environmental, and social dimensions – the three pillars of sustainability – in an integrated way towards sustainable development by using the LCSA. They also analyzed and synthesized the main differences of LCSA applications in the manufacturing sector and significant deficits of the state-of-the-art regarding each LCSA step. Relating to the application, they figured out that definitions of system boundary are not yet clear, and the weighting determination and aggregation are inconsistent. Additionally, the shortage of data collection and methodology for the LCA and Social LCA in line with ignoring long-term evaluation in the LCC (e.g., net present value) remain significant deficits from the state-of-the-art. They also concluded that the LCSA should be applied in more fields.

In general, the application of the LCSA is believed to encounter several obstacles. By looking into the studies on the subject so far, it is conceivable that the LCSA method has been applied to the construction industry. Nevertheless, only a minority of studies express their interest in construction material selection (Visentin et al., 2020). Although the preliminary design phase plays an essential role in the final design's sustainability (Bertoni et al., 2015), no study applies the LCSA to assess the sustainability impacts in this phase. Moreover, the material-dependent activities and close-out phase are neglected in the current studies. Besides, the data and methodology deficiency for the LCA and Social LCA together with the ignoring of long-term evaluation in the LCC remain major obstacles (Schramm et al., 2020). These motivate this thesis to establish a comprehensive LCSA framework to assess the sustainability performance of road construction materials in the preliminary design phase. The proposed procedure framework should provide a detailed guideline, use site-specific data, avoid double-counting, determine the importance weightings, aggregate into a single score, and support making-decision transparently. After that, a case study needs to be conducted to demonstrate the framework.

Multi-Criteria Decision-Making (MCDM) methods are effective tools to help experts decide and show potentials in combining with the LCSA (Bachmann, 2013; Hossaini et al., 2014; Benedict, 2017; Liu and Qian, 2019b; Zheng et al., 2019). The following section introduces the advantages and limitations of the main MCDM methods.

3.6.2. Multi-criteria Decision-Making methods

Integrating the LCC, LCA, and Social LCA into the LCSA is essential for assessing sustainability performance, as suggested in section 3.6.1. However, it is necessary to investigate how importance weightings of the LCC, LCA, and Social LCA results impact the LCSA outcome and how stakeholders estimate them. The aggregation of the LCC, LCA, and Social LCA into the LCSA has been researched by several authors (Bachmann, 2013; Hossaini et al., 2014; Govindan et al., 2015; Benedict, 2017; Onat et al., 2017; Ren et al., 2017; Liu and Qian, 2019b; Tarne et al., 2019; Zheng et al., 2019; Visentin et al., 2020). The MCDM methods promise great potentials for determining the importance weightings of LCC, LCA, and Social LCA results, integrating them into the LCSA result and supporting comprehensible decision-making (Onat et al., 2017; Tarne et al., 2019; Visentin et al., 2020). For example, Govindan et al. (Govindan et al., 2015) proposed a method to determine the most suitable construction structure by considering the sustainable criteria and MCDM methods. They collected the sustainable criteria imposing upon economic, environmental, and social aspects from previous research to achieve this goal. Then, the AHP method was brought into play to analyze the interdependence among these indicators; and simultaneously, the TOPSIS method was exercised to lay a foundation for evaluating weights of sustainable structures. Likewise, Ren et al. (Ren et al., 2017) applied the AHP method to determine the weightings of sustainability criteria for helping the decision-makers assess the sustainability performance.

Basically, MCDM is a cluster of sub-methods, such as the AHP, TOPSIS, ANP, and UAV methods. These tools are collectively designed with the purpose of helping decision-makers compare alternatives under consideration of more than one criterion. Several main MCDM methods are introduced below.

The Analytic Hierarchy Process (AHP) was developed by Saaty (Saaty, 1980) in the early 1970s. It is a method that simplifies complicated problems and transforms them into a hierarchy (Abdel-malak et al., 2017). The collected AHP data are analyzed using pairwise comparisons

(Triantaphyllou and Mann, 1995). The AHP method divides the target into sub-targets in order to structure and simplify it in a hierarchy. The hierarchy created includes multiple target levels, and the alternatives are put at the lowest level(s) of the hierarchy. According to Götze et al. (Götze et al., 2015), the AHP include the following steps: (1) Formation of the hierarchy; (2) Determination of the priorities; (3) Determination of local priority vectors (weighting factors); (4) Examination of the consistency of the priority assessments; (5) Determination of (global) priorities. This method has many advantages. It reduces subjectivity by synthesizing recommendations from a large assortment of experts. Besides, this method incorporates tangible and intangible criteria as well as their trade-offs (Saaty, 1980; Iwasaki and Tone, 1998; Götze et al., 2015). This method is easily comprehendible and requires only minor computational efforts (Götze et al., 2015). Moreover, the AHP method has been applied to aggregate the LCC, LCA, and Social LCA results in the LCSA outcome (Hossaini et al., 2014; Liu and Qian, 2019a). However, the AHP method mainly uses a scale to conduct comparisons, which potentially induces certain issues. Particularly, the difficulties in distinguishing between 'considerably greater' (scale value 5) and 'very much greater' (scale value 7) lead to inconsistencies (Götze et al., 2015). Moreover, the AHP method reverses the rank in case of adding new alternatives (Belton and Gear, 1983; Arroyo et al., 2015; Götze et al., 2015).

The *Technique for Order Preference by Similarity to Ideal Solution (TOPSIS method*) was developed by Hwang and Yoon (Hwang and Yoon, 1981). This method selects the alternative that has the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. According to Behzadian et al. (Behzadian et al., 2012), the TOPSIS procedure includes: (1) Build a normalized decision matrix; (2) Build the weighted normalized decision matrix; (3) Evaluate the positive and negative solutions; (4) Determine the separation measures; (5) Calculate the relative closeness to the ideal solution. One of the outstanding advantages of the TOPSIS is that it can evaluate quantitative and qualitative criteria (Sultana et al., 2016). Besides, there is no change in the calculation procedure when adding additional alternatives and criteria and the TOPSIS method is easy and convenient with systematic steps (Ertuğrul and Karakaşoğlu, 2009). It also takes advantage of linguistic variables to solve undocumented data problems (Abdel-malak et al., 2017). However, the method is challenging to determine weights, and each criterion must increase or decrease monotonically (Aruldoss et al., 2013). It also does not consider the relative distances between the ideal and negative ideal solution (Sakthivel et al., 2015).

In 1999, Saaty proposed the *Analytic Network Process (ANP)* method developed from the AHP method (Saaty, 1999). The method is applied by following the steps: (1) Build model construction and problem structuring; (2) Evaluate pairwise comparisons and priority vectors; (3) Format supermatrix; (4) Synthesize the criteria and alternatives' priorities; (5) Select the alternatives (Chung et al., 2005; Yüksel and Dagˇdeviren, 2007). The ANP method helps solve the problem of dependence among options and criteria (Wey and Wu, 2007). It deals with uncertainty and complex situations, and analyzes quantitative and qualitative criteria (Bayazit, 2006). However, the method requires more comparisons and efforts than the AHP method (Bayazit, 2006), and decision-makers do not perform relative comparisons clearly because they are significantly complex (Cooper, 2012).

The *Utility Value Analysis* (UAV method) analyzes and compares complex alternatives by preferences of the decision-makers in a multidimensional target system (Götze et al., 2015; Cardeal et al., 2020). According to Götze et al. (Götze et al., 2015), it evolves the following steps: (1) Determination of target criteria; (2) Weighting of each target criterion; (3) Calculation of partial utility values; (4) Calculation of (total) utility values; (5) Assessment of profitability. This method is a comparatively simple method to select the most valuable alternative. It requires only minor efforts in the calculation, and the results are interpreted (Götze et al., 2015; Halstenberg et al., 2019). However, data collection is a significant problem, and the definition of selected criteria, importance weightings, and partial utility values require extensive effort (Götze et al., 2015).

A ternary diagram/plot is applied in case the contributions of three factors/variables to the final result need to be estimated. It contains three axes (representing different issues) arranged as an equilateral triangle, such that each axis scaled from 0 to 100% is a side of the triangle. Any point inside the diagram depicts the relative contribution of each factor on each side of the diagram (Briffa et al., 2020). The ternary diagram offers a comprehensive picture of the material comparison results in various scenarios. It provides a transparent visualization and straightforward interpretation of each perspective's result (Paulo et al., 2011; Carvalho et al., 2016).

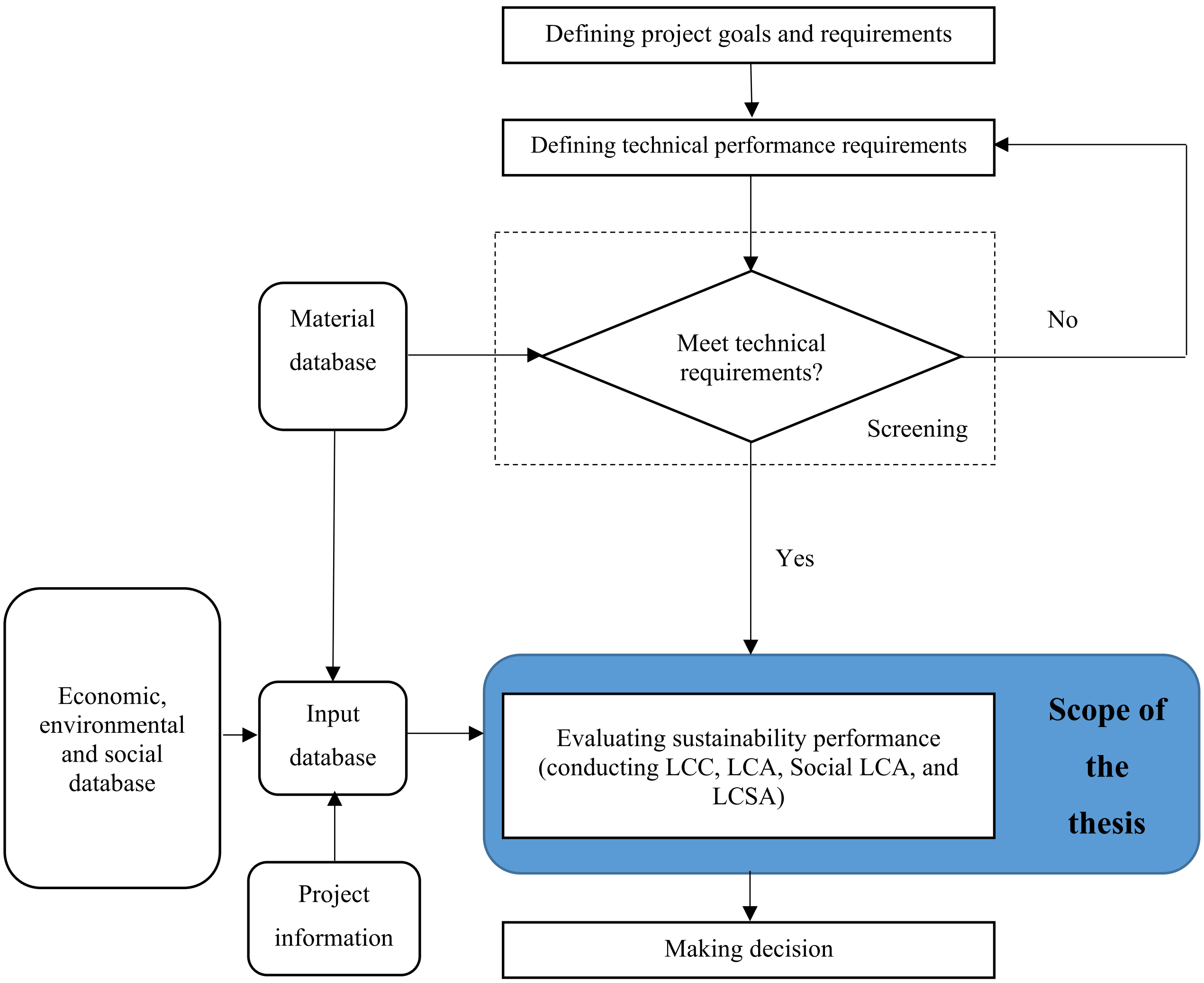
In the preliminary design phase, developing a procedure model that can harmonize the economic, environmental, and social dimensions altogether into road construction material selection is so crucial. In addition, it is essential to assess the importance levels/weightings of LCC, LCA, and Social LCA results when estimating the overall LCSA result. It can be seen that the MCDM methods promise potentials for aggregating the LCC, LCA, and Social LCA into the LCSA value. They can be applied to estimate the weightings of LCC, LCA, and Social LCA results in the LCSA model. The next section proposes a procedure model, including the LCC, LCA, Social LCA, LCSA and MCDM methods, to select road construction materials based on sustainability performance assessment.

4. Instruments for selecting road construction materials towards sustainability in the preliminary design phase

4.1. Procedure models for road construction material selection and sustainability assessment

With the broad assortment of construction materials available and their impact on sustainability, selecting materials is crucial to achieve high sustainability of road construction projects. In order to support decision-making under consideration of the variety of material alternatives, influencing factors, etc., a systematic and structured procedure is necessary. This refers to the material selection itself as well as to the underlying evaluation of the materials´ impact on sustainability. Such a systematic and structured procedure, including the usage of adequate methods, is supported by procedure models. In the following, firstly, a procedure model for road construction material selection is suggested. Secondly, a more detailed procedure model for sustainability assessment is proposed.

The suggested procedure model for road construction material selection in the preliminary design phase developed from general procedures for selecting material alternatives (Ashby et al., 2004; Deng and Edwards, 2007; Ogunkah and Yang, 2012) is illustrated in Figure 4.1. Overall, the procedure model begins with defining project goals and requirements which are determined according to project information and preliminary design drawings. Afterwards, technical performance requirements are identified with crucial characteristics such as strength, durability, and density, and then a screening analysis is conducted to determine which materials meet the technical requirements. This analysis is carried out by comparing the physical characteristics of materials with the technical requirements in order to pre-select materials. If there is not any material meeting the demands, the technical performance requirements need to be adjusted. The screening result is a list of pre-selected materials. Next, the evaluation of sustainability performance is carried out to assess the level of sustainability of the pre-selected materials. Therefore, sustainability criteria have to be determined, and adequate methods are selected in order to enable the measurement and evaluation of the economic, environmental, and social impacts of the materials used in a road construction project with its specific requirements. Therefore, the methods presented in chapter 3 –LCC, LCA, Social LCA, LCSA – are suggested for answering research question 3 and its sub-questions. The LCSA result is calculated from the assessment of the three dimensions of sustainability by using the LCC, LCA, and Social LCA as the state-of-the-art methods (as it is assumed here). Thereby, trade-offs between the achievement of economic, environmental, and social goals can be identified and considered. Finally, the final decision concerning the most suitable materials can be made based on the dimension-specific as well as the overall sustainability evaluation of the pre-selected materials.



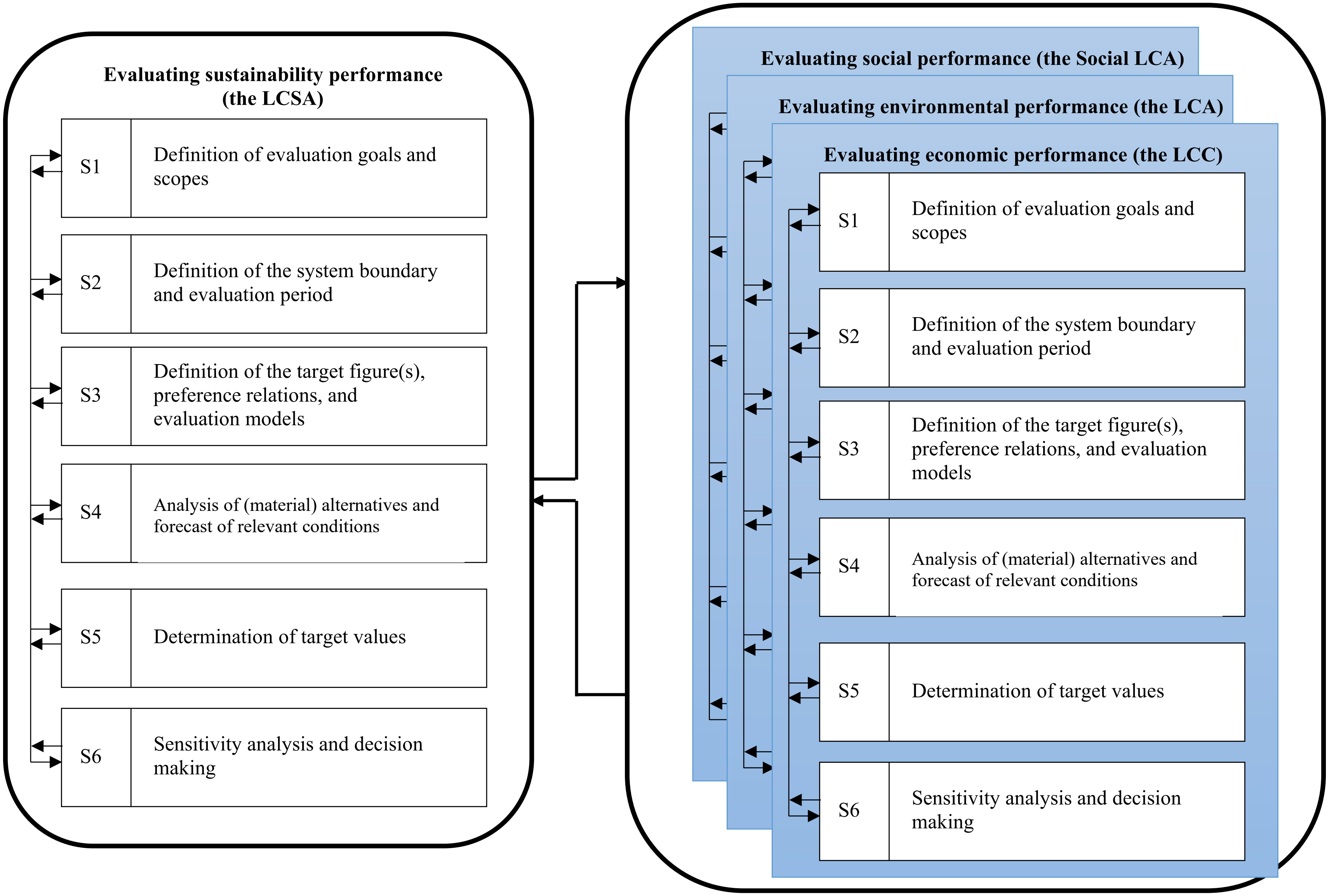
(Adapted from sources: (Ashby et al., 2004; Deng and Edwards, 2007; Akadiri and Olomolaiye, 2012; Ogunkah and Yang, 2012; Zhang et al., 2017))

Figure 4.1. Procedure model for material selection

The procedure model illustrated in Figure 4.1 is suggested as a framework for guiding the designer in selecting the materials with regard on sustainable development. According to the procedure model, some material alternatives are pre-selected based on the identified technical criteria, and their sustainability performance is assessed by LCC, LCA, Social LCA, and LCSA. During the pre-selection and assessment activities, a plenty of necessary data and information has to be acquired or generated using diverse databases.

For further structuring, various assessment activities and methods processing the data, a procedure model for evaluating the sustainability performance of road construction materials is proposed to answer research question 3. Therefore, different existing procedure models can serve as a basis. One is the procedure model presented in Figure 4.2 (Köhler et al., 2017; Meynerts et al., 2017; Götze et al., 2020). As it is shown, the procedure model is hierarchically structured in order to reduce complexity and enhance transparency: The evaluation process is divided into two levels, with the overall sustainability performance evaluation at the first level and the evaluation of the economic, ecological, and social performances at the second level. Furthermore, the procedure model is decision theory-based – it includes target figures, alternatives, states (or scenarios summarizing all relevant conditions) as well as the outcomes of the alternatives as the elements of the basic model of decision theory.

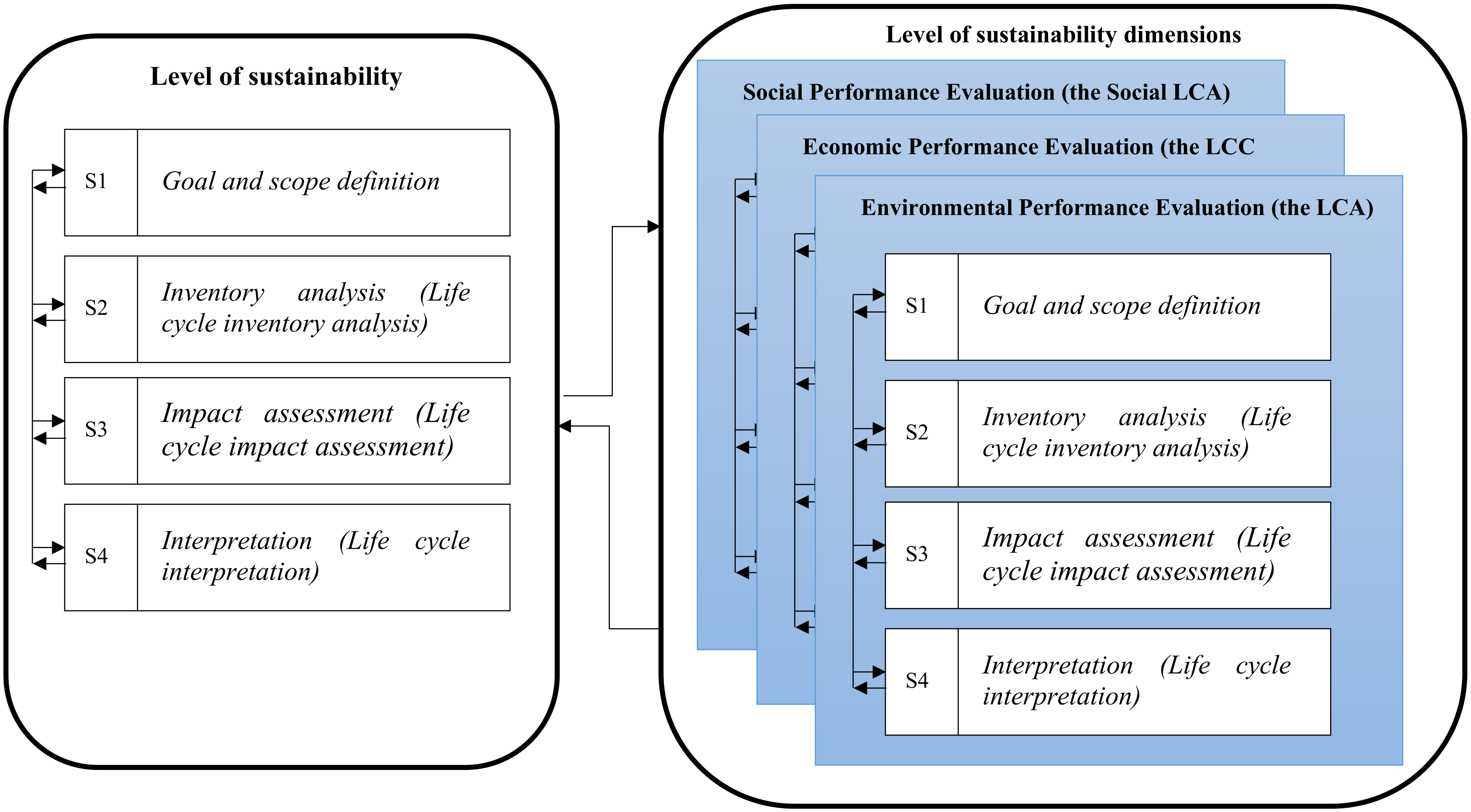
At *the top level*, evaluation activities that refer to all sustainability dimensions are conducted. These activities generate a common evaluation basis, including the scope with a functional unit, the system boundary, assumptions, data and an overall target figure. This enables to ensure consistency between the assumptions made and data used for the single dimension-specific evaluations, to avoid the double generation of data, and to identify and handle overlaps between the dimension-specific evaluations. The overlaps might occur if effects are relevant for more than one dimension, such as energy availability and usage, pollution and its avoidance, or re-usage/recycling of waste. This can be handled by using the common database for dimension-specific evaluations that consider the specific impacts on each of the dimensions of sustainability. The dimension-specific evaluations are positioned *at the second level* of the procedure model. They concretize the scope, the system boundary and the target figure for each dimension, generate and process specific data by using adequate methods and models, and calculate the dimension-specific target figure(s). The obtained target values are then aggregated at the top level by calculating an overall sustainability value. Thereby, the procedure model allows for systematic and structured integration of LCC, LCA, and Social LCA into LCSA.



(Adapted from sources: (Köhler et al., 2017; Meynerts et al., 2017; Götze et al., 2020))

Figure 4.2. The decision theory-based procedure model for evaluating sustainability performance

Although this procedure model shows some advantages and has been applied in some cases, the four-step procedure of LCA seems to be more common and applicable. Therefore, it is suggested here to integrate both approaches: Steps S1, S2 and S3 of the decision theory-based procedure model correspond with the first step of the LCA procedure (goal and scope definition), steps S4 and S5 with the second and third steps of LCA (life cycle inventory analysis and life cycle impact assessment) and, finally, step 6 with the fourth step of LCA (interpretation). Due to its dissemination, the four-step procedure of LCA (and Social LCA, LCSA) should be the primary approach. Therefore, the four steps of LCA are maintained. With regard to the decision theory-based procedure model, a hierarchical structure is introduced (Figure 4.3). Additionally, the elements of the basic model of decision theory (target figures, alternatives, scenarios, outcomes, etc.) are included systematically in the four steps of the procedure model. In the following, the steps of the integrated procedure model are described briefly.



(Adapted from sources: (ISO, 2006b; Köhler et al., 2017; Meynerts et al., 2017; Götze et al., 2020))

Figure 4.3. The ISO 14044-based procedure model for evaluating sustainability performance

Step 1 – Goal and scope definition

According to Figure 4.3, in the beginning, the evaluation goals and scope are determined. This will largely be done at the “Level of Sustainability”, providing a common base for the dimension-specific evaluations at the second level of the procedure model. These will require dimension-specific concretizations and refinements.

This thesis focuses on assessing the sustainability performance of road construction materials and selecting the material with the best sustainability performance – this generic evaluation goal has to be concretized in specific application cases. The scope covers the functional unit, system boundary, impact categories, and category indicators. The functional unit should be consistently defined for all evaluations, providing a common evaluation base for both two levels of the procedure model. It should take the form of “Road infrastructure between “A” and “B” over a time horizon of a defined number of years.” (Brattebø et al., 2013). The product system covers the product itself, all product-related activities and inputs and outputs, including material extraction, material manufacturing, material acquisition, material usage, material repairing activities, and other material-dependent activities (for a generic flow chart see Figure 4.4).

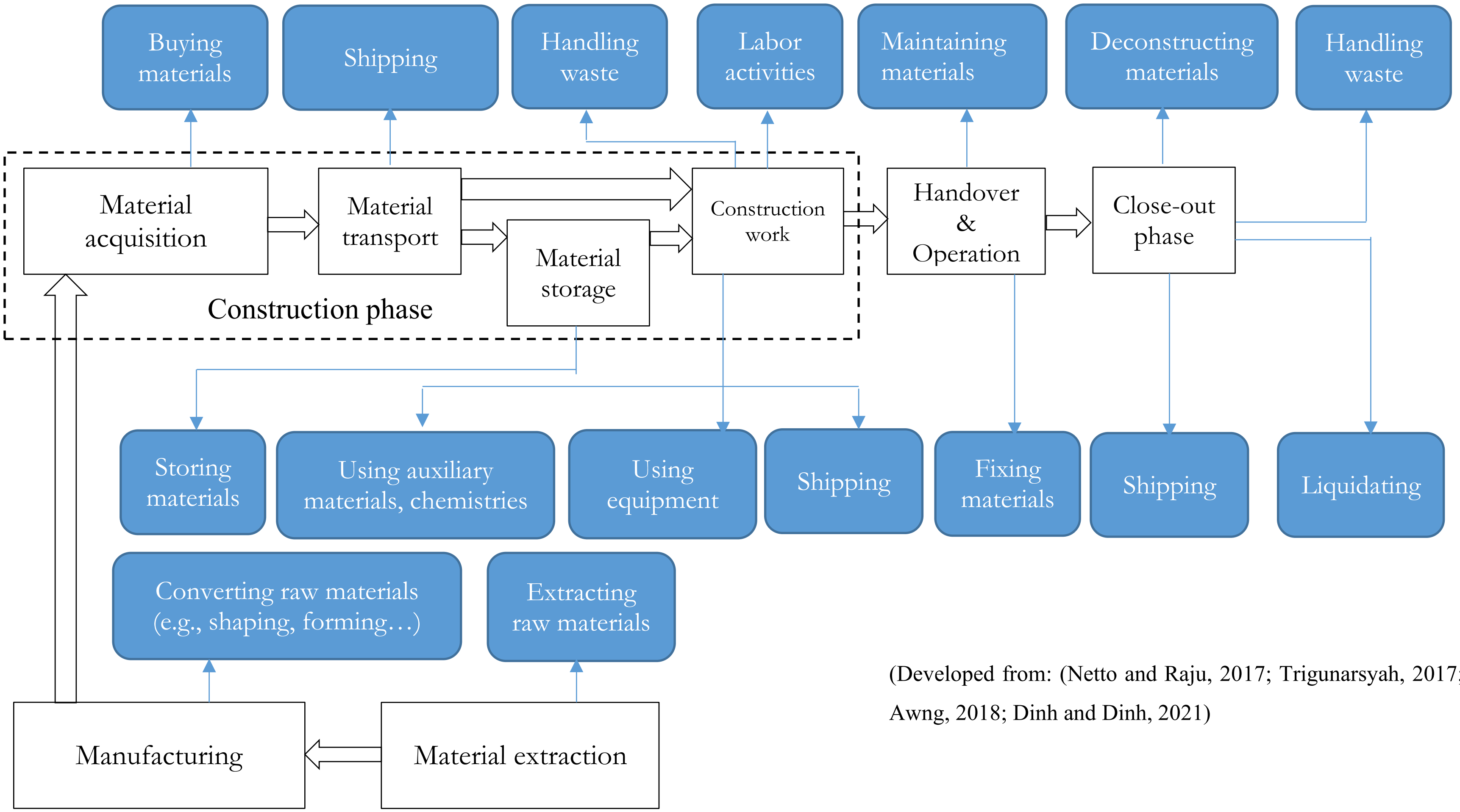
With regard to the product system, the system boundary has to be defined. It concretizes which activities (unit processes) in the phases mentioned above are included, together with their inputs and outputs. According to Zanni et all., (Zanni et al., 2020) the LCSA system boundaries can be defined based on the following definitions: (1) “from cradle to gate” approach refers to the collection of data and information from the extraction of raw materials to the final assembly of the product; (2) “from cradle to grave” approach includes the extraction of raw materials and their return to the environment as waste or emissions; (3) “From gate to gate" perspective, consider what lies within the company's manufacturing, excluding supply and distribution; (4) “from gate to grave “ approach includes distribution phase, use phase, and end of life phase; (5) "from cradle to cradle" approach assumes that all outputs (such as emissions, water, and waste) produced at the end of life will return in the input of the following products. Due to technological limitations, some road construction materials (such as asphalt and chemical glue) do not meet the condition of "from cradle to cradle" approach, that is "*all outputs* (such as emissions, water, and waste) produced at the end of life will return in input of the following products". So, this thesis complies with the “the cradle to grave” approach to estimate the sustainability performance of road construction materials.

Accordingly, it is assumed that the extraction, manufacturing, construction, handover and operation, and close-out phases should be involved. The "from cradle to grave" approach is referred to as life cycle analysis, which looks holistically at the life cycle of road construction materials and thereby selects and informs alternatives to reach such better sustainability performance. Besides, “from cradle to gate” approach, “from gate to gate" approach and “from gate to grave“ approach are subdivisions of the "from cradle to grave" approach and can be applied to specific case studies based on their goals, scopes, and available data.

In principle, the system boundary should be used in common for evaluating the overall sustainability performance and assessing the economic, environmental, and social performances in order to ensure a consistent evaluation (Janjua et al., 2019b), so the step is (primarily) executed at the top level of the procedure model. However, if a phase or activity is not relevant to one sustainability dimension, it can be neglected in the dimension-specific evaluation.

A common assumption in this step might be that the quantity and intended quality of traffic is pre-determined for the whole. In that case, the sustainability impacts resulting from traffic should be nearly identical for comparing all material alternatives and can be eliminated in comparisons. Meanwhile, several specific material-relevant activities in extraction and manufacturing companies are not determined in the preliminary design, so their influences on sustainability are also excluded. For example, the sustainable performance of material storage in manufacturing companies depends on the actual time of purchase, which is only defined by the suppliers in the later design phase.

Additionally, the evaluation periods have to be defined. They depend on the road’s life cycle and can be pre-designed by the owner (or decision-maker). Besides, the temporal range of impacts of material selection and data availability might influence the evaluation period. If the time horizon of impacts differs between the sustainability dimensions, different evaluation periods might be defined. However, consistency should be maintained.



(Developed from: (Netto and Raju, 2017; Trigunarsyah, 2017; Awng, 2018; Dinh and Dinh, 2021)

Figure 4.4. Flowchart of main material-dependent activities of road construction materials

According to the guidelines defined in the ISO standard, impact categories and category indicators have to be determined in this step as well. They are closely connected to the target figures applied as well as the methods used for the evaluations (which are focused in step S3 of the decision theory-based procedure model).

At the sustainability level, the target figure of the whole evaluation has to be defined. According to the LCSA, this should be a single score representing the overall sustainability performance of all included material alternatives. LCSA is a comprehensive method or framework for evaluating economic, environmental, and social impacts throughout the life cycle of objects, revealing trade-offs between the outcomes of LCC, LCA, and Social LCA, and thereby supporting decision-making processes towards more sustainable development (Kloepffer, 2008; UNEP and SETAC, 2011). For the calculation of this single score, a suitable aggregation method – e.g. a method of multi-criteria decision-making – can be chosen. Additionally, preference relations are needed to express the importance of the single sustainability dimensions in a specific case of application. They can be expressed by importance weightings with which the LCC, LCA, and Social LCA results (target figures of the second level) are multiplied to calculate the LCSA result (see section 4.2.4).

For the dimension-specific evaluations at the second level, it is suggested to use the state-of-the-art instruments outlined in chapter 3 together with their typical target figures:

- LCC is a tool for assessing economic performance by estimating the total life cycle-related cost or profit (as target figures, expressed by net present values) considering life cycle phases of road construction materials.
- LCA for estimating the total environmental impacts of alternatives during their life cycle; therefore (at least) one of the established methods with its specific target figures should be selected at this step (e. g. the ReCiPe method with midpoint impact categories, such as climate change).
- Social LCA for assessing the social impacts and calculating a Social LCA score; here, relevant social impacts (e.g., fair salary, working hours, health and safety of the local community) and methods for measuring these impacts have to be defined.

As some of the examples show, impact categories and category indicators have to be defined as well – they determine the outcome of the target figures and should be included in the modelling and calculation of the target figures. Differentiated suggestions for conducting these evaluations are presented in section 4.2.

Step 2 – Life cycle inventory analysis

The life cycle inventory analysis is concerned with the collection, adaption, and validation of data. This step should include an analysis of the material alternatives and their impacts on the road construction project as well as the relevant (external) sustainability conditions (for example, availability, prices of materials, suppliers, etc.), and it is explicitly suggested in the decision theory-based procedure model (Step S4). This comprises the identification and consideration of the relationships between different road construction material alternatives – the entity of specific material types that are needed for a road can be understood as a "material alternative". In this step, the input and output data are collected according to the material database, project information, and sustainability database that are mainly drawn from the given project, historical data, designer's experience, and similar projects. The material database comprises specific characteristics of available materials, such as strength, waste rate, and durability. Project information includes the project life, discount rate, construction schedule, or maintenance plan. The sustainability database covers sustainable information, such as costs, unit price, characterization factors, or social impact categories.

The application of LC approaches in the preliminary design phase encounters the obstacle of restricted information. According to (Ehrlenspiel et al., 2007a), the designers want to determine the result quickly in the early design phase, but the relevant documents may not be yet completed. To manage the problem of restricted data availability, two approaches are suggested for distinguishing between two scenarios of data availability. These scenarios refer to a crucial group of input data: the amount of necessary materials for road construction items.

- In scenario (1), it is assumed that the amount of materials has already been estimated in the preliminary design phase and, therefore, is available as a basis of the sustainability assessment. The amount of materials is estimated based on preliminary drawings and blueprints. It is recorded in a quantity take-off – a measurement of materials and labor needed to complete a road construction project (Umair and Wani, 2022). The quantity take-off is developed by estimators during the planning and design phase.

- In scenario (2), it is assumed that the amount of materials has **not** yet been estimated in the preliminary design phase.

The two scenarios are derived from the typical sequence of the planning and design phase for a road (Adeyeye et al., 2013; Erebor et al., 2019). At first, in the preliminary design phase, the main layout will be designed to determine the shapes, dimensions, or technical requirements. According to the layouts, the designers will pre-select the potential materials which meet all mandatory requirements. In some projects, material-related dimensions (for example, the length and the width of the materials) can be provided in the preliminary design phase based on the provided structure, so the amount of potential materials can be pre-estimated (scenario (1)). For example, if the length of the road is known, it is possible to estimate the square of the pavement and calculate the required amount of two potential material alternatives: concrete and asphalt. On the contrary, the material selection might be intended or necessary **before** the designers provide the material-related dimensions and, therefore, before the amount of materials can be estimated with a sufficient significance (scenario (2)). In scenario (2), the material-dependent activities can be identified, but numeric values concerning the number of labor and equipment cannot be estimated due to the shortage of the amount of materials. Putting all alternatives in the same scenario is the most suitable approach. However, if single materials or whole material alternatives are in different scenarios, a hybrid approach can be applied. In such an approach, the sustainability level of each material and material alternatives is estimated based on the individual best possible scenario.

Besides, it is suggested to use and adapt the existing methods of data generation in preliminary design phases to solve the problems of material selection for road construction projects. This comprises the usage of various databases, modelling techniques and, especially, the application of methods of development-concurrent cost calculation (Ehrlenspiel et al., 2007a; Ehrlenspiel et al., 2007b; Meynerts et al., 2017). Thirdly, the use of sensitivity analysis can help to cope with the uncertainty of data (see step 4).

Step 3 – Life cycle impact assessment

The purpose of this phase is to support assessing the sustainability performance of LCI results so as to make substantiated decisions concerning the selection of material alternatives. Corresponding with step S5 of the decision theory-based procedure model, it estimates indicator results for the different impact categories, which together represent the sustainability burden for the material alternatives. Firstly, at the level of dimension-specific evaluations, the economic, environmental, and social performance results are estimated according to the relevant LCI results in step 2 (see sections 4.2.1, 4.2.2, and 4.2.3). However, The LCIA phase in the LCC can be neglected because its LCI data are reported in monetary units that can be compared clearly (UNEP and SETAC, 2011; Dong and Ng, 2016; Costa et al., 2019). Afterwards, at the sustainability level, the LCC, LCA, and Social LCA results are aggregated by MCDM methods to determine the LCSA result (see section 4.2.4). In other words, a single score expressing the overall sustainability performance of the material alternatives is calculated based on the economic, environmental, and social targets and the weightings of these dimensions.

Step 4 –Life cycle Interpretation

In accordance with the purpose and scope specification, the findings of an LCI and LCIA are compiled and discussed in order to derive conclusions and provide a basis for suggestions and decision-making. For decision-making, the sustainability scores calculated for the alternatives at the sustainability level can be compared with each other to identify the material with the best single score representing the most sustainability-efficient alternative. To substantiate and reflect the decision recommendation, the different evaluation results should be interpreted carefully together with the assumptions and limitations of the study (including limited data availability). Additionally, sensitivity analysis can be conducted to cope with the uncertainty of data if necessary. According to (Götze et al., 2015), sensitivity analysis investigates the relationships between the various data and the outcomes to examine the influence of uncertain model data and assumptions on the model’s results. For example, using a ternary diagram, a sensitivity analysis regarding the weightings of the sustainability dimensions can be conducted. Based on these weightings, a ternary diagram provides a thorough view of the advantages of road construction materials.

The suggested procedure model shows potentials. Firstly, a complex issue can be systematically divided into sub-issues to reduce its complexity. Secondly, the three pillars of sustainability can be comprehensively captured and assessed, and the results can then be aggregated transparently. Thirdly, some methods rather than the LCC, LCA, Social LCA, and LCSA can also be integrated and applied transparently to assess sustainability performance. One example is the scenario method for forecasting relevant input factors and distinguishing possible cases. Another example is the ternary diagram that can be used to display the favourable alternatives (materials) in dependence on the weightings of the economic, environmental and social dimensions. The procedure model serves as a framework for sustainability evaluation. More concrete suggestions for the dimension-specific modelling and evaluation activities, as well as the aggregation of an overall sustainability figure, are topics of the following sections.

4.2. Specific instruments for assessing the sustainability performance of road construction materials in the preliminary design phase

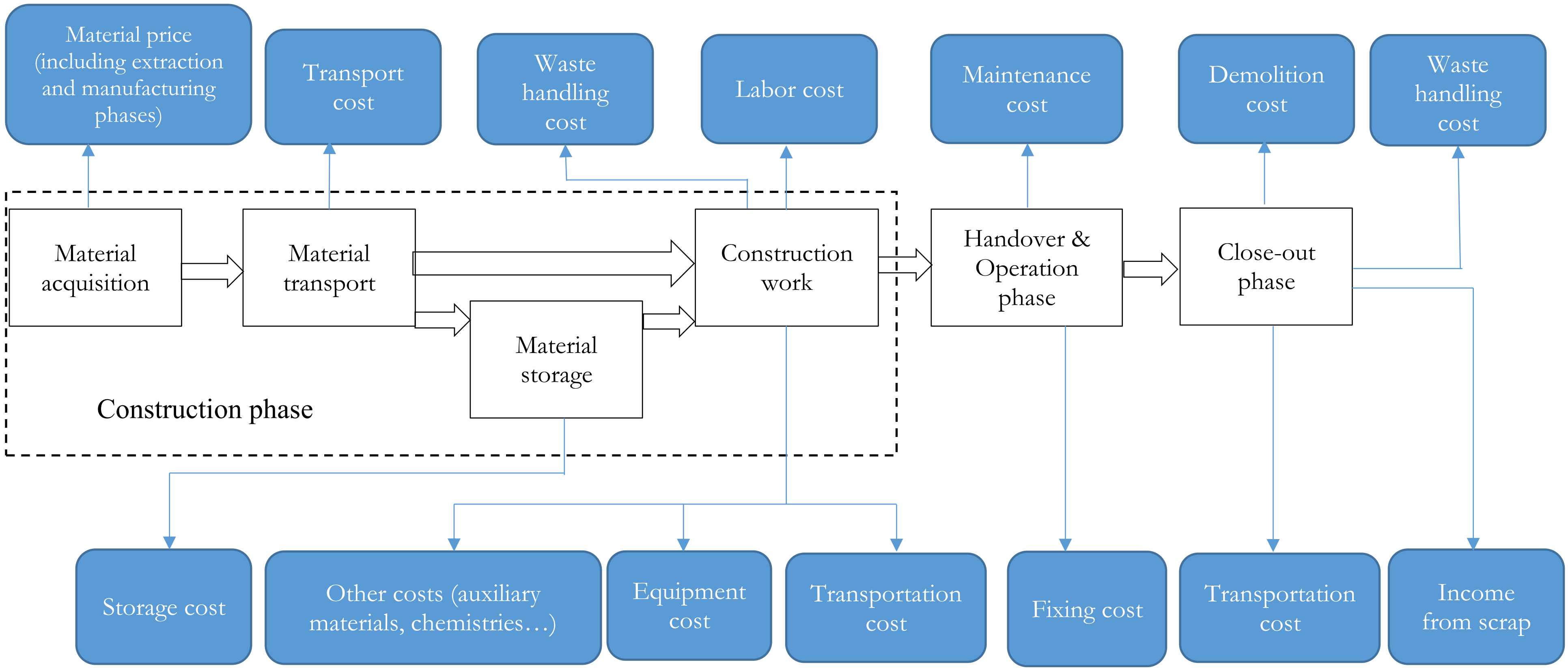
4.2.1. Economic assessment

4.2.1.1. Introduction of economic assessment

For the economic assessment, it is suggested here to apply life cycle cost (LCC) together with the Net Present Value (NPV) method as the most widely accepted method for estimating the economic performance in long-term projects. LCC is applied widely in different areas and seems to be suitable for road construction material selection and answering research question 3b as well, as reviewed in chapters 2 and 3. In essence, this method allows for including all the costs incurred during the life cycle and comparing material alternatives (Babashamsi et al., 2016b; Coleri et al., 2018; Fantozzi et al., 2019; Feria and Amado, 2019; Gao et al., 2019; Kumar et al., 2019; Moins et al., 2020). Accordingly, the cost items (e.g., construction costs, transport cost, and disposal cost) can be estimated separately as a part of the LCC equation (Gurum, 2018; Li et al., 2020; He et al., 2021). Furthermore, the time value of money is involved by using the NPV method and discount rate (Wolthuis, 2014; Metwally and Abouhamad, 2019; Potkány et al., 2019). So, the total material-dependent cost can be calculated comprehensively.

Therefore, an LCC model for the economic assessment of road construction materials is developed by building LCC equations to calculate the economic impact of the usage of materials in road construction projects and, thereby, contribute to choosing the most sustainable materials in the preliminary design phase. The model includes all material-dependent activities along the material life cycle and the costs resulting from them. They are defined in a generic model of life cycle-related activities and cost elements, serving as a framework for modeling material-dependent life cycle costs (Figure 4.5). The framework can be applied to identify the scope and the system boundary for the economic evaluation in the first step of the procedure model. The system boundary of the economic aspect can be derived based on the system boundary defined at the sustainability level. The costs in material extraction and the material manufacture phases are assumed to be included in the material price. That means that material extraction and material manufacture phases are ignored and not explicitly included in the relevant life cycles´ material activities.

Meanwhile, indirect costs such as administration costs and cleaning costs are not included because it can be assumed that these costs are not strongly impacted by the material selection. The administration and cleaning costs mainly depend on the length/square of the road. Additionally, traffic costs in the handover and operation phase are also neglected because they are assumed to be identical for all material alternatives. In fact, the expected amount of traffic is forecasted or pre-determined by the owners, and it is the same for all material alternatives; furthermore, the influence of the selected materials on the traffic cost is assumed to be negligible.



(Developed from sources: (Gurum, 2018; Li et al., 2020; He et al., 2021)

Figure 4.5. Flow chart of material-dependent life cycle costs

The diagram defines the relevant material's life cycle and its cost elements. At the beginning of the construction phase, contractors order necessary materials from suppliers and the material price is estimated or bargained accordingly. After that, materials are transported from suppliers to construction areas resulting in transport cost. This cost is dependent on contracts between contractors and suppliers. In particular, if the material price includes transport cost, this cost could be omitted in the LCC calculation. When materials arrive, they are used immediately or stored in the warehouse. Regarding the construction phase, labor cost, equipment cost, waste transportation, and waste material handling cost are calculated based on construction activities. Besides, additional expenses, such as for auxiliary materials, chemistries, and transportation of scraps, are vital in this phase. Next, material-dependent costs for maintaining and repairing during the handover and operation phase will arise. Lastly, in the close-out period, deconstruction cost, transportation cost, and waste material handling cost are to be expected – but incomes from scrap liquidation as well. The diagram can also be applied to define the scope and the system boundary for the economic evaluation in the first step of the procedure model.

Based on this framework, the cost elements calculated in the LCC model can be structured and defined in a second step:

$$LCC_m = MAC_m + TrC_m + WC_m + CoW_m + MC_m + CO_m \qquad 4.1$$

Where:

- LCC_m is the life cycle cost of material type m (in currency unit).
- MAC_m represents the total acquisition cost of material type m incurred in the material acquisition phase.
- TrC_m denotes the total transport cost of material type m.
- WC_m is the total warehouse cost (or storage cost) of material type m.
- CoW_m is the total cost of construction works when using material type m.
- MC_m denotes the total cost in the handover and operation phase for material type m.
- CO_m represents the total cost in the close-out phase of material type m.

In the equation above, the material-dependent life cycle cost – which has to be calculated for each material alternative – is the sum of all cost elements defined in the framework. After having generated the necessary data in the second step of the procedure model, each of these elements can be calculated as NPV comprising the discounted cash flows corresponding with the cost of a specific type in each period of the life cycle. These calculations as well as the aggregation of the life cycle cost can be seen as tasks in the third step of the procedure model, while the interpretation and sensitivity analyses are conducted in the fourth step.

In the next sections, models, represented by formulas, methods for data acquisition, and databases for the material-dependent cost elements distinguished in the framework are suggested for each scenario defined in section 4.1.

4.2.1.2. Life cycle cost model for scenario 1

In scenario (1), the different elements of the total material-dependent cost summarized in formula 4.1 can be calculated according to the amount of materials as well as on construction and maintenance plans.

a. Acquisition cost of material acquisition

The material acquisition cost results from buying the materials from suppliers and consuming them. The materials summarized in one "material alternative" can be distinguished into one or more main materials and material-dependent substances. The latter are substances that are used together with the main materials to complete the construction works and construction items. For example, bricks are used with mortar to build a wall. These costs can be calculated based on the unit prices of material and material-dependent substances according to the following formula (under the assumption that only one main material is to be considered and a weighted average price of the material-dependent substances can be determined; in other cases, the formula has to be differentiated):

$$MAC_m = \sum_{t=0}^{T} (UP_{m,A,t} \cdot M_{m,t} + UP_{d,A,t} \cdot M_{d,t}) \cdot (1+r)^{-t} \qquad 4.2$$

Where:

- $UP_{m,A,t}$ and $UP_{d,A,t}$ are the expected unit prices at time t of the considered material and material-dependent substances, respectively. Each of the unit prices can be gathered by using catalogues or directly asking the vendors for information or offers.
- $M_{m,t}$ and $M_{d,t}$ are the amount of the materials and material-dependent substances at time t defined based on the blueprints in the preliminary design phase. The amount of materials

and material-dependent substances includes the loss during the project, such as lost in transportation.

- r represents the discount rate (%).
- t is the time index (t from 0 to T, with 0 as the point of time when the first cash flow occurs).
- T is the whole project life (typically in years).

b. Transport cost

In general, transport cost (freight cost) is the cost incurred throughout moving goods and commodities from one point to another. In the construction industry, this cost is incurred especially when moving road construction materials and material-dependent substances from suppliers to the construction area. In several cases, this cost is included in the original material price, which means that transport costs are omitted in the LCC calculation. If not, this cost has to be calculated and included explicitly in the LCC. Therefore, it is suggested here, to distinguish between two cases which refer to the "make or buy" decision concerning the material transport: Whether a transportation company is hired to move the materials and material-dependent substances from the supplier to the construction area or the transport is done by the contractor itself influences the transport cost and the way they have to be determined. This is reflected by the following formulas for determining the transport cost:

$$TrC_m = TrC1_m + TrC2_m \qquad 4.3$$

Where:

- TrC_m is the transport cost of material type m and its material-dependent substances.
- $TrC1_m$ denotes the transport cost of material type m and its material-dependent substances when hiring a transportation company.
- $TrC2_m$ is the transport cost of material type m and its material-dependent substances when the contractors transport it themselves.

- Calculating transport cost in case of hiring a transportation company ($TrC1_m$): In this case, the transport cost can be calculated by the following equation:

$$TrC1_m = \sum_{t=0}^{T} \frac{[(UP_{m,TrC1,t} \cdot M_{m,TrC1,t} + UP_{d,TrC1,t} \cdot M_{d,TrC1,t} + TO1_t)]}{(1+r)^t} \qquad 4.4$$

Where:

- $UP_{m,TrC1,t}$ and $UP_{d,TrC1,t}$ are a price for transporting a unit of material type m and its material-dependent substances at time t when hiring a transportation company, respectively. These unit prices reflect the total distance and type of materials (with volume, weight, safety and other logistical requirements) that are negotiated between the contractor and the transportation company.
- $M_{m,TrC1,t}$ and $M_{d,TrC1,t}$ represent the amount of material type m and its material-dependent substances at time t, which are transported by the transportation company, respectively.
- $TO1_t$ is an additional charge that might be payable to use bridges, roads or for custom duties between different countries in case of hiring a transportation company; for the sake of simplification, it is included as one amount of money (not explicitly dependent on the amount or value of the material) here.

- Calculating transport cost in case contractors transport materials themselves ($TrC2_m$): contractors use their facilities (e.g., vehicle, lorry, and train) for material transportation. The cost is affected by transportation modes (truck, rail, or ship) and the corresponding cost, distance, and types of materials. It can be estimated by the following equation:

$$TrC2_m = \sum_{t=0}^{T} \frac{[(VL_{m,t} \cdot L_m \cdot M_{m,TrC2,t} + VL_{d,t} \cdot L_d \cdot M_{d,TrC2,t} + TO2_t)\ ]}{(1+r)^t} \qquad 4.5$$

Where:

- $VL_{m,t}$ and $VL_{d,t}$ are the transport rate/freight rate of one unit of material type m and its material-dependent substances for each one km at time t, respectively. These rates are defined based on the material's characteristics (for example, specific materials, such as asphalt and concrete, require additional charges in the transportation process; e.g., costs for concrete mixer system in concrete mixer truck) as well as the transportation mode and are estimated based on historical data, cost accounting data, and benchmarks (data from other companies, including transport companies, and Government Policies, such as in Vietnam). Based on the initial value (VL_0) the future development of VL has to be forecast based on scenarios of energy/fuel prices, inflation, etc.
- L_m and L_d denote the distance between the suppliers and the construction area of material type m and its material-dependent substances that has to be overcome by transport, respectively (kilometer).

- $M_{m,TrC2,t}$ and $M_{d,TrC2,t}$ are the amount of material type m and its material-dependent substances that the contractor transports at time t, respectively.
- $TO2_t$ is an additional charge that might be payable to use bridges, roads or for custom duties between different countries in case contractors transport materials themselves; for the sake of simplification, it is included as one amount of money (not explicitly dependent on the amount or value of the material) here.

c. Storage cost

After transporting materials to the construction area, these materials are used immediately or stored in the warehouse. The cost of storing materials is the cost incurred by the process of placing and keeping materials in the storage and removing them from it. Many factors impact these warehouse costs, such as the volume of materials, occupied area, or storage time. Additionally, the way of providing the storage services influences the cost and the procedure of their calculation – again, a "make or buy" decision has to be made here. Therefore, it is distinguished between two cases: building and operating the warehouse by the contractor or hiring a warehouse. This is reflected by the following formulas for the total warehouse cost:

$$WC_m = WC1_m + WC2_m \tag{4.6}$$

Where:

- WC_m is the total cost of storing material type m and its material-dependent substances
- $WC1_m$ denotes the warehouse cost of material type m and its material-dependent substances when hiring the warehouse.
- $WC2_m$ is the warehouse cost of material type m and its material-dependent substances when the contractor builds and operates the warehouse.

- Case 1: contractors hire a warehouse to store their materials ($WC1_m$). The warehouse cost for material type m and its material-dependent substances is derived based on the warehouse's renting price. WC1 can be calculated by the following equation:

$$WC1_m = \sum_{t=0}^{T} \frac{[\,(UP_{WCR,t} \cdot (S_{m,t} \cdot T_{m,WC,t} + S_{d,t} \cdot T_{d,WC,t}) + AC_{WC1,t})\,]}{(1+r)^t} \tag{4.7}$$

Where:

- $UP_{WCR,t}$ is the warehouse's renting price per m^2 and time unit at time t.

- $T_{m,WC,t}$ and $T_{d,WC,t}$ are the duration (in time units) of storing material type m and its material-dependent substances at the warehouse according to the construction schedule, respectively.
- $S_{m,t}$ and $S_{d,t}$ are the area that is used to store material type m and its material-dependent substances at time t (in m^2), respectively. This value is measured based on the amount of material type m, its material-dependent substances and their size.
- $AC_{WC1,t}$ denotes additional costs for storing in the warehouse when hiring the warehouse at time t, for example, freezing costs.

- Case 2: contractors build a warehouse to store their materials ($WC2_m$). The warehouse cost for the material can be calculated as follows:

$$WC2_m = \sum_{t=0}^{T} \frac{[UP_{WCB} \cdot (S_{m,t} \cdot T_{m,WC,t} + S_{d,t} \cdot T_{d,WC,t}) + AC_{WC2,t})\ ]}{(1+r)^t} \quad 4.8$$

Where:

- UP_{WCB} is the total expected unit price per m^2 and year resulting from building the warehouse. This value is calculated with the equation below:

$$UP_{WCB} = \frac{I_{WC} \cdot \frac{(1+r)^{T'} \cdot r}{(1+r)^{T'} - 1}}{S_{WC}} \quad 4.9$$

Where:

- I_{WC} is the total initial cost of building the warehouse (it is assumed here, that a liquidation value or deconstruction cost can be neglected).
- T’ is the economic life of the warehouse.
- S_{WC} denotes the total area of the warehouse. It is estimated based on the total amount of all road construction materials and their material-dependent substances that need to be stored in the warehouse.

- $T_{m,WC,t}$ and $T_{d,WC,t}$ are the duration (here in years) of storing material type m and its material-dependent substances at the warehouse according to the construction schedule, respectively.
- $AC_{WC2,t}$ denotes additional costs for storing in the warehouse at time t in case of building the warehouse. The costs for labor, electricity and equipment are included in the additional

cost. This cost can be determined from previous projects. A detailed estimation can be conducted in the detailed design phase.

d. Construction cost

The total material-dependent cost of the road construction works (CoW_m) of material type m includes costs of labor, equipment, and wastes:

$$CoW_m = LB_m + EQ_m + WM_m \quad 4.10$$

Where:

- LB_m is the total material-dependent labor cost of material type m and its material-dependent substances in the construction phase.
- EQ_m is the total material-dependent cost of equipment used for material type m and its material-dependent substances in the construction phase.
- WM_m is the total material-dependent cost of wastes of material type m and its material-dependent substances in the construction phase.

The cost items' cost equations are presented below.

d1. Estimating the total material-dependent cost of labor

The total material-dependent cost of labor (LB) depends on the types of labor needed, working durations (labor hours) and wage rates. It is the present value of the yearly sum of labor costs generated by different kinds of workers (or labor) – such as bricklayer, mason, and carpenter – who altogether partake in finishing the given tasks (the cost of operators are not included here). This includes the cost of overtime work. Developing from Dagostino and Peterson (Dagostino and Peterson, 2011), the total material-dependent cost of labor in the construction phase can be calculated by applying the equation presented below:

$$LB_m = \sum_{t=0}^{T}\sum_{n=1}^{N}\left[(WH_{m,n,t} \cdot WG_{n,t})(1 + O_r)(1 + r)^{-t}\right] \quad 4.11$$

Where:

- n is the type of labor.
- N is the number of labor types.
- $WH_{m,n,t}$ is the total work duration of labor type n (in hours) during year t

- $WG_{n,t}$ denotes the wage rate of labor n at time t (including social insurance such as for health, unemployment, and pension)
- O_r is the average overtime percentage drawn from historical data (it is assumed that the wage rate is not increased for overtime work).

- The work duration (or labor hours) of labor type n ($WH_{m,n}$) in equation 4.11 can be calculated utilizing the equation below:

$$WH_{m,n} = \frac{M_{CI,m}}{P_n} \qquad 4.12$$

Where:

- $M_{CI,m}$ is the total amount of the construction item that is finished by using material m and its material-dependent substances.
- P_n denotes the labor productivity rate of labor type n. It is the number of the construction item produced per labor's working hour (Shehata and El-Gohary, 2011). This value can be gathered from published sources, previous projects, and internal norms, amongst others.

- The wage rate of type n (WG_n) in equation 4.11 is the amount of money being paid per hour for labors in type n. The wage rate is determined in a mutual contract between contractors and employees. It is influenced by the type of labor, the skills needed, working condition, location, average wage in the labor market, law provisions, and bargaining power, amongst others. The rate can be derived from historical data, by observing the average wage rate in the market, referring to existing contracts, and forecasting.

d2. Estimating the total material-dependent cost of equipment (EQ)

The total material-dependent cost of equipment (EQ_m) covers all the costs incurred from using the different types of construction equipment needed (such as trucks, cranes, and compactors). This cost can be calculated with the help of the formula below:

$$EQ_m = \sum_{t=0}^{T}\sum_{q=1}^{Q}\left[(EH_{m,q,t} \cdot ER_{q,t})(1 + r)^{-t}\right] \qquad 4.13$$

Where:

- q is the type of equipment.
- Q is the number of equipment types.

- $EH_{m,q,t}$ is the total duration of using equipment q during year t for processing material type m and its material-dependent substances under evaluation.
- $ER_{q,t}$ denotes the cost per hour of using equipment q at time t.

- The total work duration of equipment q ($EH_{m,q}$) in equation 4.13 is the total hours that a specific type of equipment is required to finish the given construction tasks. It is calculated by the following equation:

$$EH_{m,q} = \frac{M_{CI,m}}{EP_q} \qquad 4.14$$

Where:

- EP_q denotes the productivity rate of equipment q. This rate can be gathered from published sources, previous projects and internal norms, amongst others.

- The equipment cost per hour ($ER_{q,t}$) in equation 4.13 is the total cost of using equipment q at time t for one hour. In literature, this is defined as the sum of ownership cost and operating cost, including interest cost, depreciation, operation's wage, maintenance and repair costs, energy costs, and additional cost per time unit (Gransberg et al., 2006; Schaufelberger and Migliaccio, 2019). However, the interest cost should not be included since they are considered by discounting the cash flows. Depreciation should not be involved as well because it is no cash flow, and the loss of value of the equipment should be considered referring to the initial investment outlay and the liquidation value. As a result, the equipment cost per hour includes loss of value of equipment, equipment operator wages, maintenance and repair costs, energy costs, and additional cost. Accordingly, the total equipment cost per hour is calculated as follows:

$$ER_{q,t} = LV_q + Ow_{q,t} + MCE_{ERq,t} + F_{q,t} + AC_{q,t} \qquad 4.15$$

Where:

- LV_q represents the loss of value induced by using equipment q during the project.
- $OW_{q,t}$ is the equipment operators wage per hour of using equipment q at time t.
- $MCE_{ERq,t}$ is the maintenance and repairing cost per hour of using equipment q at time t.
- $F_{q,t}$ is the energy cost per hour of using equipment q at time t.
- $AC_{q,t}$ is the additional cost per hour of using equipment q at time t.

The cost elements of equation 4.15 can be calculated based on the following approaches.

- LV_q is the loss of value per time unit of using equipment q. It can be calculated by firstly determining the total loss of value TLV over the economic life of the equipment as the initial investment outlay minus the present value of liquidation value:

$$TLV_q \quad = \quad IIO_q - LiV_q \qquad 4.16$$

Where:

- IIO_q is the initial investment outlay of equipment q
- LiV_q is the present value of liquidation value of equipment q

Assuming a constant usage in each period of the life cycle, a yearly loss of value YLV can be calculated by transforming the TLV_q into an annuity (per year) with T" - the total time using of equipment q.

$$YLV_q \quad = \quad TLV_q \cdot \frac{(1+r)^{T"} \cdot r}{(1+r)^{T"}-1} \qquad 4.17$$

Finally, LV can be calculated by dividing YLV by the yearly usage time UT_q of equipment q (in hours).

$$LVq = \frac{YLV_q}{UT_q} \qquad 4.18$$

- Operation's wage (OW_t) per hour is the wage paid to operators per hour at time t. This rate can be estimated based on the type of equipment, level of skills needed, working condition, location, average wage at the labor market, law provisions, and bargaining power, amongst others.
- The maintenance and repairing cost per hour of using the equipment (MCE_{ER}) results from the activities intended to keep the equipment in good condition. The annual maintenance and repairing cost can be calculated based on a percentage of the annual cost of depreciation (Gransberg et al., 2006). Popescu et al., (Popescu et al., 2003) also suggested that the maintenance and repairing cost can be estimated based on actual costs from similar and previous projects or equipment manufacturer data. In this thesis, the maintenance and repairing cost are assumed to depend on the initial investment of the equipment. So, the hourly maintenance and repairing cost is determined by dividing annual costs by operation hours during a year. It is calculated by the following equation:

$$MCE_{ERq,t} = \frac{ILO \cdot q_t}{UT_q} \tag{4.19}$$

Where:

- $MCE_{ERq,t}$ is the hourly maintenance and repairing cost of equipment q at time t.
- q_t is the annual maintenance and repairing rate of equipment q at time t (in %), varying depending on the age of equipment and equipment types. This rate can be obtained from historical data and manufacturer's information.

- Energy cost (F_t) is the cost of using energy when operating equipment at time t. The energy cost per hour is calculated by multiplying the energy consumption rate per hour by the unit price of energy. It is calculated by the following equation:

$$F_t = FC_t \cdot UF_t \tag{4.20}$$

Where:

- F_t is the hourly energy cost at time t.
- FC_t is the energy consumption per hour at time t, which might be drawn from historical data or manufacturers' specifications.
- UF_t is the energy unit price at time t. The price can be drawn from data of energy suppliers and forecast based on energy price scenarios.

- The additional cost per hour of using equipment ($AC_{q,t}$) represents the hourly other costs, such as insurance, storage, and mobilization (moving equipment from one site to another), if these or other cost items are relevant. The additional cost can be estimated as a percentage of the equipment's initial cost and then converted to an hourly value.

d3. Estimating the total material-dependent cost of wastes (WM)

The total material-dependent cost of wastes (WM_m) incurred in the construction phase includes the cost of transporting waste materials (FCW_m) from the construction area to a waste material treatment plant and the cost of the waste material treatment (TrM_m). The cost of transporting waste can be calculated as shown below (here, for the sake of simplification, it is not distinguished between make or buy of transport):

$$FCW_m = \sum_{t=0}^{T}[((VL_{W,t} \cdot L_W) \cdot (M_{m,W,t} + M_{d,W,t}) + TO_t)(1 + r)^{-t}] \tag{4.21}$$

Where:

- $VL_{W,t}$ is the transport rate of one unit of waste for each kilometer at time t. This transport rate is defined based on the historical data or information from waste treatment plants.
- L_W is the (weighted average) distance from the construction site to the waste treatment plants.
- $M_{m,W,t}$ and $M_{d,W,t}$ are the volume of waste materials and waste material-dependent substances that need to be transported at the time t, respectively. That can be forecasted by designers.

It is assumed here that the material treatment is done by an external service provider. In that case and further assuming that all costs of construction waste treatment are included in a price per unit which is independent of the volume of road construction materials, the cost of the waste material treatment (TrM) can be calculated using the formula below:

$$TrM_m = \sum_{t=0}^{T}[\left((M_{m,W,t} \cdot UP_{m,TrM,t} + M_{d,W,t} \cdot UP_{d,TrM,t}\right)(1 + r)^{-t}] \quad 4.22$$

Where:

- $UP_{m,TrM,t}$ and $UP_{d,TrM,t}$ are the unit prices for waste treatment of the material type m and its material-dependent substances at time t, respectively, which can be derived from a price quotation presented by construction waste treatment plants, amongst others.

e. Cost of handover and operation

Maintenance tries to preserve road's functionality, while fixing/replacing aims to restore its functionality. Maintenance consists of those activities necessary to keep infrastructures in good working order, such as cleaning, inspection, or landscaping (Bharil, 2022). Fixing and replacing activities focus on restoring infrastructure to working order (for example, fixing and replacing broken road construction materials). Maintenance, fixing, and replacement activities incurred in the handover and operation phase impact the total cost of material alternatives. The maintenance cost covers labor cost, material cost, and equipment cost to keep structures in good condition, while replacement cost and fixing cost are caused by damaged structures (Krstić and Marenjak, 2012). On the one hand, these costs can be estimated based on a preliminary maintenance plan that identifies maintaining activities/tasks. It defines which works should be done and which materials, tools, equipment, and documentation will be required during the handover and operation phase. On the other hand, the amount of damaged structures during the handover and operation period neededs to be estimated. Therefore, a repairing rate and replacement rate for the materials can be estimated based on the material's characteristics, historical data, the experience of experts, and owners' demands. In fact, the rates can be fixed or increased every year. The total maintenance, fixing and replacement cost (MC) in the handover and operation phase is the sum of these cost items.

$$MC_m = \sum_t^T \left(MaC_{m,t} + FiC_{m,t} + ReP_{m,t}\right) \quad 4.23$$

Where:

- $MaC_{m,t}$ is the maintenance cost of material type m at time t. The maintenance cost at time t is evaluated by adding up the costs of materials, labor, and equipment at time t. The material cost can be calculated analogously to the cost of material acquisition (see equation 4.2). The labor cost can be assessed based on equation 4.11, while equation 4.13 can be used to estimate the equipment cost.
- $FiC_{m,t}$ and $ReP_{m,t}$ are the fixing cost and replacement cost of material type m at time t, respectively. This cost covers the repairing cost and replacement cost of the road construction materials. The costs are also assessed, including material cost, labor cost, and equipment cost at time t, which can be estimated by applying equations 4.2, 4.11, and 4.13, respectively.

When *the preliminary maintenance plan has not been created yet*, costs can be estimated based on rates of expectable periodical and unexpected non-periodical costs (Li and Guo, 2012). Both of these rates can be withdrawn from the practical experience of designers themselves or historical data (for example, the fixing cost of broken materials). According to this approach, MC is calculated by the following equation:

$$MC_m = k_{MC1} \cdot MAC_m + \sum_{t=0}^{T} [k_{MC2,t} \cdot MAC_m \cdot (1 + r)^{-t}] \quad 4.24$$

Where:

- MAC_m is the total material acquisition cost of material type m.
- k_{MC1} is the rate of unexpectable non-periodical costs in the handover and operation phase. This rate is defined by the experience of the designer and historical data.
- $k_{MC2,t}$ is the rate of expectable periodical cost in the handover and operation phase at time t. This rate is constant or increasing dependent on time.

f. Cost of close-out

In the close-out phase, when construction projects reach the end of their life cycle, the whole range of road construction materials used in the construction product becomes relevant waste products (Arslan et al., 2012). In general, the cost that project's owners are responsible for in the close-out phase includes costs for deconstruction, transportation costs, and waste treatment costs, and incomes from asset liquidation may be generated (Elkhayat et al., 2020; Lee et al., 2020b). So the overall cost in the close-out phase of the road construction project (CO) is expressed below:

$$CO_m = DE_m + TrCW_m + TrMW_m - ML_m \qquad 4.25$$

Where:

- DE_m is the cost of material type m and its material-dependent substances for deconstruction/demolition in the close-out phase.
- $TrCW_m$ denotes the transportation cost of the waste of material type m and its material-dependent substances in the close-out phase.
- $TrMW_m$ is the cost of waste treatment of material type m and its material-dependent substances.
- ML_m is the income from the liquidation of material type m and its material-dependent substances.

Assuming that all the expenses in the close-out phase are incurred at the end of the project (point in time T), all items mentioned above can be calculated as present value by discounting the corresponding cash flows from T to the beginning of the planning period (point in time point 0).

Fundamentally, the cost for deconstruction (DE) varies depending on how to deconstruct road construction materials. Here, again a make-or-buy-decision has to be made: The owners hire a construction demolition company or do it themselves. Additionally, the knowledge about the deconstruction activities and the corresponding labor and equipment requirements will influence the determination of the deconstruction cost. When a deconstruction company is hired, the material demolition cost is estimated based on a contract developed from the deconstruction area. When the owners decide to perform the deconstructing or dismantling task themselves and the deconstruction activities with their labor and equipment requirements are already known, designers can apply equations 4.11 and 4.13 to estimate the cost for deconstruction. On the contrary, if deconstruction activities cannot be identified with an acceptable effort, the cost of deconstruction (DE) can be estimated below based on price quotations of demolition companies in the market or historical data.

$$DE_m = UP_{m,D,T} \cdot M_{D,T} \cdot k_{DE} \cdot (1+r)^{-T} \qquad 4.26$$

Where:

- $UP_{D,T}$ is the expected unit price of the demolition of material type m at time T.
- $M_{D,T}$ is the amount of material to be deconstructed at time T.
- k_{DE} is an index representing the influence of factors such as the road condition or location.

The transportation cost of waste (TrCW) can be estimated analogously to equation 4.21.

There are numerous methods for handling the construction waste depending on the waste treatment plant, such as landfill or incineration. The decision about the usage of one of these methods is assumed to be made dependent on the specific case (Gökçekuş et al., 2022). For estimating the treatment cost (TrMW), equation 4.22 can be applied.

Some waste road construction materials can be sold in the close-out phase, such as steel. The corresponding income from road construction material liquidation (ML) can be calculated by multiplying the unit price of liquidated waste materials by their amount. The formula is expressed below:

$$ML = \left(UP_{ML,T} \cdot M_{ML,T}\right)(1 + r)^{-T} \qquad 4.27$$

Where:

- $UP_{ML,T}$ is the unit price of liquidated waste materials at time T.
- $M_{ML,T}$ denotes the amount of waste that can be liquidated at time T. The amount of liquidated materials is estimated based on their characteristics and historical data (for example, which materials can be sold in previous projects).

4.2.1.3. Life cycle cost model for scenario 2

Regarding scenario (2), the LCC result is also the sum of costs incurred in the construction phase, handover and operation phase, and close-out phase, analogously to scenario (1). However, the amount of road construction material is not known in this scenario. To estimate the cost in the early design phase, Ehrlenspiel et al. (Ehrlenspiel et al., 2007a) proposed using the quick calculation approach, including short, similarity, and equivalence-figure calculation. According to this reference, the preliminary cost can be estimated based on a similar product, the material cost method, the weight-based ratio of products, performance parameters, or regression analysis. Referring to *similar products* is a rapid means for estimating the cost of new products. This method compares the cost of new products to the cost of existing similar products to evaluate the cost of the new one. Therefore, firstly similar and comparable existing products have to be identified. Then, a measure expressing the relationship between the cost of the new and the existing has to be identified and applied to derive the cost of the new from that of the existing product. The *material cost method* uses the rate of existing total cost and material cost to estimate the new costs. It is conducted by evaluating the ratio of material cost between the material cost and manufacture cost. Then the new cost is calculated by multiplying the ratio and the new material cost. *The weight-based ratio* is calculated by dividing the cost of an existing product by its weight; then the ratio is multiplied by the weight of the given product. The *performance parameter method* assumes that the manufacturing cost depends on performance-related factors. Accordingly, the relationship between the manufacture cost and these parameters has to be specified and then applied to determine the cost. *The regression analysis* assesses the manufacturing cost by creating linear/non-linear regression equations.

Based on the approaches from Ehrlenspiel et al. (Ehrlenspiel et al., 2007a), the total cost of using the road construction material in the construction phase (CC) can be calculated according to the unit cost of similar projects.

$$\mathrm{CC} = \mathrm{UC_0} \cdot \mathrm{L} \cdot \frac{\mathrm{i_1}}{\mathrm{i_0}} \cdot \mathrm{k_L} \qquad 4.28$$

Where:

- UC_0 refers to unit costs per km at the time "0" of materials and material-dependent substances of completed similar roads. Similar roads should have the same or at least similar characteristics (e.g., they have the same road surface type, road width and materials) as the given road project. The data of similar roads can be generated from the historical data of the designers.
- L represents the total length of the road to be built.

- i_1 and i_0 are construction price indices at time "1" and time "0", respectively. It is a common practice worldwide and official state authorities declare construction price indices (Wang and Ashuri, 2017; Elfahham, 2019). For example, construction price indices are published by the Ministry of Construction in Vietnam specified for five construction work types, including civil, industrial, transport, waterworks, and technical infrastructural works. The index helps estimate the project costs and prepares the budget in the preliminary design phase (Cao and Ashuri, 2020; Nguyen and Nguyen, 2020). In a nutshell, this index helps convert construction prices between different points of time.
- k_L is the location index that is useful for transforming project costs from one specific geographical location to another concerning differences in productivity, material price, or wage (Choi et al., 2016). However, Bayram and Al-Jibouri (Bayram and Al-Jibouri, 2018) suggested that this index can be neglected if the country has the same material price and wages for all regions.

In a quite simplifying approach, the cost of the road construction material in the handover and operation phase (MC) in scenario (2) is assessed according to the total cost of using the material in the construction phase. It can be estimated based on the formula below:

$$MC = CC \cdot k_{MC} \quad 4.29$$

Where:

- k_{MC} is the total ratio of maintenance, fixing and repairing activities drawn from previous projects or assigned by owners (Wu and Clements-Croome, 2007).

Besides, the total cost of the road construction material in the handover and operation phase can also be calculated according to the unit cost of similar projects.

$$MC = UC_{MC} \cdot L \cdot \frac{i_1}{i_0} \cdot k_L \quad 4.30$$

Where:

- UC_{MC} refers to unit costs per km at the time "0" of materials and material-dependent substances of completed similar roads in the handover and operation phase.

Similar to the cost of the handover and operation phase, the road construction material cost in the close-out phase (CO) in scenario (2) can be estimated based on the total cost of using the material in the construction phase. It is calculated based on the following equation:

$$\mathrm{CO} = \mathrm{CC} \cdot k_{\mathrm{CO}} \cdot (1 + r)^{-T} \qquad 4.31$$

Where:

- k_{CO} is the ratio of disposal material costs drawn from previous projects or estimated by owners.

Moreover, the total cost of the road construction material in the close-out phase can also be calculated according to the unit cost of similar projects.

$$\mathrm{CO} = \mathrm{UC}_{CO} \cdot \mathrm{L} \cdot \frac{i_1}{i_0} \cdot k_L \qquad 4.32$$

Where:

- UC_{CO} refers to unit costs per km at the time “0” of materials and material-dependent substances of completed similar roads in the close-out phase.

In general, the equations presented in scenario (2) are much more straightforward than those in scenario (1). However, many cost items are not specifically forecasted in scenario (2) due to information deficiency. This makes the results calculated in scenario (2) less accurate than the results in scenario (1).

All proposed LCC models can be used for road construction material selection in the preliminary design phase. Potential scenarios are considered, and the total cost covers direct costs incurred during the construction, handover and operation, and the close-out phases. The indirect costs, such as administration costs, are not included because these costs are not strongly impacted by road construction material selection.

According to the proposed LCC equations, the relevant cost items can be estimated to evaluate the total cost of road construction materials in the preliminary design phase. All future costs are converted to present values to make the comparison between alternatives straightforward. The deficiency of a detailed LCC for road construction material comparison in the preliminary design phase, as pointed out in section 3.3.5, is solved by the proposed models. All stages of the project life cycle are broken down, and two scenarios are assumed according to the available information.

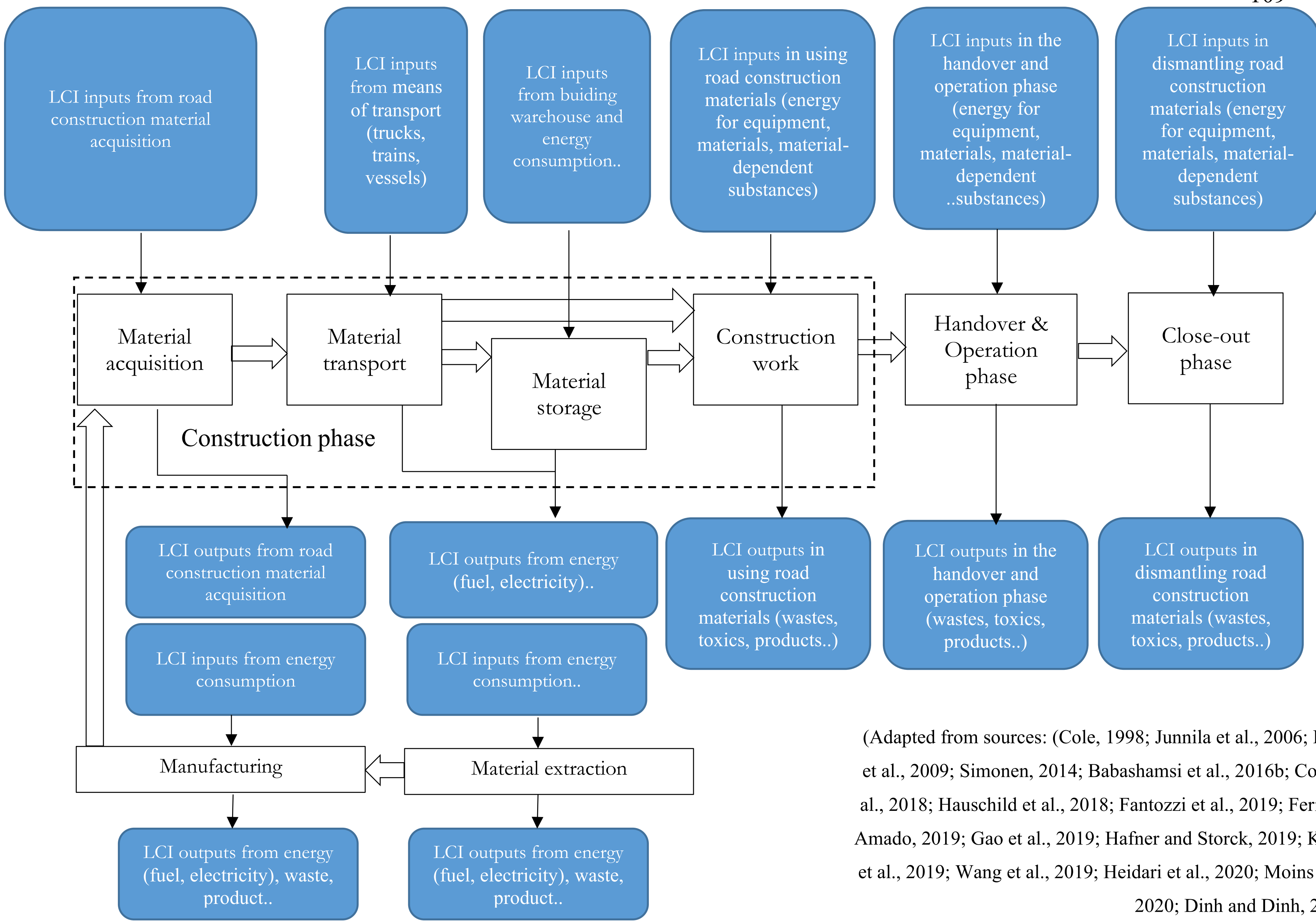
Besides, the models take into consideration potential cost items, specifically material-dependent activities, including material-dependent costs of laborers, equipment, and auxiliary items, that are not considered in the previous studies.

The LCC results are used together with the life cycle assessment and the social life cycle assessment results to assess the sustainability performance. So, the proposed LCA and Social LCA will be introduced in sections 4.2.2 and 4.2.3.

4.2.2. Environmental assessment

The life cycle assessment analysis is a holistic way of assessing the environmental burdens of objects, e. g. materials, along the life cycle (Meex et al., 2018; Nizam et al., 2018; Seyis, 2020). It offers an insight into environmental performance in the construction industry (Simonen, 2014) and serves as decision support in selecting construction materials (Simonen, 2014; Hauschild et al., 2018). This section is intended to develop a methodological approach for assessing the environmental burden of road construction materials in the early design phase and answering research question 3c. As explained in section 4.1, the proposed model considers two distinguished scenarios: (1) the amount of material is estimated and (2) the amount of material is not estimated.

In the LCC's chart, the activities that cause costs are covered, such as using labor and equipment (see section 4.2.1). For LCA, the same life cycle materials – extraction and manufacturing, construction, handover and operation, and close-out phase – and basically the same activities are relevant. In LCA, the activities´ consumption of raw materials, resources, energy, and generation of waste and emissions are analyzed from an environmental perspective. In order to ensure consistency in the sustainability assessment of road construction materials, the system boundary should be identical or at least consistent. Analogously to Figure 4.4 and Figure 4.5, the activities and their inputs and outputs being relevant for the environmental assessment can be displayed in a flow diagram (see Figure 4.6). The flowchart considers the material-dependent activities such as using equipment, labor and material-dependent substances. Firstly, the raw materials are extracted from sources, such as quarries and mineral mines with the help of equipment and consumed energy (fuel, electricity). Then, in the factory, the raw materials are converted to road construction materials by shaping, forming, and other methods. The LCI inputs of this process are energy (fuel, electricity) and auxiliary substances, while toxic emissions and wastes are LCI outputs. Then, the completed road construction materials are ordered by contractors and they are transported from suppliers to the construction site by means of transport (e.g., trucks, trains, vessels). Accordingly, LCI input includes energy consumption (e.g., fuel, electricity), while toxic emissions and wastes are LCI outputs. When the materials reach the construction area, they are used immediately or stored in the warehouse. Essentially, storing in the warehouse causes electricity consumption (an LCI input) and toxins (LCI output). In the construction phase, construction activities consume materials, material-dependent substances, and energy for equipment (LCI inputs) as well as generate emissions and waste (LCI outputs). In the handover and operation phase, the damaged material has to be replaced or repaired, that impacts the environment. The activities consume materials, material-dependent substances and energy for equipment as LCI inputs and emit toxins and waste to the environment as LCI outputs. In the last phase, the materials are dismantled and moved to construction waste treatment plants. The activities in this phase also require LCI inputs (e.g., energy for equipment, materials etc.) and result in LCI outputs (e.g., wastes, toxins, recycled materials).



(Adapted from sources: (Cole, 1998; Junnila et al., 2006; Horne et al., 2009; Simonen, 2014; Babashamsi et al., 2016b; Coleri et al., 2018; Hauschild et al., 2018; Fantozzi et al., 2019; Feria and Amado, 2019; Gao et al., 2019; Hafner and Storck, 2019; Kumar et al., 2019; Wang et al., 2019; Heidari et al., 2020; Moins et al., 2020; Dinh and Dinh, 2021))

Figure 4.6. The flow diagram of road construction materials for the LCA

The ecological assessment procedure model is developed from the LCA analysis standardized in the ISO norm (see section 3.4). The four main steps involved in carrying out the LCA analysis comprise (1) Goal and scope definition; (2) Life cycle inventory analysis; (3) Life cycle impact assessment; (4) Interpretation.

Step 1: Goal and scope definition

In this step, the designers define the goals of the study and its scope, including functions, functional units, reference flows, manufacturing system, system boundary as well as basic methodological issues.

Goal definition: In the first step, goals of the study, including the reasons for carrying out the study, the intended application of the results, and the stakeholders (such as owners, contractors, local community, suppliers, etc.), have to be defined and justified (ISO, 2006a). These contents should always be defined unambiguously and transparently. In the case of road construction materials, it might be intended:

- to offer an insight into the environmental performance of these materials by systematically determining the environmental impacts caused by them and the activities related to them,
- to compare road construction material alternatives and to identify the most environmentally-friendly alternatives based on the LCA results; this serves as decision support in selecting road construction materials.
- to contribute to an LCSA analysis by providing the LCA results for the overall proposed model outlined in sections 4.1 and 4.2.4.
- to deal with the problems concerning the lack of information in the preliminary design phase.

In a concrete case of application, the owners have to select and concretize such targets in order to generate a basis for the following steps and activities of environmental assessment.

Scope definition: The International Organization for Standardization emphasized the main aspects that should be considered and clearly described by defining the scope of the study (ISO, 2006b). The scope definition is conducted by defining functions, the functional unit, reference flows, and system boundary, which should be used in common for evaluating the overall sustainability performance. Additionally, basic methodological issues should be clarified. These aspects are concretized for road construction materials as follows.

- *Definition of functions, functional unit, reference flows and manufacturing system:* The functions of the products, processes, and services being studied are specified, such as performance characteristics (EC et al., 2010). In the field of material selection for meeting functions of a road (for example, connecting between "A" and "B"), the functional unit should take the form of "Road infrastructure between "A" and "B" over an analysis time horizon of a defined number of years." (Brattebø et al., 2013). After choosing the functional unit, the reference flow shall be defined. According to ISO, reference flow is a measure of the outputs of processes in a given product system required to fulfil the function expressed by the functional unit (ISO, 2006b). For example, the reference flow is illustrated as "25 km of a road between A and B from 2022 to 2072". The manufacturing system covers the material-dependent activities in its life cycle, such as material acquisition, material usage, and material repairing activities.
- By defining the *system boundary,* based on the goal of the study, it is decided which unit processes are included (ISO, 2006b). In this thesis, it is assumed that all relevant material-dependent activities (e.g., using equipment) in the material extraction phase, manufacturing phase, construction phase, handover and operation phase, and close-out phase should be included, which are relevant for environmental sustainability. This complies with the "from cradle to grave" approach. An illustrative diagram (see Figure 4.6) is used to depict the unit processes and their inter-relationships in order to provide an overview of which parts are included or excluded. The decision, which activities are seen as relevant and therefore included, can be made based on the dependence on material selection, the expected magnitude of the inputs and outputs and their impact, and the availability of data. Here, especially traffic impacts during the handover and operation phases are ignored because they are assumed to be the same for all material options.
- Furthermore, the basic LCI methodology, impact categories, category indicators and characterization factors should be determined (ISO, 2006b; Hauschild et al., 2018). Common impact categories that can be applied for road construction material selection are illustrated in Table 4.2 and Table 4.3. The impact categories, category indicators, and characterization

factors shown there were drawn from similar studies concerning road construction projects to ensure the adaption into this research, such as (Balaguera et al., 2018; Oladazimi et al., 2020; Desai and Bheemrao, 2022).

Step 2: Inventory analysis (Life cycle inventory analysis)

The inventory analysis phase (or life cycle inventory analysis – LCI) deals with the *collection, categorization, and calculation* (Cabeza et al., 2014). In this step, the LCI inputs and outputs are determined in order to create an adequate database. LCI sub-steps are presented below.

- *Completing and concretizing the flow diagram*: The structure of all unit processes – understood as a set of interrelated or interacting activities that transform inputs into outputs – and their relationships are illustrated in flow diagrams so that the system is modelled coherently and easily understandable. The concrete achievement of this chart depends upon its complexity level. In the flow chart, the boxes denote unit processes of road construction material alternatives, and the arrows represent their flows or connections.
- *Collecting data*: After defining the unit processes, qualitative and quantitative data of road construction material alternatives is collected from various sources to estimate the inputs and outputs of unit processes. The sources have to be documented and referenced in the final report. Several authors recommended that for foreground processes, case-specific primary data are utilized while general data are applied for background processes (Guinée, 2002; EC et al., 2010; Owsianiak et al., 2018). For the case of material selection for road construction, data for foreground processes might be drawn from the contractor's historical data, while data for the background processes might be taken from law documents, publications, and accepted construction databases. LCI data of background processes concerning road construction materials can be obtained from databases, such as Ecoinvent or GaBi, and software applications, such as GaBi, SimaPro, Umberto, and OpenLCA. They enable data acquisition for a couple of products and processes, including road construction materials and their material-dependent substances (Pai and Elzarka, 2021). Specifically for road construction materials, Pai et al. (Pai and Elzarka, 2021) pointed to several applications that help to collect environmental data to support the LCI step, such as Tally, One Click LCA, and Athena Impact Estimator. The Tally application is integrated into Revit software to help assess the environmental burdens of materials across the project's life cycle. One Click LCA includes

construction material data from the U.S. and Canada (Arashpour, 2022). Athena Impact Estimator was built based on the Athena Sustainable Materials Institute's sources (Desai and Bheemrao, 2022), and it can model over 1200 structural and envelope assembly combinations.

- Next, the gathered data *are classified* into the following categories: data concerning (1) energy inputs, raw material inputs; (2) products, co-products and waste; (3) releases to air, water and soil; (4) other environmental aspects (e.g., noise) (ISO, 2006b). The data are then validated to demonstrate that it comes from a reliable database and can be related to the unit processes, functional unit and reference flow.
- *Relating data to unit processes, functional unit and reference flow*: The quantitative inputs and outputs are calculated for each unit process. Next, all of them are related to the reference flow and thereby to the functional unit as well (ISO, 2006b). For example, Figure 4.7 illustrates how to relate the road construction material alternative to the reference flow. The functional unit is the whole road, and the reference flow is 25 km for the whole road. At first, process 1 was scaled to match the reference flow (the whole road – label "D"). Accordingly, 25,000 m of "Dicht type A1"– label "C" - (25 km * 1,000m/km) was required. Second, to provide 25,000m of C, process 2 requires 4,000 m^3 of concrete - label "B" (25,000m * 0.16m^3/m). Third, process 3 uses 2,000m^3 of sand - label "A" (0.5 m^3 per 1 m^3 of concrete * 4,000m^3) to produce 4,000m^3 of concrete. Analogously, other inputs and outputs can be related to reference flows.

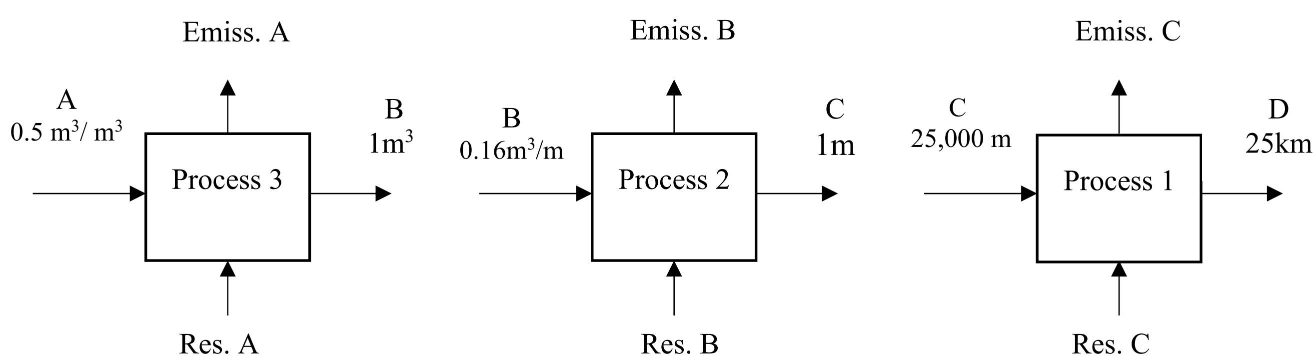


Figure 4.7. An illustration of unit processes related to reference flows

- *Calculating the LCI results*: The LCI results of road construction materials are calculated by summing up the inputs and outputs that have been determined for all unit processes in relation to the reference flow and functional unit (Guinée, 2002; EC et al., 2010). For example, the release of 143 g/ton-km of CO_2 (emission factor) caused by a material transportation vehicle releasing is multiplied by the length of the road (60kms), resulting in 8,580 g of CO_2 emitted per 1 ton of the material.

As pointed out in section 4.1, due to the considered application of the method in the early design phase, two scenarios are distinguished in this thesis: (1) the amount of material has been estimated and (2) the amount of material has not been estimated.

For scenario 1, the number of material-dependent substances, equipment, and labor can be evaluated based on the estimated amount of materials. Accordingly, the amount of waste, emissions to air/soil/water, energy consumption other environmental aspects can be calculated as LCI inputs and outputs in each phase during the material life cycles ($LCI1_{m,c,s}$). The total LCI results of LCI inputs/outputs type c are calculated by the following equation.

$$LCI1_{m,c} = \sum_s LCI1_{m,c,s} \qquad 4.33$$

Where:

- $LCI1_{m,c}$ denotes results of LCI inputs/outputs type c of material type m. The type of LCI inputs/outputs, such as carbon dioxide and nitrogen oxides, were defined in step 2.
- $LCI1_{m,c,s}$ represents the LCI inputs/outputs type c of material type m in phase s.

In *scenario 2,* the amount of materials is not estimated in the early design phase. It means that the ecological assessment is carried out without knowing the quantity of the input and output. Consequently, it is not possible to determine any equations for calculating the LCI inputs and outputs, such as shown for scenario 1. To solve this problem, data from similar road construction projects – projects that are nearby the actual one – can be applied to estimate the LCI inputs and outputs. The owners have to decide which projects are adequate as a reference. Similar roads should have the same scale (e.g., expected budget) and characteristics (e.g., structures, construction method) as the given road project so that they can reflect the environmental impacts of the considered project. Preliminary geotechnical and topographic surveys also need to be carried out to ensure the similarity of soil and environmental conditions. As a result, the LCI inputs and outputs can be estimated based on the data from the similar one by using the equation below.

$$LCI2_{m,c} = \frac{LCI2_{1,m,c}}{L_1} \cdot L \cdot k \quad 4.34$$

Where:

- $LCI2_{1,m,c}$ is the total LCI inputs/outputs type c of material type m in a similar project.
- L_1 and L are the lengths of the similar project and the given one, respectively.
- k is the LCI converting factor with which the LCI inputs/outputs are converted from another project to the given project. This factor should reflect the influence of different locations, weather, or construction conditions. It can be estimated by the owner or by judgments of a group of experts with specialized education, knowledge, skill, experience, or training in the construction industry.

In general, as a result of the life cycle inventory phase, the total LCI inputs and outputs are calculated. The input and output quantity is the sum of *specific* inputs or outputs (such as waste) during the material life cycle, including the material extraction phase, manufacturing phase, construction phase, handover and operation phase, and close-out phase. To illustrate the LCI result, Table 4.1 depicts the aggregated LCI results from using hot mix asphalt in a road construction project. They are calculated by summing up the LCI input and output data during the material life cycle.

Table 4.1. An example of total LCI results of using hot mix asphalt in a road

Name	Unit	LCI inputs and outputs
Inputs		
Energy consumption		
Fuel consumption (oil)	kg	6,338.51
Electricity consumption	kWh	2,591
………		
Outputs		
Emission to air		
CO_2 emission	tons	3,390
……….		

(Source: (Vega et al., 2022))

Step 3: Impact assessment (Life cycle impact assessment phase)

Since the procedure in step 3 – the assessment of the environmental burden of road construction materials after calculating LCI results – largely depends on the method used, next such a method shall be proposed. Popular methods for assessing the environmental burden are Carbon footprint, CML, Eco-Indicator 99, and ReCiPe.

The "Carbon footprint" method was proposed by Wackernagel and Rees (Wackernagel and Rees, 1996). According to Pandey et al., (Pandey et al., 2011), the carbon footprint can be determined as the quantity of Greenhouse Gas expressed in terms of CO_2-e, emitted into the atmosphere by a process, organization, or product. In the construction industry, carbon footprint can refer to the total greenhouse gas emissions during the material extraction, manufacturing, and construction project life cycle, including construction, handover & operation, and close-out phases.

The CML2001 method, developed by the Centre for Environmental Sciences of Leiden University, assesses ten midpoint impact categories, including global warming, human toxicity, abiotic depletion, ecotoxicity, terrestrial ecotoxicity, eutrophication, marine aquatic ecotoxicity, and photochemical oxidation (Ligthart et al., 2010). Nevertheless, CML2001 does not support the weighted aggregation of the results into one score (Vinodh et al., 2012).

The first version of Eco-Indicator 99 was presented in 1995. It is an endpoint approach that assesses the environmental damage, including human health, ecosystem quality, and resources (Goedkoop et al., 2000). By using this method, a single environmental score can be estimated (Solé et al., 2018). However, it mostly relies on a model that estimates the average damage in Europe. (Goedkoop et al., 2000). Besides, the designers must have comprehensive environmental-related knowledge to define the environmental endpoint damage (Pushkar, 2014).

ReCiPe method represents a combination of Eco-Indicator 99 and CML method (Goedkoop et al., 2009; Huijbregts et al., 2016). It analyses a wide range of environmental impacts, including 17 midpoint and three endpoint categories (Meynerts et al., 2017). The ReCiPe method contains a global database (Huijbregts et al., 2016).

Because the ReCiPe method allows the assessment of the environmental impacts on a global scale (Huijbregts et al., 2016), it is applicable in developing countries that are unable to build a regional database. The method includes a wide range of data and impact categories being (possibly) relevant for the evaluation of road construction materials' environmental burdens (Pai and Elzarka, 2021). Besides, the impact category results can be integrated into a single score which can be an input of an LCSA model intended to assess the sustainability performance of road construction materials. Hence, the use of the ReCiPe method is suggested here.

According to Rashedi and Khanam (Rashedi and Khanam, 2020), the ReCiPe method is conducted in the LCIA in conformance with the LCIA procedure in general, including the following steps: (1) selection, (2) classification, (3) characterization, (4) normalization, (5) weighting, and (6) calculation of a single score. The ISO standards also define selection, classification, and characterization as mandatory, while other steps are optional (ISO, 2006a; ISO, 2006b). The integrated assessment is proposed below.

In the *selection* step (1), designers select the impact categories according to the LCI results. Impact categories are classes representing the environmental issues of concern. In general, the impact categories and category indicators must be chosen in a way that allows assigning the actual LCI results to them. In detail, the impact categories are pre-defined in step 1 (Goal and scope definition) based on the study's goal, while the LCI inputs and outputs are collected and estimated in step 2 (inventory analysis). In step 3 (impact assessment), LCI results are assigned to pre-defined impact categories. However, some impact categories may not cover any LCI inputs and outputs, while some LCI results cannot be classified into any categories. So, the impact categories, category indicators, and characterization models are re-determined. Several common category indicators and common units characterizing the impact categories are illustrated in Table 4.2 and Table 4.3.

These generally applicable indicators can also be applied to materials used for road construction projects. In Table 4.2, seventeen midpoint impact categories are illustrated with respect to materials for road construction projects. These categories are proposed according to (Goedkoop et al., 2009; Huijbregts et al., 2016; Huijbregts et al., 2017; Rashedi and Khanam, 2020). The midpoint categories, their characterization factors, and their units are regulated by the ReCiPe method. Accordingly, the impacts by road construction materials are pointed out for each impact category. The impacts are assumed to be caused by material-dependent activities during the project life cycle. For these impacts, examples for corresponding LCI inputs and outputs are listed, such as emissions from material transportation vehicles, land occupation for building a warehouse, and electricity consumption for construction equipment. For example, the midpoint impact category

"Terrestrial acidification" is assessed by "Terrestrial acidification potential" caused by "Changes in soil chemical properties and in acidity in the soil resulting from material-dependent activities". Emissions from material transportation vehicles (e.g., SO_2, NH_x) are typical LCI inputs and outputs for this impact category.

Table 4.2. The midpoint impact categories of the ReCiPe method

ID	Midpoint impact categories	Characterization factors	Unit	Impacts by road construction materials	LCI inputs and outputs (Examples)
1	Terrestrial acidification	Terrestrial acidification potential	kg SO_2 eq.	Soil chemical properties and acidity can be changed because of material-dependent activities.	Emissions from material transportation vehicles
2	Landuse	Land transformation/ occupation	annual crop eq.	It is characterized by species loss due to land occupation resulting from material-dependent activities. Change of land cover directly impacts the original habitat and species.	Land occupation for building a warehouse
3	Climate change	Global warming potential	kg CO_2 eq.	It is characterized by the increase of Greenhouse Gas emission that impacts the global temperature resulting from material-dependent activities.	Emissions from material transportation vehicles
4	Fossil resource scarcity	Fossil depletion potential	kg oil-eq.	It is characterized by fossil depletion potential resulting from material-dependent activities.	Electricity consumption for construction equipment.
5	Water depletion	Water depletion potential	m^3	It is characterized by the potential depletion of water because of material-dependent activities	Mortal mix
6	Photochemical oxidant formation: Human damage	Photochemical oxidant formation potential	kg NO_x eq	It is characterized by the impact of ozone on human health, such as damaging the lungs. The	Emissions from material transportation vehicles

				material-dependent activities could lead to emitting NO_x into the atmosphere.	
7	Photochemical oxidant formation: terrestrial ecosystems	Ecosystem ozone formation Potential	kg NO_x eq	It is characterized by the impact of ozone on the ecosystem because it can reduce plant growth, seed production, and plant species. Material-dependent activities could lead to emitting NO_x into the atmosphere.	Emissions from material transportation vehicles
8	Fine particulate matter formation	Particulate matter formation potential	kg PM2.5-eq	It is characterized by the amount of PM2.5-eq resulting from material-dependent activities. The PM2.5-eq damages human health because it reaches the upper part of the airways and lungs when inhaled.	Emissions from material transportation vehicles
9	Ozone depletion	Ozone depletion potential	kg CFC-11 eq/kg	It is characterized by the reduction in atmospheric ozone concentration due to material-dependent activities. The decrease leads to the resultant increase in the UVB radiation from the sun.	Electricity consumption for construction equipment.
10	Mineral resource depletion	Surplus ore potential	kg CU-eq	It is characterized by the excess of resource consumption over its reproduction due to material-dependent activities.	Electricity consumption for construction equipment.
11	Freshwater eutrophication	Freshwater eutrophication potential	kg P-eq to freshwater	Material-dependent activities cause the transfer of phosphorus from soil to the freshwater body.	Fossil fuel combustion for material manufacture

				This eutrophication leads to the relative loss of species.	
12	Human toxicity: cancer	Human toxicity performance potential	kg 1,4-DCB-eq to urban air	It is characterized by the potential of carcinogenic substances resulting from material-dependent activities.	Fossil fuel combustion for material manufacture
13	Human toxicity: non-cancer	Human toxicity performance potential	kg 1,4-DCB-eq to urban air	It is characterized by the potential of non-carcinogenic substances resulting from material-dependent activities through inhalation of air, food/water ingestion, and penetration through the skin.	Fossil fuel combustion for material manufacture
14	Terrestrial ecotoxicity	Terrestrial toxicity performance potential	kg 1,4-DCB-eq to industrial soil	It is characterized by chemical emissions for terrestrial ecotoxicity resulting from material-dependent activities.	Soil in the construction area.
15	Freshwater ecotoxicity	Freshwater toxicity performance potential	kg 1,4-DCB-eq to freshwater	It is characterized by chemical emissions for freshwater ecotoxicity resulting from material-dependent activities.	Rivers, streams, and groundwater in the construction area.
16	Marine ecotoxicity	Marine toxicity performance potential	kg 1,4-DCB-eq to marine water	It is characterized by chemical emissions for marine ecotoxicity resulting from material-dependent activities.	Marine situation in the construction area.
17	Ionizing radiation	Ionizing radiation	kBq Co-60-eq to air	It is characterized by the emission of reference substance cobalt-60 to air that assesses the	Material waste combustion

				magnitude of ionizing radiation. The emission comes from material-dependent activities.	

(Sources: (Goedkoop et al., 2009; Huijbregts et al., 2016; Huijbregts et al., 2017; Rashedi and Khanam, 2020))

For the *classification* - step (2), according to Guinée (Guinée, 2002), the environmental burdens from using road construction materials estimated in the inventory analysis are assigned to the various selected impact categories. It means that the LCI results estimated in step 2 (Inventory analysis) will be sorted and assigned to the various impact categories determined in the selection step above.

The *characterization - step* (3) - quantifies how much impact a type of road construction material has in each category. For this step, according to (Goedkoop et al., 2009; Huijbregts et al., 2017), the environmental impact indicator type i of road construction material type m obtained in the midpoint level ($I_{m,i}$) can be estimated as follow:

$$I_{m,i} = \sum_{c}^{ni} CF_{m,i} \cdot LCI_{m,c} \qquad 4.35$$

Where:

- $CF_{m,i}$ is the characterization factor of midpoint impact category type i of using road construction material type m. The characterization factor can be drawn from (Goedkoop et al., 2009; Huijbregts et al., 2017; RIVM, 2020).
- $LCI_{m,c}$ is the total LCI inputs and outputs type c of material type m.
- ni denotes the total number of LCI inputs and outputs that are assigned to midpoint impact category type i. Some kinds of LCI inputs and outputs can be classified into one impact category.

Likewise, the environmental impact indicators type e of road construction materials obtained in the endpoint level ($I_{m,e}$) can be estimated as follow (Goedkoop et al., 2009; Huijbregts et al., 2017):

$$I_{m,e} = \sum_{c}^{ne} CF_{m,e} \cdot LCI_{m,c} \qquad 4.36$$

Where:

- $CF_{m,e}$ is the characterization factor of the endpoint impact category type e of using road construction material type m and material-dependent activities (such as using equipment). The characterization factor can be drawn from (Goedkoop et al., 2009; Huijbregts et al., 2017; RIVM, 2020).

- ne denotes the total number of LCI inputs and outputs that are assigned to endpoint impact category type e. Some kinds of LCI inputs and outputs can be classified into one endpoint impact category.

In general, the midpoint and the endpoint indicators can be calculated independently of each other. Additionally, the midpoint impact category indicators related to a specific endpoint or damage category indicator can be aggregated to achieve the endpoint indicator result. The relationship between midpoint indicators and endpoint indicators can be illustrated based on the following equation (Andersson and Listén, 2014):

$$I_{m,e} = \sum_{i} CF_{m,em} \cdot I_{m,i} \tag{4.37}$$

Where:

- $CF_{m,em}$ is the characterization factor of material type m between the midpoint impact category type i and the endpoint impact category type e coming from the road construction material and material-dependent activities. The characterization factor can be drawn from (Goedkoop et al., 2009; Huijbregts et al., 2017; RIVM, 2020).

The decision about using either midpoint or endpoint indicators (or both) has to be made by the owner or experts according to the study's goal. According to (Dong and Ng, 2014), both indicators can be applied to assess the environmental performance, but the endpoint may result in greater uncertainties, while the midpoint is more reliable. Besides, Ismaeel (Ismaeel, 2018) pointed out that the midpoint indicator assessment is more related to elementary flows and takes into account all aspects along the cause-effect chain. On the contrary, the endpoint indicators focus on the damage to the environment, including the damage to human health, ecosystems, and resource availability.

Table 4.3 illustrates the endpoint impact categories suggested for the ReCiPe method (Goedkoop et al., 2009; Huijbregts et al., 2016; Huijbregts et al., 2017; Rashedi and Khanam, 2020). The table depicts the name of the endpoint impact categories, units, and their meanings. Besides, the potential impacts of using road construction materials that may affect the environmental burden are presented together with related midpoint impact categories from Table 4.2. For instance, the endpoint impact category "Damage to Human health" is measured by "Years of life lost and disabled" to evaluate the magnitude of respiratory disease, cancer, and others. Table 4.3 also shows typical impacts of road construction materials on the category indicators. The outcomes of the category indicators can be determined by aggregating the results of corresponding midpoint impact categories, such as climate change, water depletion, and photochemical oxidant formation.

Table 4.3. The endpoint impact categories of the ReCiPe method

ID	Endpoint impact categories	Meanings	Unit	Potential impacts by road construction materials	Several typical related midpoint impact categories
1	Damage to Human health	Years of life lost and disabled	year	Increase in respiratory disease Increase in various types of cancer Increase in other diseases/causes Increase in malnutrition	Climate change; Water depletion; Photochemical oxidant formation: Human health; Fine particulate matter formation; Ozone depletion; Human toxicity: cancer; Human toxicity: non-cancer; Ionizing radiation.
2	Damage to ecosystems	Time-integrated species loss	Species. yr	Damage to freshwater species. Damage to terrestrial species. Damage to marine species	Terrestrial acidification; Landuse; Climate change; Water depletion; Photochemical oxidant formation: Terrestrial ecosystems Freshwater eutrophication; Terrestrial ecotoxicity; Freshwater ecotoxicity; Marine ecotoxicity
3	Damage to resources availability	Surplus cost	Dollar	Increased extraction costs Oils/ gas/coal energy cost	Fossil resource scarcity; Mineral resource depletion

(Sources: (Goedkoop et al., 2009; Huijbregts et al., 2016; Huijbregts et al., 2017; Rashedi and Khanam, 2020))

The *normalization* step (4) is conducted to estimate the category indicator results referring to a reference value, which may be chosen freely (ISO, 2006b). This step helps to eliminate the different units between impact category indicators, normalize the results to a reference system, and facilitate the comparison. According to the ReCiPe method, the normalized indicator results of road construction materials obtained in the midpoint level ($I_{m,nor,i}$) can be estimated as follow (Goedkoop et al., 2009):

$$I_{m,nor,i} = \frac{I_{m,i}}{N_i} \quad 4.38$$

Where:

- $I_{m,nor,i}$ denotes the normalized indicator result of midpoint impact category type i of material type m.
- N_i is the *normalization factor* for midpoint impact category type i. A normalization factor is a reference value that is drawn from a historical database to eliminate the different units between impact categories. For example, the normalization factor can be the average indicator result of midpoint impact category type i derived from previous projects.

Likewise, the normalized indicator results of road construction materials obtained at the endpoint level ($I_{m,nor,e}$) can be estimated as follow (Goedkoop et al., 2009):

$$I_{m,nor,e} = \frac{I_{m,e}}{N_e} \quad 4.39$$

Where:

- $I_{m,nor,e}$ denotes the normalized indicator result of endpoint impact category type e of material type m.
- N_e is the *normalization factor* for endpoint impact category type e.

Next, the *weightings of impact categories* (5) are determined for the impact categories. The weightings represent the different preferences of impact categories for environmental burden. The step helps convert the indicator results or normalized results by using numerical factors (weightings). The weightings can be generated by the designers – possibly supported by the use of MCDM methods (see section 4.2.4). Different designers may have different preferences;

consequently, it is possible that weighting outcomes from different parties will be distinct based on the same indicator.

After determining the weightings of impact categories, a single score (LCA result) can be achieved by summing up the (normalized) indicator results of road construction materials. This score is a measure of the total environmental performance of road construction materials. Again, this single score can be determined at the midpoint and/or endpoint level.

For calculating the single score at the midpoint level, the following equation can be used (Huijbregts et al., 2017):

$$LCA_{m,mid} = \sum I_{m,nor,i} \cdot W_i \quad 4.40$$

Where:

- $LCA_{m,mid}$ is the environmental performance result of road construction material type m obtained at the midpoint level (points).
- W_i is the weighting for midpoint impact category type i.

Analogously, the environmental performance result of road construction materials obtained at the endpoint level can be estimated by the following equation (Andersson and Listén, 2014):

$$LCA_{m,end} = \sum I_{m,nor,e} \cdot W_e \quad 4.41$$

Where:

- $LCA_{m,end}$ is the environmental performance result of road construction material type m obtained at the endpoint level (points).
- W_e is the weighting for endpoint impact category type e

Step 4: Interpretation (Interpretation phase)

The scores calculated in the previous step represent the environmental performance of alternatives. They can be used to compare alternative materials to identify the most environmental-efficient alternative and to support material selection. The results of the LCIA phase can also be integrated into the LCSA to assess sustainability performance. Therefore, the LCA results can be normalized to eliminate the differences between the units of LCC, LCA, and Social LCA results.

Decision-makers are suggested to conduct the *consistency check, completeness check, contribution analysis, sensitivity, and uncertainty analysis* to reach a sound conclusion about the results. The consistency check task is carried out to find out if the data of road construction materials and their relevant activities have any conflicts. The completeness check process ensures that all the substantial inputs and outputs concerning road construction materials are available and ready to use. The contribution analysis may be conducted to review the significance of each project phase to the total ecological performance. The sensitivity analysis and uncertainty analysis segments assess the influences of certain parameters and their variations on the environmental performance of road construction materials.

In summary, this section suggested a procedure model for evaluating the LCA results to assess the environmental performance of road construction materials. The procedure is developed based on the typical LCA, including four main parts. The proposed LCA method provides a guideline for assessing the holistically sustainable performance of road construction materials in the preliminary design phase. It is useful for material selection making-decision in the preliminary design phase and covers environmental burdens identified during the whole material's life cycle, including the relevant material-dependent activities. For handling the problem of unavailable data in the preliminary design phase, it suggests two considering two separate scenarios: (1) the amount of material is estimated and (2) the amount of material is not estimated.

As mentioned above, the LCA results can be used together with the life cycle cost and the social life cycle assessment results to assess the sustainability performance. The proposed Social LCA method will be introduced in the following section.

4.2.3. Social assessment

The *social life cycle assessment (Social LCA) method* is a social impact evaluation method focusing on the social aspects of products and services. The Social LCA analysis can be applied to achieve an insight into social performance in the construction field and give details on social aspects for decision-making that improves organizations' performance and the well-being of stakeholders (Dong and Ng, 2015; Zheng et al., 2020b). This section is aimed to develop a Social LCA method for answering research question 3d and assessing the social burdens of road construction materials in the preliminary design phase. According to section 4.1, the proposed method should be able to include both specific scenarios: (1) the amount of material is estimated and (2) the amount of material is not estimated.

The Social LCA results shall be integrated with the LCC and LCA results to assess the sustainability performance of road construction materials. The three proposed LCC, LCA, and Social LCA methods should define the same system boundary, functional unit, and reference flow to ensure consistency.

For assessing the social performance, some studies suggested applying the "Impact Pathway" (IP) approach or the "Reference Scale Assessment/Performance Reference Point" (PRP) approach (Ramirez et al., 2014; Siebert et al., 2018; Sureau et al., 2019; Huertas-Valdivia et al., 2020; UNEP and SLCA, 2020). The *IP approach* is conducted based on the concept of social burdens (UNEP and SLCA, 2020). It offers general measures/values for assessing social performance using midpoint and endpoint indicators. The IP approach includes linking Social LCI data from social activities/stressors reflected in inventory indicators to midpoint indicators revealing intermediate social effects and to endpoint indicators showing "final" social consequences (Benoit-Norris et al., 2012; Neugebauer, 2016; UNEP and SLCA, 2020). However, the IP approach is difficult to conduct since there is very little information concerning cause-effect chain models that would help practitioners aggregate Social LCI results (generated in the characterization step) in an accurate manner (UNEP and SETAC, 2013). In other words, there are no transparent pathways established between the inputs and outputs. It means that the cause-effect relationship is not identified clearly, so the characterization models and characterization factors can hardly be determined accurately. In addition to that, some proposed cause-effect chain models (e.g., measuring the technology development for society) are still not accepted and widely agreed upon by Social LCA experts (Russo Garrido et al., 2018; Bonilla-Alicea and Fu, 2019; UNEP and SLCA, 2020). As a result, some authors assess social performance based on only one indicator, such as fair wage or labor hours, instead of offering a general social performance result (Neugebauer, 2016; Junior and Kripka, 2020).

The *PRP approach* assesses the social performance of activities according to specific reference points of expected activity (called performance reference points - PRPs). The "Reference Scale Assessment/Performance Reference Point" approach is carried out by establishing reference scales for impact subcategories. The scales are normally from level 1 to level 5, corresponding with PRPs. Next, the collected data are compared to the corresponding PRPs' benchmark to assign scores for each indicator. The subcategory scores are then converted into impact categories, and their weightings are also determined. Lastly, the impact category results are aggregated to a single overall score by utilizing the determined importance weightings (UNEP and SLCA, 2020).

Based on the "Performance Preference Point" (PPR) approach, the Subcategory Assessment Method (SAM) was proposed by Ramirez et al. (Ramirez et al., 2014). This method establishes a (set of) Basic Requirement(s) (BR(s)) for each social impact category indicator and evaluates whether they are fulfilled or not. Additionally, this method provides a systematic and quite transparent way to appraise the subcategories and serves as an instrument to transform qualitative information into quantitative data. Furthermore, the method is developed from the UNEP and SETAC guidelines, so it shows a noticeable prospect of application in the future. Its database is principally built-in virtue of questionnaires; therefore, this method builds its own data to deal with the information deficiency in the early design phase. So, it is suggested to improve the SAM for the social assessment of material alternatives for road construction projects here. The method may be applied for both of the two scenarios because it does not take into account the amount of materials.

In general, a Social LCA analysis is built based on the traditional LCA analysis; hence, it applies an analogue procedure. The main steps employed in this method contain (1) Goal and Scope definitions, (2) Social inventory analysis, (3) Social mpact assessment, and (4) Social interpretation (UNEP and SETAC, 2009; UNEP and SLCA, 2020).

a. Step 1 - Goal and scope definition

The term '*goal*' does not merely refer to the objectives of a Social LCA study. Particularly, the Social LCA goals include the study's objectives, the anticipated use of the results, purposes for carrying out research, the stakeholders, their social impact categories and the target audiences (e.g., contractors) (UNEP and SLCA, 2020). In this thesis, the main goals include:

- Determining social impacts regarding road construction material alternatives, including the consideration of material-dependent activities.
- Identifying the most social-friendly alternatives based on the Social LCA results.
- Enabling to integrate Social LCA results into the LCSA analysis.
- Solving the problem concerning the lack of information in the preliminary design phase.

The *scope* should be determined clearly to be feasible and compatible with the given goals. For this thesis, the scope needs to cover the contents below.

- *The system boundary* is established in a way akin to the LCA analysis. It aims to appoint which unit processes are considered for the social assessment (Martínez-Blanco et al., 2015; UNEP and SLCA, 2020). The unit processes and their inter-relationships should be illustrated in a diagram because this provides an overview of which parts of the studied system are included or excluded. As already mentioned, the system boundary of LCC, LCA, Social LCA, and LCSA should be identical. Figure 4.8 and Figure 4.9 illustrate the generic system and flow diagram that have to be regarded for assessing the social performance of road construction materials. Although the flow diagram includes material-dependent activities (e.g., using equipment), traffic impacts are disregarded, similar to the economic and environmental assessments.
- The social LCA scope also specifies *the functional unit* of the products, processes, and services. The term 'functional unit' is described as a measure of the studied system's function, playing an important role in ensuring that all alternatives being compared to provide an equivalent level of function or service (Bayer et al., 2010). The functional unit should take a form similar to the LCA as "Road infrastructure between "A" and "B" over an analysis time horizon of a defined number of years." (Brattebø et al., 2013).
- Stakeholders (workers, customers, local communities, society and other actors of the value chain) and subcategories (such as., working hour, child labor, etc..) are also determined in the scope.

b. Step 2 - Social inventory analysis

The social life cycle inventory analysis (Social LCI) is conducted after identifying the goals and scope to collect and analyze the data from all unit processes. The main steps of the method are proposed in Figure 4.8.

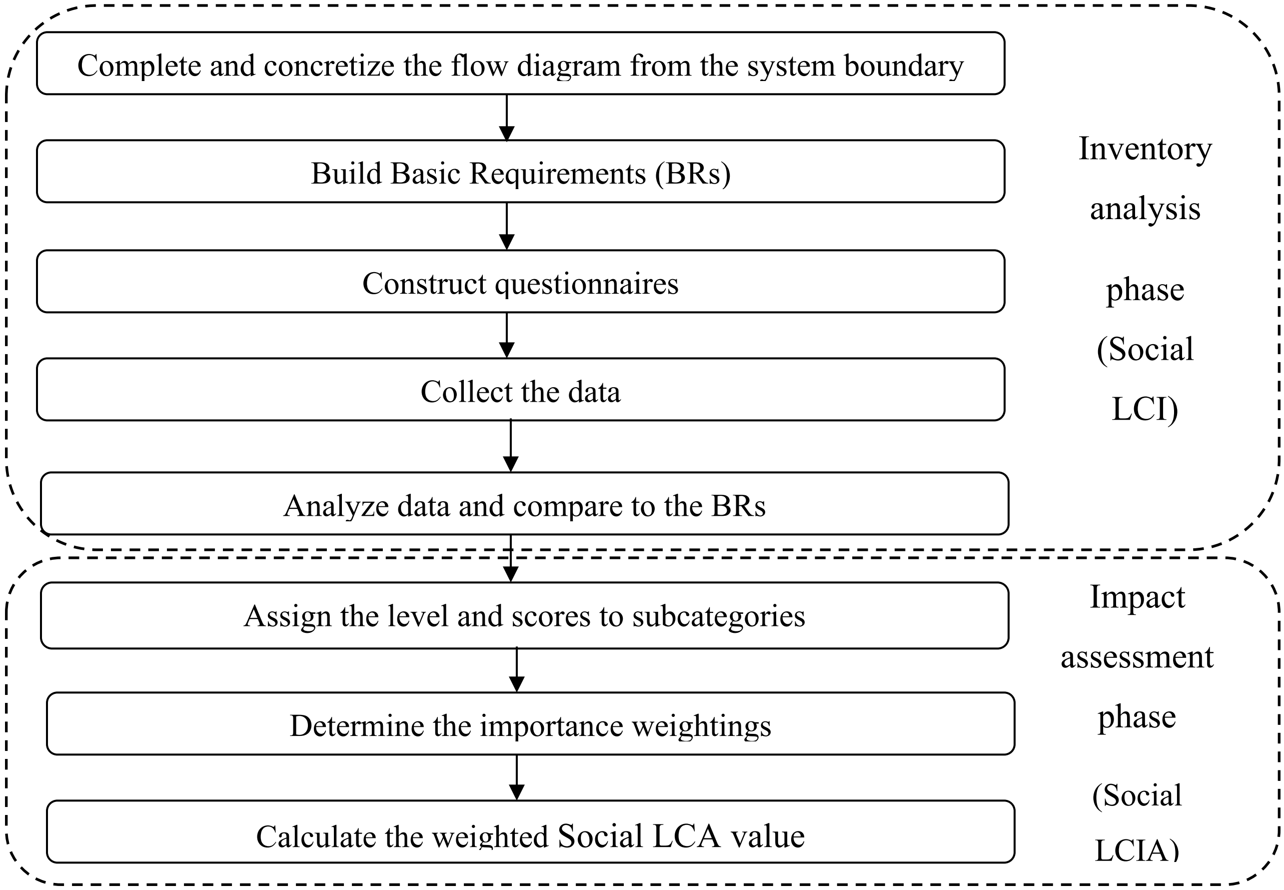
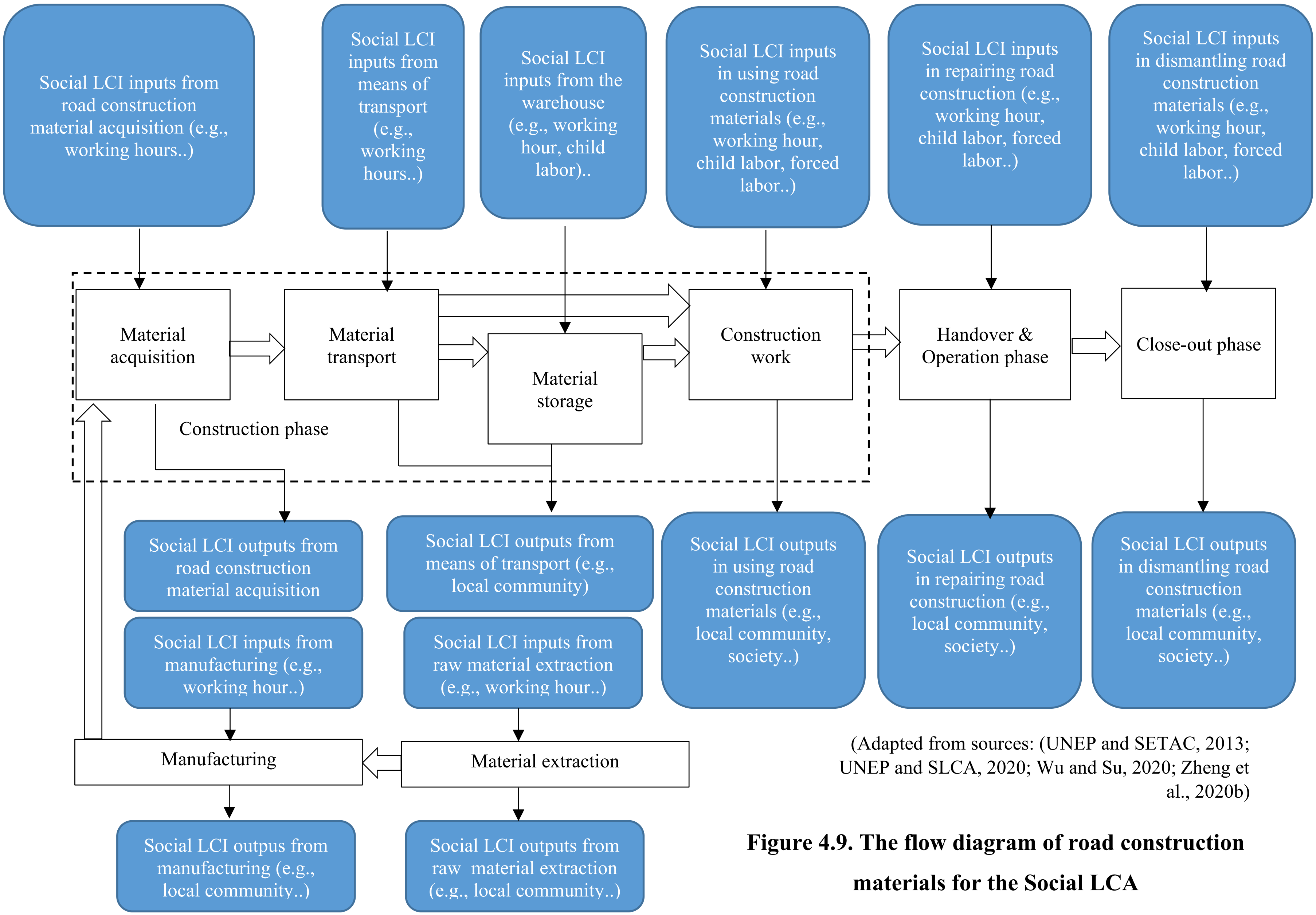


Figure 4.8. The proposed LCI and Social LCIA method

Figure 4.8 illustrates the two steps in the middle of the proposed Social LCA procedure – Social LCI and Social LCIA. The detailed guideline is presented below.

- *Complete and concretize the flow diagram from the system boundary:*

Flow diagrams are used to illustrate the structure of all unit processes. Like that of LCA, the flow diagram of the Social LCA displaying the aggregated processes should be illustrated by boxes and arrows. The boxes denote unit processes, and the arrows represent the flows or connections. The flow chart is developed based on the system boundary and includes material-dependent activities during the extraction phase, the manufacturing phase, the construction phase, the handover and operation phase, and the close-out phase (see Figure 4.9).



(Adapted from sources: (UNEP and SETAC, 2013; UNEP and SLCA, 2020; Wu and Su, 2020; Zheng et al., 2020b)

Figure 4.9. The flow diagram of road construction materials for the Social LCA

The flow chart of the Social LCA is developed according to the general flow chart (Figure 4.4), the LCC flow chart (Figure 4.5) and the LCA flow chart (Figure 4.6) to ensure consistency in the sustainability assessment of road construction materials. They all cover the material extraction phase, the material manufacturing phase, the construction phase, the handover and operation phase, and the close-out phase of a road construction project. It also considers the material-dependent factors such as using equipment, labor and other substances. Firstly, the raw materials will be extracted from sources, such as queries, leading to Social LCI inputs and outputs like working hours or the safety of laborers. Then, the manufacturing process needs labor, equipment, and auxiliary substances that may impact on the working hours, local community, and forced labour in Social LCI data. Next, completed road construction materials are transported from suppliers to the construction site by means of transport (trucks, trains, vessels) – causing Social LCI inputs and outputs such as working hours and impacts on the local community. When the materials reach the construction area, they are used immediately or stored in the warehouse, leading to Social LCI inputs and outputs. In the construction phase, construction activities consuming materials, ancillary items, and equipment can impact society, such as local community, working hours and local employers. In the handover and operation phase, the damaged material would be replaced and repaired in maintenance activities. The social performance can be influenced by these activities, such as forced labor, child labor and working hours. The materials are dismantled and moved to waste treatment plants in the last phase, which may impact on the local community and society.

- *Build Basic Requirements (BRs)*:

The Basic Requirements (BRs), termed by Ramirez et al. (Ramirez et al., 2014), are reference points for assessing social impacts. These requirements were developed based on the methodological sheets provided by the UNEP/SETAC guideline (UNEP and SETAC, 2013) to determine benchmarks for assessing subcategories. The BRs are explicated from the perspective of international agreements, local policies, or internal organization management. In this thesis, the BRs are developed based on studies from (Ramirez et al., 2014; Ramirez et al., 2016) and the guideline of the United Nations Environment Programme (UNEP and SLCA, 2020). The suggested main social impact subcategories and Basic Requirements for comparing social performance of road construction materials, as well as the essential contents of the questionnaires used for evaluation, are described below:

Table 4.4. The main social impact subcategories and Basic Requirements for comparing social performance of road construction materials

Stakeholders	Subcategories	Impacts by road construction materials	Basic Requirements (BRs)	The main content of the questionnaires
Worker	Child labor	Not using child labor for material-dependent activities	The absence of children working in the material-dependent activities	Whether there are policies considering child labor or not The contractor encourages the prohibition of child labor or not
	Working hours	The worker has to work overtime in material-dependent activities or not	The average number of working hours per employee must not exceed the amount of eight hours per day and forty-eight hours per week	The worker has to work overtime or not. The workers obey maximum working hour regulations or not. The working hours per employee are higher than the average value in the relevant region.
	Health and Safety	Health and safety of labor in material-dependent activities	The presence of a detailed policy/guideline or program considering health and safety of the laborers in the material-dependent activities.	The worker gets protection clothes or not. The contractor encourages the policies concerning health and safety of labor in material-dependent activities or not.
	Fair salary	Workers are paid equally in material-dependent activities	The lowest salary is equal to or higher than the minimum wage in the sector/country where material-dependent activities take place	The worker gets a fair salary or not. The paid salary is higher than the average salary or not The contractor encourages the policies concerning fair salary or not

Customer	End-of-life responsibility	Material suppliers provide End-of-life information in the close-out phase of materials.	There are management systems that provide clear information to contractors on end-of-life options for materials.	Material suppliers provide End-of-life information in the close-out phase of materials or not.
Local Community	Local employment	Hiring local employees for material-dependent activities	The presence of a policy hiring local employees for material-dependent activities.	Local employees are hired or not The contractor encourages the policies concerning local employment or not
	Secure living conditions	Material-dependent activities impact living animals and local community	There is a policy preventing the encroachment of material-dependent activities in local living conditions and species.	Material-dependent activities impact on living animals or not. The contractor has policies protecting living animals or not
Society	Technology development	Material-dependent activities develop technology in the construction industry.	The material-dependent activities participate in the development of efficient technologies for society.	Material-dependent activities require developed technology or not. The contractor encourages the technology development or not
Other actors of the value chain	Fair competition	Material suppliers have similar opportunities	There is a policy encouraging fair competition and compliance with anti-monopoly regulations for material suppliers.	The material suppliers are selected equally or not. The contractor encourages the fair competition of suppliers or not

(Sources: developed from (Ramirez et al., 2014; Ramirez et al., 2016; UNEP and SLCA, 2020))

Table 4.4 presents the primary social impact subcategories and BRs for comparing the social performance of road construction materials. In the table, the stakeholders are listed according to (UNEP and SLCA, 2020), including worker, customer, local community, society, and other actors of the value chain. The social performance of alternatives is assessed by main subcategories (UNEP and SLCA, 2020), including child labor, working hours, health and safety, fair salary, end-of-life responsibility, local employment, secure living conditions, technology development, and fair competition. The materials used for road construction projects normally have no direct effect on other subcategories, such as cultural heritage and corruption, so the subcategories are omitted in this thesis. According to the selected subcategories, their influences impacted by road construction materials are described. For example, the subcategory working hour is assessed by asking whether workers must work overtime in material-dependent activities or not. After that, the Basic Requirements are set up as benchmarks/reference points for assessing the social performance. Studies from (Ramirez et al., 2014; Ramirez et al., 2016) proposed Basic Requirements for assessing the social performance of organizations. However, these are not suitable for evaluating the social level of material-dependent activities. Therefore, a new set of Basic Requirements is developed focusing on material-dependent activities during the project life cycle. After that, a questionnaire is built from the BRs to compare the actual social performance of alternatives with the BRs and, finally, assess the social performance of material-dependent activities. The remaining subcategories and stakeholders are able to add to evaluate the social performance.

- *Construct a questionnaire*

Based on Table 4.4 , a questionnaire should be created to assess the social performance of each subcategory. The questionnaire should enable respondents to answer the question whether the Basic Requirement is or is not achieved. Each subcategory is evaluated by at least one question. Table 4.5 presents the main questions used to evaluate the social performance of road construction material alternatives. They are used to survey the actual social performance of road construction materials and compare the results to the BRs. The designed questionnaires must answer the question: “Whether the Basic Requirements are met or not?”. The experts can add more questions to the questionnaire to get a deep insight into actual social influences.

Table 4.5. The questionnaire assessing the social performance of road construction materials during the project life cycle

<table>
<tr><th>Stakeholders</th><th>Subcategories</th><th colspan="2">Questions</th><th>Level</th></tr>
<tr><th>(1)</th><th>(2)</th><th>(3)</th><th>(4)</th><th>(5)</th></tr>
<tr><td rowspan="16">Worker</td><td rowspan="4">Child labor</td><td rowspan="4">Is child labor (less than 16 years old) prohibited in material-dependent activities?</td><td rowspan="2">(if yes) Does the organization using the material and executing related-material activities have any support/policy for preventing child labor towards other construction activities?</td><td>(if yes) A</td></tr>
<tr><td>(if no) B</td></tr>
<tr><td rowspan="2">(if no) Does the country have any laws preventing child labor?</td><td>(if no) C</td></tr>
<tr><td>(if yes) D</td></tr>
<tr><td rowspan="4">Working hours</td><td rowspan="4">Do employees executing material-dependent activities must work overtime (more than eight hours per day and forty-eight hours per week)?</td><td rowspan="2">(if no) Does the organization using the material and executing related-material activities have any support for obeying maximum working hour regulations towards other construction activities?</td><td>(if yes) A</td></tr>
<tr><td>(if no) B</td></tr>
<tr><td rowspan="2">(if yes) Are the actual working hours higher than the average number of hours in the relevant area?</td><td>(if no) C</td></tr>
<tr><td>(if yes) D</td></tr>
<tr><td rowspan="4">Health and safety</td><td rowspan="4">Do employees executing material-dependent activities get any policies ensuring their health and safety? (e.g., protection clothes requirements)</td><td rowspan="2">(if yes) Does the organization using the material and executing related-material activities have any support for ensuring health and safety of labors towards other construction activities?</td><td>(if yes) A</td></tr>
<tr><td>(if no) B</td></tr>
<tr><td rowspan="2">(if no) Is the rate of frequency of project's occupational accidents (fatal and non-fatal) lower than the average figure of the country/ sector?</td><td>(if yes) C</td></tr>
<tr><td>(if no) D</td></tr>
<tr><td rowspan="4">Fair salary</td><td rowspan="4">Do employees executing material-dependent activities get a fair salary which is higher than the average salary in the country?</td><td rowspan="2">(if yes) Does the organization using the material and executing related-material activities have any support for paying equal salaries towards other construction activities?</td><td>(if yes) A</td></tr>
<tr><td>(if no) B</td></tr>
<tr><td rowspan="2">(if no) Are there any records concerning the unfair salary?</td><td>(if no) C</td></tr>
<tr><td>(if yes) D</td></tr>
<tr><td rowspan="2">Customer</td><td rowspan="2">End-of-life responsibility</td><td rowspan="2">Does the material supplier provide any End-of-life information for broken materials</td><td rowspan="2">(if yes) Do the suppliers have any support for providing End-of-life information towards other construction materials?</td><td>(if yes) A</td></tr>
<tr><td>(if no) B</td></tr>
</table>

		and the close-out phase? (e.g., handling broken materials)	(if no) Can the material be recycled or reused?	(if yes) C
				(if no) D
Local Community	Local employment	Are local employees hired to execute related-material activities?	(if yes) Does the organization have any support in increasing the rate of local employees towards other construction activities?	(if yes) A
				(if no) B
			(if no) Is local employee ratio of the project lower than the average number in the evaluated area?	(if yes) C
				(if no) D
	Secure living conditions	Is there any policy preventing the encroachment of material-dependent activities in local living conditions and species? (e.g., the construction site must be away from animals)	(if yes) Does the organization have any policies protecting the living conditions and local people towards other construction activities?	(if yes) A
				(if no) B
			(If no) Is the perception of live condition safety percentage lower than 50%? (analysed by a survey)	(if yes) C
				(if no) D
Society	Technology development	Do material-dependent activities develop technology in the construction industry? (e.g., using new equipment)	(if yes) Does the organization have any support in developing technology towards other construction activities?	(if yes) A
				(if no) B
			(if no) Is the rate of the country's incremental capital output ratio (ICOR) lower than 5? (Hayes, 2020)	(if yes) C
				(if no) D
Other actors in the value chain	Fair competition	Are material suppliers selected by a fair competition? (e.g., finding the best suppliers by a bidding)	(if yes) Does the organization have any support for fair competition and anti-monopoly towards other construction activities?	(if yes) A
				(if no) B
			(if no) Are there any records adversely affecting fair competition and anti-monopoly?	(if no) C
				(if yes) D

The use of the questionnaire is presented in detail below.

- The first two columns of Table 4.5 represent the stakeholders and related subcategories determined in the guideline of the United Nations Environment Programme (UNEP and SLCA, 2020). Column (3) depicts the questions directly asking about the social performance of material-dependent activities for each social subcategory. The questions are formulated in a 'Yes/No' form to reduce the complexity of answers.
- According to the answers of column (3), column (4) proposes questions in 2 options of the answers.
  - In "yes" case, the social performance of the alternative meets the corresponding Basic Requirement. A further question relating to proactive supports of the organization in a 'Yes/No' form is given for a more differentiated evaluation .
  - In "no" case, the social performance of the alternative is not able to reach the corresponding Basic Requirement. Again, a further question relating to specific contents in a 'Yes/No' form is given.

- *Collect the data*

The questionnaire will be sent to extraction companies, manufacturing companies, contractors, suppliers, owners, and local communities, who are corresponding stakeholders according to Table 4.5 and/or participate in the material extraction, the material manufacturing, the construction, handover & operation, and close-out phases. For the material extraction phase, extraction companies and local communities may be participants who answer the questionnaire, while the manufacturing companies, local communities and distribution agents participate in the questionnaire with respect to the manufacturing phase. Referring to the construction phase, suppliers, contractors and local communities may be chosen for the survey. Local communities and owners become key stakeholders who answer the questionnaire for the handover and operation phase. For the close-out phase, owners and local communities near the waste treatment plant may be selected. Each participant will answer questions related to their role in the material life cycle, which will be written at the top of the questionnaire. The questionnaire may include two parts. The first part introduces the personal information of respondents and their role, and the main questions are presented in the second one.

The questionnaire should be sent directly to the corresponding stakeholders by mailpost, email or link. The participants will have an adequate period of time to respond. After that, the answers are resent back to the questioners, and the data are gathered from questionnaire responses. Besides, a subcategory is assessed by some respondents, so if a false answer is given, the remaining true answer will help the designer see the right picture. Besides, the respondents will write their names to take responsibility for their answers.

- *Analyze data and compare to the BRs*

The answers gathered are compared to the BRs (Table 4.5) for assigning the labels A, B, C, or D for each respondent. Column (5) of Table 4.5 assigns labels 'A, B, C, D' according to the answers obtained from columns (3) and (4). For example, the question 'Is child labor (less than 16 years old) prohibited in material-dependent activities?' is used to assess the social performance regarding the stakeholder 'worker' and subcategory 'child labor'. Its answer is used for a differentiation of two options:

- If the answer is 'yes', the question 'Does the organization using the material and executing related-material activities have any support/policy for preventing child labor towards other construction activities?' has to be answered to assess the proactive behavior of the organization. If the second answer is 'yes', label A is assigned. Label B is given when the answer is "no".
- On the contrary, if the answer is 'no', the question 'Does the country have any laws preventing child labor?' is asked to assess the context of preventing child labor in the country. If the answer is "no", label C is assigned. Label D is given when the answer is "yes".

c. Step 3 - Social life cycle impact assessment

In the social life cycle impact assessment (or social impact assessment, impact assessment (Social LCIA)), the magnitude of the selected social impact categories is analyzed and assessed. According to Figure 4.8, the Social LCIA phase includes three primary sub-steps below.

- *Assign the level and scores to subcategories*

After assigning the letter A, B, C, or D to each participant's response, the social impact subcategories are labeled A, B, C, or D according to the aggregation of assignment's results. The designers select the most appropriate label using the majority decision-making rule. It indicates that the label will be assigned if it has a majority compared to the others. In the event that no label reaches a majority consensus, the designers make their own decision or distribute questionnaires to other stakeholders.

In this thesis, level A is assigned to the highest rank, implying the proactive support of the organization in fulfilling the BRs. Level B is assigned to the organization when it solely fulfills its BR but provides no additional promotional activities. Level C represents subcategories that may not achieve BRs due to the background of technological or policy aspects. Lastly, level D is labelled when subcategories may not meet a BR despite the organization being encouraged by technological or policy considerations. For example, for the subcategory ‘Child labor’, if there are child laborers in the organization, level C is labelled if the laws do not have a policy related to child labor. In contrast to that, level D is assigned if the country regulates a child labor policy in laws.

Next, the relevant scores are assigned to subcategories. Ramirez et al. (Ramirez et al., 2014; Ramirez et al., 2016) attached ratings 4, 3, 2, 1 to the A, B, C, D levels, respectively. Fundamentally, the higher the score means the better social performance. However, the comparisons derived from the life cycle cost and life cycle assessment methods give priority to the lower value. Therefore, in this thesis, the A, B, C, and D levels are assigned to the numeric values in ascending order - 1, 2, 3, and 4, respectively. Accordingly, the lower score would signify a more fruitful social performance.

- *Determine the importance weightings*

In the study of (Ramirez et al., 2014), social performance of subcategories is assessed without including the importance of weightings. However, several subcategories might conceivably be more critical or relevant than others; thus, the owners may require considering the importance of specific subcategories. Accordingly, the weightings can be assigned by the owners. This can be done by (subjective) estimations without any methodical support or supported by the MCDM method, such as the AHP method. According to its general procedure, such as described by (Götze et al., 2015), the AHP can be used for determining weightings in the following way: *Firstly*, a hierarchy is established by determining and structuring the relevant social subcategories. *Secondly*, pair-wise comparisons are conducted as a base for estimating and quantifying the relative importance of every social subcategory. *Thirdly*, the calculation of local priority vectors (weighting vector) for every pair-wise comparison matrix is conducted. The *fourth* step comprises the calculation of values of consistency for examining the consistency of the priority assessments. The results of these checks might induce the need of examining and possibly revising the pair comparisons. In the *fifth* step, the Social LCA target and alternative priorities are calculated with respect to the whole hierarchy – expressing the relevance (importance weightings) for the Social LCA and its subcategories. The AHP method can also be applied to estimate the weightings of stakeholders. The detailed weighting determination is presented in section 4.2.4.

- *Calculate the Social LCA value*

The (weighted) Social LCIA value is computed by aggregating the subcategory scores and corresponding weightings. The weighted Social LCA value of stakeholders in each phase is illustrated as below:

$$SLCIA_s = \sum_{i=1}^{n}(V_{s,i} \cdot W_{s,i}) \qquad 4.42$$

Where

- s is the type of stakeholder defined in the (UNEP and SLCA, 2020), including worker, local community, society, customer, and other actors of value chain.
- n denotes the total number of subcategories
- $V_{s,i}$ represents pre-assigned scores of subcategory i of stakeholder s;
- $W_{s,i}$ denotes the corresponding weightings of subcategory i of stakeholder s.

The total Social LCA value is the sum of the weighted Social LCIA values of all stakeholders during the material extraction phase, the manufacturing phase, and the project life cycle, including the construction, handover & operation, and close-out phase. The alternative with the lowest Social LCIA value shows the best social performance.

d. Step 4 - Social life cycle interpretation

This phase evaluates the Social LCIA results in order to draw conclusions. The subtasks comprise the identification of significant issues, consideration of consistency and completeness, participation of stakeholders, recommendations, and reporting documents. According to the UNEP/SETAC (UNEP and SETAC, 2009), "significant issues" refers to limitations, assumptions, or significant concerns of subcategories. For example, the list of subcategories should be reviewed to reduce the absence of significant impacts. The term "consistency" refers to the appropriateness of the data and methodology. "Completeness" focuses on whether or not the pertinent issues are resolved. Additionally, the conclusion, recommendations, and pertinent documents regarding the purpose and scope of the study are provided. In this thesis, the Social LCA results will also be converted to the normalized form in order to integrate into the LCSA model (section 4.2.4).

In general, the proposed Social LCA method performs potentials for material selection making-decision in the preliminary design phase. It can be applied to both two scenarios: (1) the amount of material is estimated, and (2) the amount of material is not estimated.

The proposed method analyzes the behaviours of stakeholders for assessing the social performance of road construction materials based on the guideline of the Social LCA method (UNEP and SLCA, 2020). The database is predominantly constituted with the assistance of questionnaires, so this method is favourable for the construction industry, where hardly social databases do exist. Moreover, the proposed Basic Requirements could be specified for industries and regions. Roads generally spread across multiple regions, so it would be a difficult task to collect their region-based social data. Additionally, especially in the preliminary design phase, road construction material selection encounters problems, such as the information about the lack of material quantities, used full data and detailed guidelines (section 3.1 and section 3.5.3). The proposed method addresses this problem – by relying on the use of the questionnaire. It is applicable for assessing the social performance without an established database and especially in the early design phase. The proposed method is also established to deal with the lack of information and assess the social performance of alternatives comprehensively.

On the contrary, this method also possesses a number of shortcomings. Firstly, the method does not consider the amount of the material and its related activities. Secondly, the assessment has only four levels (A, B, C, and D), meaning that specific organizations with a wide range of proactive actions might be assigned to the same level as an entity implementing fewer activities. However, this can be quite easily resolved by introducing a more differentiated scale. Thirdly, the usage of questionnaires implies a considerable effort as well.

The Social LCA results are integrated with the life cycle cost and the life cycle assessment results to assess sustainability performance. The next section suggests the aggregation of LCC, LCA, and Social LCA results into the LCSA model to assess the sustainable performance of road construction material alternatives (section 4.2.4).

4.2.4. Sustainability assessment

The original model of the LCSA assesses sustainability performance by considering the economic, environmental, and social aspects equally (see section 3.6). However, from the perspective of decision-makers, the relevance of the single sustainability dimensions might be considered to be different. This causes the requirement of estimating the importance weightings of the sustainability dimensions and considering them in the sustainability evaluation. Accordingly, it is proposed here to include the possibly different importance weightings of the sustainability dimensions and their results into the overall sustainability assessment of road construction materials. This is another element of the integrated approach for identifying the most sustainable materials suggested here and described in section 4.1.

Operationalizing this approach, the overall LCSA outcome of road construction materials can be calculated based on the following equation (Dinh et al., 2020):

$$\mathrm{LCSA} = \alpha \cdot \mathrm{LCC} + \beta \cdot \mathrm{LCA} + \gamma \cdot \mathrm{SCLA} \quad (4.43)$$

Where:

- LCC, LCA, and SLCA denote the normalized LCC, LCA, and Social LCA results. The LCC, LCA, and Social LCA results of assessing road construction materials are typically measured in different units. Therefore, the normalization step is necessary to adjust the values measured to a common unit. The results are achieved by using the methods suggested in sections 4.2.1, 4.2.2 and 4.2.3.
- α, β, and γ are the weightings of LCC, LCA, and Social LCA outcomes, respectively. A methodical approach for generating these importance weightings is suggested below.

The result derived through this formula signifies the sustainability performance of road construction materials during the material extraction phase, the material manufacturing phase, the construction phase, the handover and operation phase, and the close-out phase. The target figures suggested in the previous chapters include figures with a positive contribution to sustainability, such as social contributions, and figures expressing a negative contribution, such as the LCA outcomes. Therefore, it has to be decided whether the overall sustainability measure is defined as a utility – which should be maximized – or a burden – which should be minimized. Afterwards, the outcomes have to be transformed correspondingly. In case of defining it as a burden, the materials which carry a high LCSA value are evaluated to provide poor sustainability performance. Hence, experts should pursue the alternative that displays the lowest LCSA figure.

The equation shown above considers the importance level expressed by the weightings of the economic, environmental, and social dimensions; it is a refinement of the original equation (equation 3.7) and can replace this one in the assessment of the sustainability performance of road construction materials (Dinh et al., 2020). In addition, the equation can be applied to estimate the sustainable performance of other objects like road construction items. Furthermore, it can be the basis for sensitivity analyses revealing the advantageousness of the alternatives in dependence on the weighting of the sustainability dimensions.

In the following, an approach for estimating the importance weightings needed for calculating the LCSA result of road construction materials according to equation 4.43 is suggested. Including different weightings of target criteria in an evaluation is a typical characteristic of Multi-Criteria Decision-Making methods (see section 3.6.2). Therefore, they promise to provide methodical elements for determining the importance weightings of LCC, LCA, and Social LCA results, integrating them into the LCSA result and thereby supporting comprehensible decision-making (Onat et al., 2017; Tarne et al., 2019; Visentin et al., 2020).

Some studies applied the AHP method for determining weightings and argued that this method appears to be a favourable tool for weighting estimation in the LCSA analysis (Hossaini et al., 2014; Sou et al., 2016; De Luca et al., 2018; Costa et al., 2019; Dinh et al., 2020). The AHP is a technique that assigns priorities (weightings) to each alternative by identifying the goals or the importance of attributes hierarchically. It is a structured technique supporting decision-makers in analyzing and resolving complex problems. The AHP was first developed by Thomas L. Saaty in the early 1970s (Saaty, 1980), and has been used in various cases for planning and especially determining the importance of issues and evaluating alternatives (Vaidya and Kumar, 2006). It employs an Eigenvalue approach with pair-wise comparisons. In the AHP, a nine-point scale ranging from 1 (equal importance) to 9 (absolutely dominating) may be utilized to express the importance (or preferability) of one target (or alternative) compared to another one. Using the results of the comparisons and the Eigenvalue Approach, importance measures for criteria and profitability measures for alternatives can be calculated (Götze et al., 2015).

In the frame of the instrument developed in this thesis, the AHP can be applied in different fields and cases:

- For an overall assessment of sustainability after having calculated the each one result of the three sustainability dimensions by applying LCC, LCA and Social LCA according to the procedures suggested in sections 4.2.1, 4.2.2, and 4.2.3: In that case, the hierarchy of the AHP only consists of the three dimension-specific target figures and the overall sustainability value, and only three weightings have to be determined.
- For calculating the dimension-specific target figure under consideration of a couple of relevant criteria: This seems to be relevant, especially for the assessment of social sustainability, where a lot of different criteria can be relevant (see section 4.2.3).
- For determining an overall sustainability value as well as dimension-specific target figures – including the first and the second field of application mentioned above.

The first case is not further regarded here since it does not raise specific challenges. The second case is covered by the third one – therefore, the following suggestion of an approach focuses on the third case.

In that case, the following five main steps are included in the AHP (Götze et al., 2015): *Firstly*, a hierarchy is established by determining and structuring the relevant criteria. The overall sustainability (LCSA) target is divided into LCC, LCA, and social LCA targets (level 1). Then, the LCC target (economic aspects) can be categorized into economic criteria. Similarly, the LCA goal (environmental aspects) can be split into environmental criteria, and the Social LCA target (social aspects) into social criteria (level 2 (under the assumption that there is only one level for each dimension)). Furthermore, the alternative materials to be assessed are positioned on level 3 of the hierarchy. *Secondly*, pair-wise comparisons are conducted as a base for estimating and quantifying the relative importance of every criterion as well as the priority/preferability of each alternative. *Thirdly*, the calculation of local priority vectors (weighting vector) for every pair-wise comparison matrix is conducted. The *fourth* step comprises the calculation of values of consistency for examining the consistency of the priority assessments. The results of these checks might induce the need of examining and possibly revise the pair comparisons. In the *fifth* step, the target and alternative priorities are calculated with respect to the whole hierarchy – expressing the relevance (importance weighting) for the overall sustainability value (in case of targets) or the ultimate profitability or preferability (in case of alternatives).

A crucial issue of applying the AHP method is to make the necessary expertise for conducting the pair-wise comparisons available in order to achieve significant results. On the one hand, it might be difficult to motivate experts to participate. On the other hand, a small number of experts included might cause distorted or insignificant results. In an effort to overcome these challenges, it is suggested here to design appropriate questionnaires and conduct data analysis.

In case of including all sustainability dimensions, the questionnaire should include lists of possibly relevant economic, environmental, and social sub-criteria. These can be developed from previous studies and experts' judgments. For example, the economic sub-criteria contain the price of material, shipping cost, or using cost when environmental criteria cover energy consumption, water consumption, or global warming. For the environmental assessment, midpoint and or endpoint categories might be included (see section 4.2.2). Social sub-factors might comprise safety, child labor, and working hours or the other criteria suggested in section 4.2.3.

Many authors integrated the Likert Scale into the AHP method to calculate weightings representing the significance level of each criterion included in the assessment (Kallas, 2011; Hossain et al., 2014; Çalişkan et al., 2019; Dinh et al., 2020). Using the Likert scale, respondents choose one option that best aligns with their view. Thus, it allows obtaining the preference of attributes as in the case of the AHP (Kallas, 2011) and enables the users to compare pair-wise in a straightforward and convenient form of data input (Hossain et al., 2014). Besides, it can be used to get over the inconsistency problem of pair-wise comparison matrices (Çalişkan et al., 2019). The questionnaire should be designed employing a Likert scale that could be a five, seven, or nine-point scale depending on each research conductor's ambition. It is the most common method of scaling responses in survey research, allowing respondents to express their level of agreement or disagreement with a particular statement. For example, a nine-point scale can be used to evaluate the influence of sustainability criteria in material selection. The elected questions must be described as clearly as possible to avoid ambiguity. A group of experienced experts may be consulted to check the criteria list in order to generate profound findings.

The target group of experts to which the questionnaire is sent should preferably include individuals who are responsible for selecting suitable construction materials or specifically responsible for a road construction project. If necessary, their contact details can be obtained from several different sources, including the researcher's relationships, company phonebook databases, as well as public information.

To ensure the significance of the results achieved by using a Likert scale, their reliability could be analyzed by using tools, such as the SPSS software. The gathered data from the Likert scale are checked for consistency. The Cronbach's Alpha is among the most common measure of internal consistency in SPSS Statistics. Specifically, the Alpha (α) coefficient customarily ranges from 0 to 1. Accordingly, the closer the alpha is to 1, the more reliable the results turn out to be. The lowest acceptable value of Cronbach's Alpha coefficient is suggested to be 0.70 (Hair et al., 2013). This step helps overcome the inconsistency problem of AHP data input. However, values of consistency in the fourth AHP step should still be calculated to examine the consistency of the AHP results.

The relative importance index (RI) analysis is selected to assess the relative importance between criteria of road construction materials. This index value is computed by using the equation below:

$$\mathrm{RI} = \frac{\sum \mathrm{w}}{\mathrm{A} \cdot \mathrm{N}} \qquad 4.44$$

Where:

- w is the score as assigned by each respondent
- A is the highest weight
- N is the total number of samples.

These RI values are then applied in the fourth and the following steps of the AHP method. Thereby, the priority vectors (weighting vectors) are determined by using the RI indices achieved via equation 4.44. In the fifth step, the global priorities of the target criteria at level 1 denote the importance weightings of the economic, environmental and social dimensions of sustainability. The global priorities of the alternatives (specific materials for road construction) express their preferability with respect to sustainability. After that, the importance weightings are applied to equation 4.43 to estimate the LCSA result.

In chapter 4, a methodical approach for evaluating the sustainability of road construction materials in the preliminary design phase has been suggested for answering research question 3 and its sub-questions. Next, a case study is conducted to illustrate the application and applicability of this approach.

5. Case study of material selection in a road construction project in Vietnam

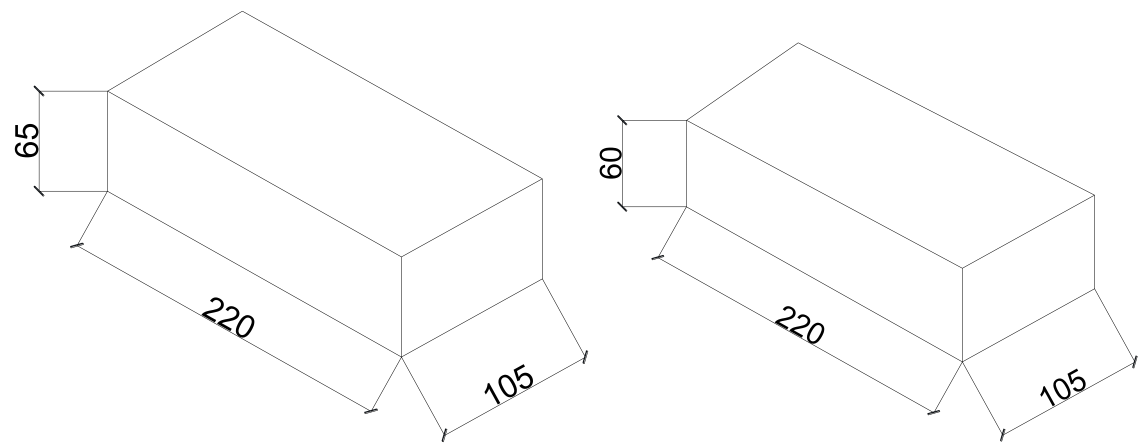
5.1. General information about the project

The proposed method is applied in selecting bricks for the task "Brick Masonry of Channel" in project "Provincial road No207 improvement construction project from Quang Uyen to Ha Lang (km 0+00 – km 31+00)". The road connects Quang Uyen district and Ha Lang district in Cao Bang province. Its length is about 31 kilometres, and the project life cycle is assumed to be 50 years, and the discount rate amounts to 11%.

In recent years, along with the development of Cao Bang province and the increase of tourists, traffic density at provincial road No207 has increased dramatically. This directly affects traffic congestion and traffic safety. Provincial road No207, connecting the two districts in Cao Bang province, is a strategic traffic axis, serving politics, economics, culture, security and foreign relations. It starts from Quang Uyen district, passing the following villages: Doc Lap, Cai Bo, An Lac, Thanh Nhat, and ending in Ha Lang district.

The task "Brick Masonry of Channel" serves as an important construction task in the project. The main material of this task is brick, which is selected firstly by technical criteria, such as strength and durability. According to the criteria and the brick market in Vietnam, two material alternatives were preselected: concrete bricks and baked bricks. The pre-selection procedure is conducted based on Figure 4.1. Firstly, the designers created the layouts and main structures of the project. According to them, the technical requirements of the material for channels were established. After that, all brick types available in the Vietnamese brick market are compared to the technical requirements to make a list of preselected materials. As a result, concrete bricks and baked bricks are identified as the two alternatives that meet the technical requirements and need to be assessed for their sustainability performance.

In Vietnam, concrete bricks are mainly made from cement, sand, and water. The most critical disadvantage of concrete bricks is the quality's inconsistency because of the cement used, so the Vietnamese government required that the concrete bricks from cement must be manufactured in factories. The baked bricks are mainly made from clays and mud, and they are then baked with fire in the brickyards. In Vietnam, there are many suppliers producing baked bricks because brickyards can be built straightforwardly by individuals. In this case study, the baked bricks can be purchased from a regional brickyard located close to the construction area in the given project, while the concrete ones have to be bought from another province (about 60 kilometers distance). The dimensions of the bricks are illustrated below:



Baked bricks Concrete bricks

Figure 5.1. The dimension of bricks (millimetres).

In the task "Brick Masonry of Channel", a totality of 321.18 m^3 of the channel has to be completed. For this case study, the actual amount of bricks and their dependent substances required is estimated by multiplying the amount of the channel being completed by the amount of bricks per 1 m^3 of the channel and by the loss coefficients. Other relevant project data are illustrated in Table 5.1.

Table 5.1. Common information for the alternatives

Information	Value	Information	Value
The volume of channel	321.18 m^3	Unit price of waste transportation	10 Euro per m^3
Project life cycle	50 years	Distance of waste transportation	20 kilometers
Discount rate	11%	Unit price of waste treatment	16.98 Euro per m^3
Annual price increase index	6.5%	Unit price of concrete brick liquidation	1 Euro per m^3

(Sources: project data)

The baked bricks and concrete bricks differ regarding unit price, volume, dimensions, the material-dependent substances and a lot of other influencing factors. Their unit prices and dependent substances are derived from supplier's quotation and historical data. In this case study, all currency units are converted from Vietnamese Dong to Euro. The detailed data for the two alternatives are depicted in Table 5.2.

Table 5.2. Input data for the two alternatives

	Baked Bricks	Concrete Bricks
Unit Price of Bricks	0.047 Euro per block (including transportation cost)	0.066 Euro per block (including transportation cost)
Estimated labor hour	5,787.66 hours	5,524.30 hours
Mortar mixed equipment	92.5 hours	86.08 hours
Amount of bricks including losses	141,125 blocks	153,638 blocks
Period of storage in warehouse (months)	0	4
Mortar	106.95 m^3	100.21 m^3
Unit price of labor	1.79 Euro/hour	1.79 Euro/hour
Unit price of mortar mixed equipment	2.08 Euro/hour	2.08 Euro/hour
Unit price of mortar	8.39 Euro/ m^3	8.39 Euro/ m^3
Overhaul/inter-maintenance period	5 years	8 years

Overhaul/inter-maintenance rate of material in the first 25 years	5 % per time	4% per time
Expected annual repairing rate of material in the first 25 years	1.5% per year	1% per year
Expected overhaul/inter-maintenance rate of material in the last 25 years	8% per time	7% per time
Expected annual repairing rate of material in the last 25 years	4% per year	3% per year
Distance from suppliers (km)	1	60
The number of trips (vehicle 7 tons)	65	66
Recycled rate in the close-out phase (%)	0	20%

(Sources: project data and historical database)

Table 5.2 shows the relevant data for the two alternatives that have been generated based on databases and a couple of assumptions. They include the unit price of bricks, estimated labor hour, and needed mortar. The unit price of bricks in Vietnam is estimated per block, so the amount of material is converted to 'blocks'. For example, the unit price of baked bricks is 0.047 Euro per block, while the unit price of concrete ones is 0.066 Euro per block. Noticeably, the unit price of concrete bricks is higher than the unit price of baked bricks mainly due to it covers the transportation cost from the brick manufacturing plant to the construction site. Besides, concrete bricks are stored for four months by occupying a small area in the warehouse only (about $1m^2$), so the storage cost can be neglected. The mortar is defined as material-dependent substances for binding bricks in the completed channels. In the table, the maintenance and repair activities are divided into two kinds: annual repairing and overhaul/inter-maintenance. The overhaul/inter-maintenance of baked bricks and concrete bricks is conducted every 5 and 8 years, respectively.

The maintenance is a thorough examination and restoration of the whole road or major construction items to an acceptable level of functionality. In the first 25 years, their rates are lower than the values of the last 25 years due to the deterioration of the road. Besides, the distance from the supplier of concrete bricks is about 60km, while baked bricks' corresponding figure is only 1km. The number of trips is calculated by dividing the vehicle's maximum load by the amount of bricks.

The next section describes how the relevant economic, environmental, and social criteria are defined, the two material alternatives are assessed with regard to them and, finally, the total sustainability performance of the material alternatives is evaluated.

5.2. Application of the proposed method for road construction material selection

5.2.1. Goal and Scope definition at the level of sustainability

In general, *the goal of the study* is to select the most sustainable material in the project's preliminary design phase based on the three pillars of sustainable development, namely, economic, environmental, and social aspects. The calculation result should be comparable and unproblematic to understand. In the case study, the goal is to assess the sustainability performance of the baked brick and concrete brick, then select the most sustainable one.

The *system boundary* specifies which unit processes are included in the estimation of bricks' sustainable performance. It specifies which activities are included, along with their inputs and outputs. Due to the lack of available data on the extraction and manufacturing phases in Vietnam, the case study applies "the gate to grave" approach to assess the sustainability performance of road construction materials. In the construction industry, Figueiredo et al., (Figueiredo et al., 2021) pointed out that "the gate to grave" approach includes the following stages of a building life-cycle: construction phase, operation and maintenance phase, and end-of-life phase. The approach was also conducted in some studies, such as (Sözer et al., 2020; Olowo, 2022). Accordingly, the sustainability performance in this case study will be assessed under consideration of the construction, handover and operation, and close-out phases. The system boundary should be depicted by a diagram (e.g., a flowchart) to clarify which phases of the life cycle have been involved. Accordingly, a flow chart is created illustrating the main brick-dependent activities during the project life cycle (see Figure 5.2).

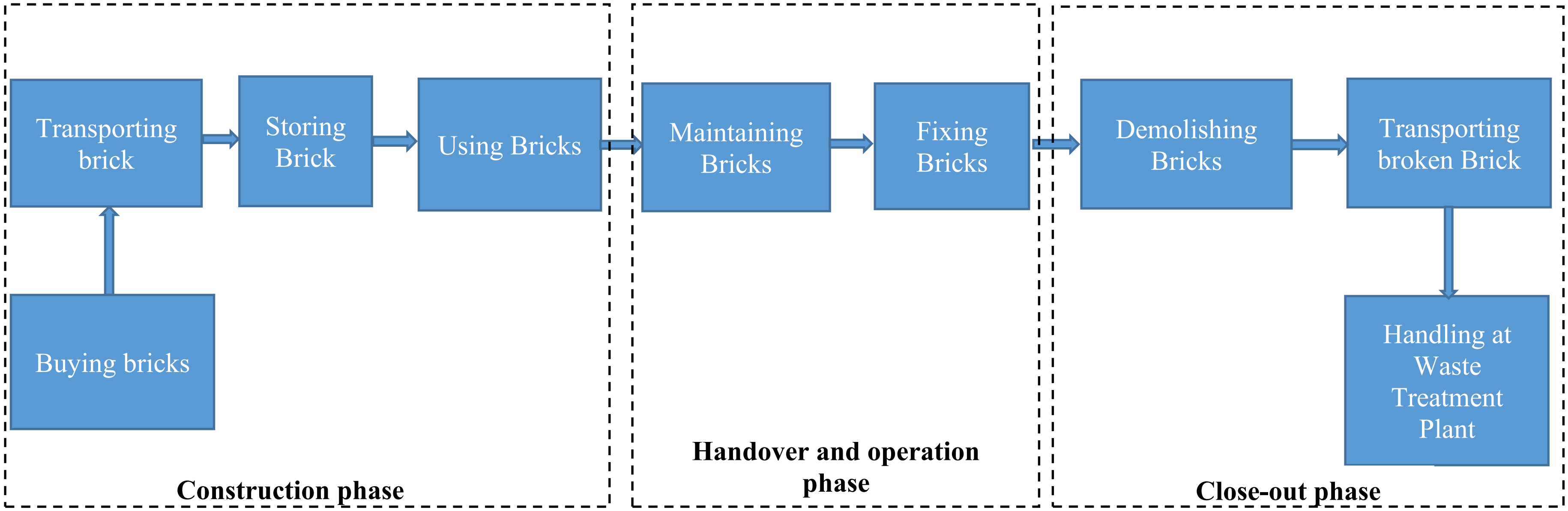


Figure 5.2. Main brick- dependent activities during the project life cycle

It is assumed that the *functional unit* is “provincial road No207 improvement construction project between Quang Uyen and Ha Lang from 2022 to 2072” (whole project). The total amount of channel is 321.18 m^3 that are necessary to provide the functional unit. So, the reference flow is 321.18 m^3 of Channels of the provincial road No207 improvement construction project between Quang Uyen and Ha Lang that have to be kept in a functioning state from 2022 to 2072.

The amounts of baked bricks and concrete bricks are estimated by designers before conducting the evaluation, so scenario 1 is applied for assessing the sustainability performance. The two alternatives are compared in the preliminary design phase. Therefore, hardly detailed information is available. Consequently, the input data are deduced from primary sources such as historical data, project requirements, and published regulations. Additionally, traffic impacts in the handover and operation phase are neglected because they are presumed to be the same for all material alternatives.

To fulfill the study’s goal, the sustainability performance of bricks has to be assessed according to all three dimensions of sustainability. So, the criteria applied in the evaluation have to cover the economic, environmental, and social aspects. According to section 4.2.4, the LCSA method is applied to assess sustainable performance, while the LCC, LCA, and Social LCA are conducted to assess economic, environmental, and social dimensions. The dimension-specific evaluations are described in sections 5.2.2, 5.2.3 and 5.2.4. The obtained dimension-specific target values are then aggregated at the top level, calculating an overall sustainability value of bricks for comparison, and importance weightings for the economic, environmental, and social dimensions are determined (section 5.2.5).

5.2.2. Economic assessment

The economic aspects of using concrete bricks and baked bricks are assessed by applying the LCC analysis. The economic performance of baked bricks and concrete bricks is evaluated by systematically determining the total cost incurred by them based on their related activities – the brick-dependent activities. By applying LCC, the total costs of baked bricks and concrete bricks are calculated as the sum of (discounted) costs in the construction, handover and operation, and close-out phases (see section 4.2.1). They express the economic performance of the alternative bricks and identify the best – in terms of economic effects – alternative. Furthermore, the LCC results are included in an LCSA such as suggested in section 4 and thereby support decision-making as well. The amount of bricks is provided, so scenario (1) of the proposed LCC in section 4.2.1 is conducted to estimate alternatives' LCC values. The LCC results are calculated by *summing up the present value of the costs of the construction phase, handover and operation phase, and close-out phase*.

The costs of alternatives *in the construction* phase are estimated for 2022 (year 0). According to equation 4.2, the material acquisition cost resulting from buying baked bricks and their dependent substances from suppliers is evaluated as below:

$$MAC_{baked} = 141{,}125 \text{ x } 0.05 + 106.95 \text{ x } 8.39 = 7{,}530.38 \text{ (Euro)} \quad 5.1$$

The total labor hour is estimated based on the total amount of completed channel and the labor productivity rate of labor (18.02 hours per m^3). So, the total cost of labor for construction activities relevant to baked bricks is estimated as below:

$$LB_{baked} = 5{,}787.66 \text{ x } 1.79 = 10{,}359.92 \text{ (Euro)} \quad 5.2$$

The mortar mixed equipment is used to mixed mortar for brick-dependent activities, so its cost is calculated based on equation 4.13, with the total duration of using equipment (92.50 hours) and the cost per hour of using equipment (2.08 Euro/hour). The waste will be crushed to mix with mortar. All results are illustrated in Table 5.3 and Table 5.4, showing that the total cost in the construction phase of concrete bricks is 21,048.56 Euro, higher than the cost of baked bricks, which amounts to 18,082.7 Euro.

Table 5.3. The total cost of baked bricks in the construction phase

	Unit	Amount	Unit Price (Euro)	Total (Euro)	Percentage (%)
Baked Bricks	Blocks	141,125	0.05	6,632.85	36.68
Labors	hour	5,787.66	1.79	10,359.92	57.29
Mortar mixed equipment	hour	92.50	2.08	192.40	1.06
Mortar	m^3	106.95	8.39	897.52	4.96
Total				**18,082.70**	**100.00**

(Source: calculation process)

Table 5.4. The total cost of concrete bricks in the construction phase

	Unit	Amount	Unit Price (Euro)	Total (Euro)	Percentage (%)
Concrete bricks	Blocks	153,638	0.07	10,140.11	48.17
Labors	hour	5,524.30	1.79	9,888.49	46.98
Mortar mixed equipment	hour	86.08	2.08	179.04	0.85
Mortar	m^3	100.21	8.39	840.92	4.00
Total				**21,048.56**	**100.00**

(Source: calculation process)

The tables show that the purchase of bricks and direct labor cost of two alternatives account for the highest proportions in the construction phase (nearly 95%). The cost of baked bricks is 6,632.85 Euro, much lower than 10,140.11 Euro - the cost of concrete bricks. In more detail, the acquisition cost of the concrete brick is higher than the baked brick. However, the labor cost of baked bricks is higher than that of concrete bricks because of the higher amount of required working hours. As a result, the construction cost of baked bricks is lower than the concrete bricks. This means that the baked bricks perform more economic-efficient than the concrete ones in the construction phase. After that, the costs *in the handover and operation phase* are reckoned by converting the repair and maintenance costs to the present value. The discount rate is assumed to be 11% per year, and the expected annual price increase index is 6.5% per year. The expected annual price increase index helps estimate the annual unit price of bricks by multiplying it by the previous year's unit price. Meanwhile, the amount of repairing materials was evaluated according to the overhaul rate and expected annual repairing rate. According to the assumption mentioned above, the overhaul period of baked bricks is 5 years. It means that in the first 25 years the repairing rate of baked bricks is annually 1.5%, and it is increased from 1.5% to 5% in years 5, 10, 15, 20, etc. In the second 25 years, these rates are assumed to be higher (see Table 5.2), because the repairing activities occur annually, but the overhaul/inter-maintenance activities are assumed to occur after every 5 years. For example, the cost of baked bricks in the handover and operation phase in 2023 (year 1) is established as below:

$$MC_{baked,1} = \frac{0.05006 * 141{,}125 * 1.5\% + 8.94 * 1.60}{(1 + 0.11)^{1}} = 108.38 \text{ (Euro)} \qquad 5.3$$

For overhaul maintenance of baked bricks, the cost of baked bricks in the handover and operation phase in 2027 (year 5) is calculated as below:

$$MC_{baked,5} = \frac{0.06439 * 141{,}125 * 5\% + 11.5 * 5.35}{(1 + 0.11)^{5}} = 306.14 \text{ (Euro)} \quad 5.4$$

The cost of concrete bricks is estimated in the same way. According to the input data, the expected costs of concrete bricks and baked bricks in the handover and operation phase are shown in Table 5.5 and Appendix 8.3.

Table 5.5. The costs of baked bricks in the handover and operation phase

Year	Unit Price (Euro/block)	The amount of new materials (blocks)	Unit Price of mortar (Euro/m^3)	The amount of mortar (m^3)	Maintenance cost (Euro)	Present Maintenance cost (Euro)
1	0.05006	2117	8.94	1.60	120.30	108.38
2	0.05331	2117	9.52	1.60	128.12	103.98
3	0.05677	2117	10.14	1.60	136.44	99.77
4	0.06046	2117	10.80	1.60	145.31	95.72
5	0.06439	*7056*	11.50	5.35	515.86	306.14
6	0.06858	2117	12.24	1.60	164.82	88.12
7	0.07304	2117	13.04	1.60	175.53	84.55
8	0.07778	2117	13.89	1.60	186.94	81.12
9	0.08284	2117	14.79	1.60	199.09	77.83
10	0.08823	*7056*	15.75	5.35	706.78	248.92
11	0.09396	2117	16.78	1.60	225.82	71.65
12	0.10007	2117	17.87	1.60	240.49	68.74
13	0.10657	2117	19.03	1.60	256.13	65.96
14	0.11350	2117	20.27	1.60	272.77	63.28
15	0.12088	*7056*	21.58	5.35	968.35	202.39
16	0.12873	2117	22.99	1.60	309.39	58.26
17	0.13710	2117	24.48	1.60	329.50	55.89
18	0.14601	2117	26.07	1.60	350.91	53.63
19	0.15550	2117	27.76	1.60	373.72	51.45
20	0.16561	*7056*	29.57	5.35	1,326.72	164.56
21	0.17638	2117	31.49	1.60	423.89	47.37
22	0.18784	2117	33.54	1.60	451.44	45.45
23	0.20005	2117	35.72	1.60	480.78	43.60
24	0.21305	2117	38.04	1.60	512.03	41.84
25	0.22690	*11290*	40.51	8.56	2,908.35	214.08
26	0.24165	5645	43.15	4.28	1,548.70	102.70
27	0.25736	5645	45.95	4.28	1,649.36	98.54
28	0.27409	5645	48.94	4.28	1,756.57	94.54
29	0.29190	5645	52.12	4.28	1,870.75	90.71
30	0.31088	*11290*	55.51	8.56	3,984.69	174.06
31	0.33108	5645	59.11	4.28	2,121.85	83.50

32	0.35260	5645	62.96	4.28	2,259.77	80.12
33	0.37552	5645	67.05	4.28	2,406.65	76.87
34	0.39993	5645	71.41	4.28	2,563.09	73.75
35	0.42593	*11290*	76.05	8.56	5,459.38	141.53
36	0.45361	5645	80.99	4.28	2,907.12	67.89
37	0.48310	5645	86.26	4.28	3,096.08	65.14
38	0.51450	5645	91.86	4.28	3,297.33	62.50
39	0.54794	5645	97.83	4.28	3,511.65	59.97
40	0.58356	*11290*	104.19	8.56	7,479.82	115.07
41	0.62149	5645	110.97	4.28	3,983.00	55.20
42	0.66188	5645	118.18	4.28	4,241.90	52.97
43	0.70491	5645	125.86	4.28	4,517.62	50.82
44	0.75072	5645	134.04	4.28	4,811.27	48.76
45	0.79952	*11290*	142.75	8.56	10,248.00	93.56
46	0.85149	5645	152.03	4.28	5,457.06	44.89
47	0.90684	5645	161.91	4.28	5,811.77	43.07
48	0.96578	5645	172.44	4.28	6,189.53	41.32
49	1.02856	5645	183.65	4.28	6,591.85	39.64
50	1.09541	5645	195.58	4.28	7,020.32	38.04
Total present maintenance cost						***4,437.81***

(Source: calculation process)

The tables show the present maintenance costs of the two alternatives. As a result, the net present value of maintenance costs of baked bricks and concrete bricks are 4,437.81 Euro and 4,328.86 Euro, respectively. It means that the total present cost of baked bricks is nearly similar to the concrete bricks' one in the handover and operation phase.

In the close-out phase, the materials costs were calculated based on equation 4.25. The costs are the sum of demolition cost, transportation cost, treatment cost, and are reduced by the liquidation value in case of concrete bricks. It is assumed that the recycling rate of concrete brick is 20%. Baked bricks are assumed not to be recycled. The costs are again discounted to achieve a present value, and the results are illustrated in Table 5.6 and Table 5.7.

Table 5.6. Cost in the close-out phase of baked bricks

Content	Unit Price (Euro/ m^3)	Volume of bricks (m^3)	Total cost (Euro)	Present value (Euro)
Demolition cost	106.05	211.90	22,470.86	121.75
Transportation cost to a treatment plant	4,661.34	211.90	987,730.07	5,351.67
Treatment cost	395.75	211.90	83,858.28	454.36
Total cost				***5,927.78***

(Source: calculation process)

Table 5.7. Cost in the close-out phase of concrete bricks

Content	Unit Price (Euro/ m^3)	Volume of bricks (m^3)	Total cost (Euro)	Present value (Euro)
Demolition cost	106.05	212.94	22,581.55	122.35
Transportation cost to a treatment plant	4,661.34	170.35	794,076.59	4,302.43
Treatment cost	395.75	170.35	67,417.10	365.28
Liquidation value	23.31	42.59	992.60	5.38
Total cost				***4,784.67***

(Source: calculation process)

Table 5.6 and Table 5.7 show the total costs in the close-out phase of the two alternatives. Accordingly, the present value of the cost in the close-out phase of concrete bricks is 4,784.67 Euro, while the corresponding present value of baked bricks is 5,927.78 Euro. It means that there is not much difference between the costs in the close-out phase.

The total LCC results of concrete bricks and baked bricks are depicted in Table 5.8.

Table 5.8. The total LCC cost of baked bricks and concrete bricks

	Baked bricks		**Concrete bricks**	
	Value (Euro)	**Percentage (%)**	**Value (Euro)**	**Percentage (%)**
Construction phase	18,082.70	63.56%	21,048.56	69.78%
Handover and operation phase	4,437.81	15.60%	4,328.86	14.35%
Close-out phase	5,927.78	20.84%	4,784.67	15.86%
Total LCC	**28,448.28**	**100.00%**	**30,162.10**	**100.00%**
LCC value in the LCSA method		**0.4854**		**0.5146**

(Source: calculation)

Table 5.8 illustrates that the LCC result of baked bricks (28,448.28 Euro) is lower than the figure of concrete bricks (30,162.10 Euro). Hence, baked bricks are economically advantageous compared to concrete bricks in this project. Besides, it is obvious that the costs of bricks in the construction phase are considerably higher than the cost in other phases. Lastly, the LCC values for the LCSA method (Normalized LCC) are calculated by normalizing the given LCC results. There are several methods for normalizing the results. For example, they can be calculated by rescaling the given LCC results into comparable values (for example, a range from 0 to 1) or estimating based on the reference value. In this thesis, the reference value is the sum of total LCC cost of baked bricks and concrete bricks. The normalized LCC result of baked bricks can be estimated as below:

$$NorLCC_{baked} = \frac{28{,}448.28}{28{,}448.28 + 30{,}162.10} = 0.4854 \quad 5.5$$

The normalized LCC result of concrete bricks is calculated in a similar way, then the normalized LCC results are included in the final LCSA calculation together with the results of the environmental and social assessment. The sensitivity analysis will be conducted for the whole three dimensions of sustainability.

5.2.3. Environmental assessment

The environmental burdens of using concrete bricks and baked bricks are assessed using the LCA analysis. Therefore, the environmental impacts caused by them and the activities related to them are systematically identified and analyzed. The assessment aims to determine the most environmentally-friendly brick alternative based on the LCA results. This serves as decision support in selecting road construction materials. Lastly, it contributes to an LCSA analysis by providing the LCA results for the overall proposed model outlined in section 4.1. For the scope, the estimation is a part of the sustainability performance evaluation, so the functional unit and system boundary of sustainability level's one are the same.

The case study applies the ReCiPe method to estimate the environmental dimension, which includes common impact categories, impact category indicators and characterization factors such as terrestrial acidification, ozone depletion, and climate change (see section 4.2.2). The result of LCA has to be estimated in the single score form due to the LCSA assignment.

After defining the functional unit and system boundary, the *LCI step* is conducted. According to the general flow chart presented in Figure 4.4, a flow diagram comprising relevant activities, and main LCI inputs and outputs impacting the environmental performance is illustrated in Figure 5.3.

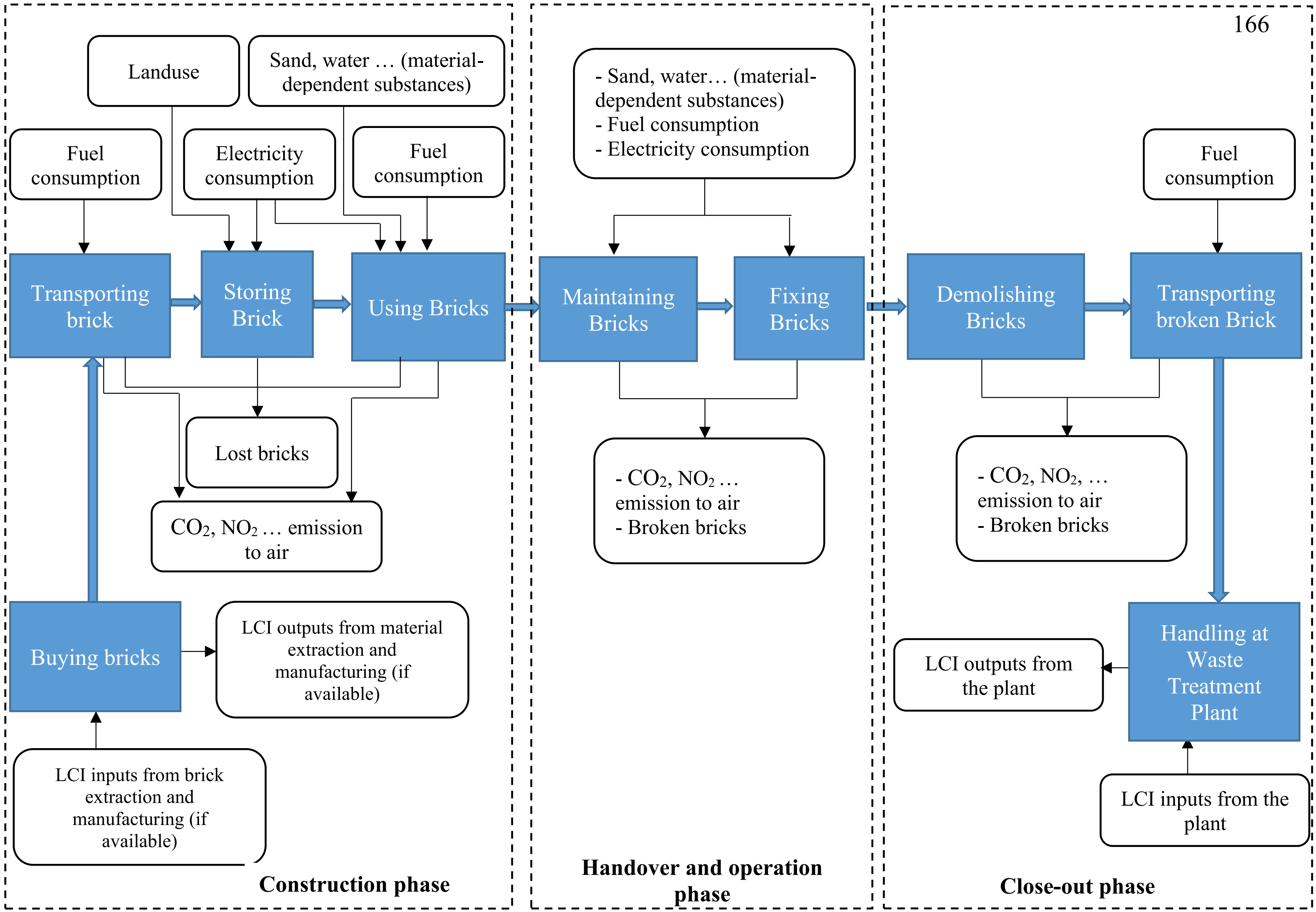


Figure 5.3. The flow diagram of main activities and their LCI inputs and outputs

According to Figure 5.3, the short-haul trucks used in the transportation phase essentially consume fuel and emit toxins (CO_2, CO, and NO_x). In the construction phase, the inputs are mainly sand and water in mortar. The replacement of broken bricks in the maintenance segment considers the amount of bricks and mortar. Regarding the close-out phase, the bricks deconstructed by workers are transported from the construction area to the waste treatment plant and then treated and recycled there.

After that, the data of baked bricks and concrete bricks are collected from various quite reliable sources to estimate the LCI inputs and outputs. For example, the data of vehicle 7 tons in Vietnam is drawn from (Lam et al., 2019) (Tan et al., 2010) and Vietnam National Petroleum Group (Petrolimex, 2021).

Then, the LCI inputs and outputs are related to the reference flow, and then estimated for each phase during the project life cycle (for example, see Table 5.9). The quantitative inputs and outputs are calculated for each unit process.

Table 5.9. The LCI inputs and outputs of concrete bricks in the transportation process

Unit process	LCI Inputs			LCI Outputs		
	Name	**Unit**	**LCI Input value**	**Name**	**Unit**	**LCI Output value**
Brick transportation	*Short-haul truck (from supplier):*			*Short-haul truck (from supplier):*		
	Fuel consumption	litre	14,256	Emission (CO_2,NO_2)		
				CO_2	kilogram	9,626.76
				CO	kilogram	23.56
				HC+ NO_x	kilogram	16.83
				PM	kilogram	2.02
				Lost Bricks	m^3	1.61

(Sources: project data and calculation process)

The other LCI inputs and outputs of the project life cycle are presented in Appendix 8.4 and Appendix 8.5. The total LCI results of alternatives are calculated by summing up the inputs and outputs in Appendix 8.4 and Appendix 8.5 (see Table 5.10).

Table 5.10. The LCI results of baked bricks and concrete bricks during project life cycle

	Unit	The quantity of LCI inputs and outputs	
		Concrete bricks	**Baked bricks**
LCI Input			
Fuel consumption (diesel)	Liter	46,929.60	16,326.00
	kg	39,045.43	13,583.23
Electricity consumption	kWh	443.41	557.59
Water consumption	m^3	243,575.97	319,425.65
Sand	m^3	67.04	87.92
Land use	m^2	100.00	-
LCI Output			
CO_2 emission	tons	31.69	11.02
CO emission	tons	0.08	0.03
HC + NO_x emission	tons	0.06	0.02
Particulate matter emission (PM)	tons	0.0066	0.0023

(Source: calculation from Appendix 8.4 and Appendix 8.5*)*

The findings unfold that the transport of concrete bricks consumes more fuel and also emits exceedingly more CO_2 than CO_2 that of baked bricks. Fuel consumption (diesel) of concrete bricks is 46,929.60 liter, while the value of baked bricks is 16,326 liter. Using concrete bricks also emits 31.69 tons of CO_2, compared to 11.02 tons of baked bricks. Furthermore, only concrete brick alternatives were stored in the warehouse, so the environmental impacts of land-use were only assessed for concrete ones (1 m^2/day * 4 months * 25 days/month).

After estimating the LCI results, the ReCiPe method is adopted to assess the environmental performance of alternatives (*LCIA step*). Here, the environmental impacts of material alternatives are evaluated with respect to the midpoint impact categories. The midpoint indicator assessment is chosen because it is more related to LCI input and output flows and accounts for all cause-effect chains of LCI data (Ismaeel, 2018). The chosen midpoint impact categories include acidification, land use, climate change, fossil resource scarcity, water use, photochemical oxidant formation, particulate matter emission, ozone depletion, and mineral resource depletion. The classification helps to sort the inventory results into impact categories of midpoints (see Table 5.11).

Table 5.11. The classification of LCI results

ID	Midpoint impact category	Relevant LCI inputs and output
1	Terrestrial acidification	SO_2
		NO_x
2	Land use	Occupancy Area
3	Climate change	CO_2
		CH_4
4	Fossil resource scarcity	Raw Coal
		Fuel Oil
5	Water depletion	Water consumption
6	Photochemical oxidant formation: Human health	NO_x
		CO
		NMVOC
7	Photochemical oxidant formation: Terrestrial ecosystems	NO_x
		CO
		NMVOC
8	Fine particulate matter formation	Particulate matter (PM)
9	Ozone depletion	N_2O
10	Mineral resource depletion	Lime

(Sources: LCI inputs/outputs and (Goedkoop et al., 2009; Huijbregts et al., 2017))

The table above assigns LCI inputs and outputs to the midpoint impact categories based on the ReCiPe method (Huijbregts et al., 2017). For example, the category 'Terrestrial acidification' is affected by SO_2 and NO_x, while CH_4 and CO_2 impact the category 'Climate change'. The environmental impact indicators of bricks can be estimated according to equation 4.35. The characterization factors of the impact categories are drawn from ReCiPe such as presented in Appendix 8.6. The result of the *characterization step* is illustrated in Table 5.12 and Table 5.13.

Table 5.12. The impact categories of concrete brick

Midpoint impact categories	Unit	Unit of LCI inputs/outputs	Characteriz-ation factor	LCI inputs/outputs	LCIA result
Terrestrial acidification	kg SO_2 eq.	SO_2	1	70.49	110.02
		NO_x	0.36	109.79	
Landuse	annual crop eq.	Occupancy area	0.55	100.00	55.00
Climate change	kg CO_2 eq.	CO_2	1	62,625.61	62,704.82
		CH_4	84	0.94	
Fossil resource scarcity	kg oil-eq.	Raw Coal	0.42	237.22	

		Fuel Oil	1	0.89	100.52
Water depletion	m^3	Water consumption	1	243,575.97	243,575.97
Photochemical oxidant formation: Human health	kg NO_x eq	NO_x	1	2,097.60	2,169.70
		CO	0.0456	574.74	
		NMVOC	0.18	254.96	
Photochemical oxidant formation: Terrestrial ecosystems	kg NO_x eq	NO_x	1	2,097.60	2,197.75
		CO	0.0456	574.74	
		NMVOC	0.29	254.96	
Fine particulate matter formation	kg PM2.5-eq	Particulate matter	1	8.04	8.04
Ozone depletion	kg CFC-11 eq/kg	N_2O	0.007	23.66	0.17
Mineral resource depletion	kg CU-eq	Lime	0.012	13.30	0.16

(Sources: calculation from Appendix 8.4 and Appendix 8.6)

Table 5.13. The impact categories of baked brick

Midpoint impact categories	Unit	Unit of LCI inputs/outputs	Characteriza-tion factor	LCI inputs/outputs	LCIA result
Terrestrial acidification	kg SO_2 eq.	SO_2	1	26.99	40.74
		NO_x	0.36	38.20	
Landuse	annual crop eq.	Occupancy area	0.55	-	-
Climate change	kg CO_2 eq.	CO_2	1	22,222.68	22,322.29
		CH_4	84	1.19	
Fossil resource scarcity	kg oil-eq.	Raw Coal	0.42	298.31	126.41
		Fuel Oil	1	1.12	
Water depletion	m^3	Water consumption	1	319,425.65	319,425.65
Photochemical oxidant formation: Human health	kg NO_x eq	NO_x	1	40.69	69.77
		CO	0.0456	636.25	
		NMVOC	0.18	0.32	
Photochemical oxidant formation: Terrestrial ecosystems	kg NO_x eq	NO_x	1	40.69	69.80
		CO	0.0456	636.25	
		NMVOC	0.29	0.32	
Fine particulate matter formation	kg PM2.5-eq	Particulate matter	1	2.85	2.85
Ozone depletion	kg CFC-11 eq/kg	N_2O	0.007	8.25	0.06
Mineral resource depletion	kg CU-eq	Lime	0.012	16.73	0.20

(Sources: calculation from Appendix 8.5 and Appendix 8.6)

Table 5.12 and Table 5.13 provide the results of the characterization phase. The environmental impact indicators of bricks obtained at the midpoint level are estimated for ten impact categories, such as climate change, ozone depletion, and terrestrial acidification. These results reveal that the environmental impact of baked bricks is higher than the impact of concrete bricks in water depletion, fossil resource scarcity, and mineral resource depletion. On the contrary, the impact of concrete bricks is greater than the baked bricks' in the remaining impacts, such as terrestrial acidification, climate change, and photochemical oxidant formation. It is assumed that all the midpoint impact categories have the same relevance, meaning that the importance weightings of these categories are identical and neglected. Under this assumption, the total LCA score is tallied based on equation 4.40 by summing up the normalization value of all midpoint impact categories (see Table 5.14).

Table 5.14. The LCA results of baked bricks and concrete bricks

Midpoint impact category	Normalization	
	Concrete bricks	**Baked bricks**
Terrestrial acidification	0.7298	0.2702
Landuse	1.0000	-
Climate change	0.7375	0.2625
Fossil resource scarcity	0.4430	0.5570
Water depletion	0.4326	0.5674
Photochemical oxidant formation: Human health	0.9688	0.0312
Photochemical oxidant formation: Terrestrial ecosystems	0.9692	0.0308
Fine particulate matter formation	0.7385	0.2615
Ozone depletion	0.7416	0.2584
Mineral resource depletion	0.4430	0.5570
Total score (points)	**7.2039**	**2.7961**
LCA value in the LCSA method	**0.7204**	**0.2796**

(Sources: calculation from Table 5.12 and Table 5.13)

The table compares the normalized results of midpoint impact categories. Next, the values are summed up to assess the total score of the two alternatives. The result shows that the summed-up LCA score of concrete bricks (**7.2039** points) is higher than that of the baked ones (**2.7961** points). It means that the baked bricks are prioritized over the concrete bricks regarding environmental performance. Lastly, the LCA values for the LCSA method (Normalized LCA) are calculated by normalizing the given LCA results, similar to the LCC. The sensitivity analysis will be undertaken for all three sustainability dimensions.

5.2.4. Social assessment

For assessing the social performance of baked bricks and concrete bricks, the Social LCA was conducted. Therefore, the social burdens of the bricks and their related activities are systematically identified and analyzed. This allows for identifying the most social-friendly bricks and supports the selection between these two road construction materials. Lastly, it contributes to an LCSA analysis by providing the Social LCA results for the overall sustainability evaluation.

The scope, functional unit, and system boundary in the Social LCA, the LCC and the LCA are the same, as assumed in section 5.2.1. The data are gathered by direct surveys and analyzed systematically. According to section 4.2.3, the subcategories child labor, working hours, health and safety, fair salary, end-of-life responsibility, local employment, secure living conditions, technology development, and fair competition are assessed with respect to the project life cycle. After selecting relevant subcategories, the BRs and main contents of the questionnaires in Table 4.4 and Table 4.5 were applied on the base of Vietnamese laws, Cao Bang province policies, and company records (National Assembly, 2019; PCCB, 2021; The Vietnamese Government, 2022).

Figure 5.4 illustrates the flow chart presenting the main brick-dependent activities and their stakeholders in the construction phase, the handover and operation phase, and the close-out phase, based on the “from cradle to gate” approach. In the construction phase, bricks are transported from the suppliers to the construction area. This transportation may affect the drivers, local community, and society. When the concrete bricks are stored in the warehouse, they may influence the worker, local community, and society. If bricks are used in construction works, they will impact the workers, equipment operators, local community, and society. In the handover and operation phase, brick-dependent activities may affect the worker, suppliers, equipment operators, local community, and society. In the close-out phase, worker, local community, society, and drivers are the main affected stakeholders.

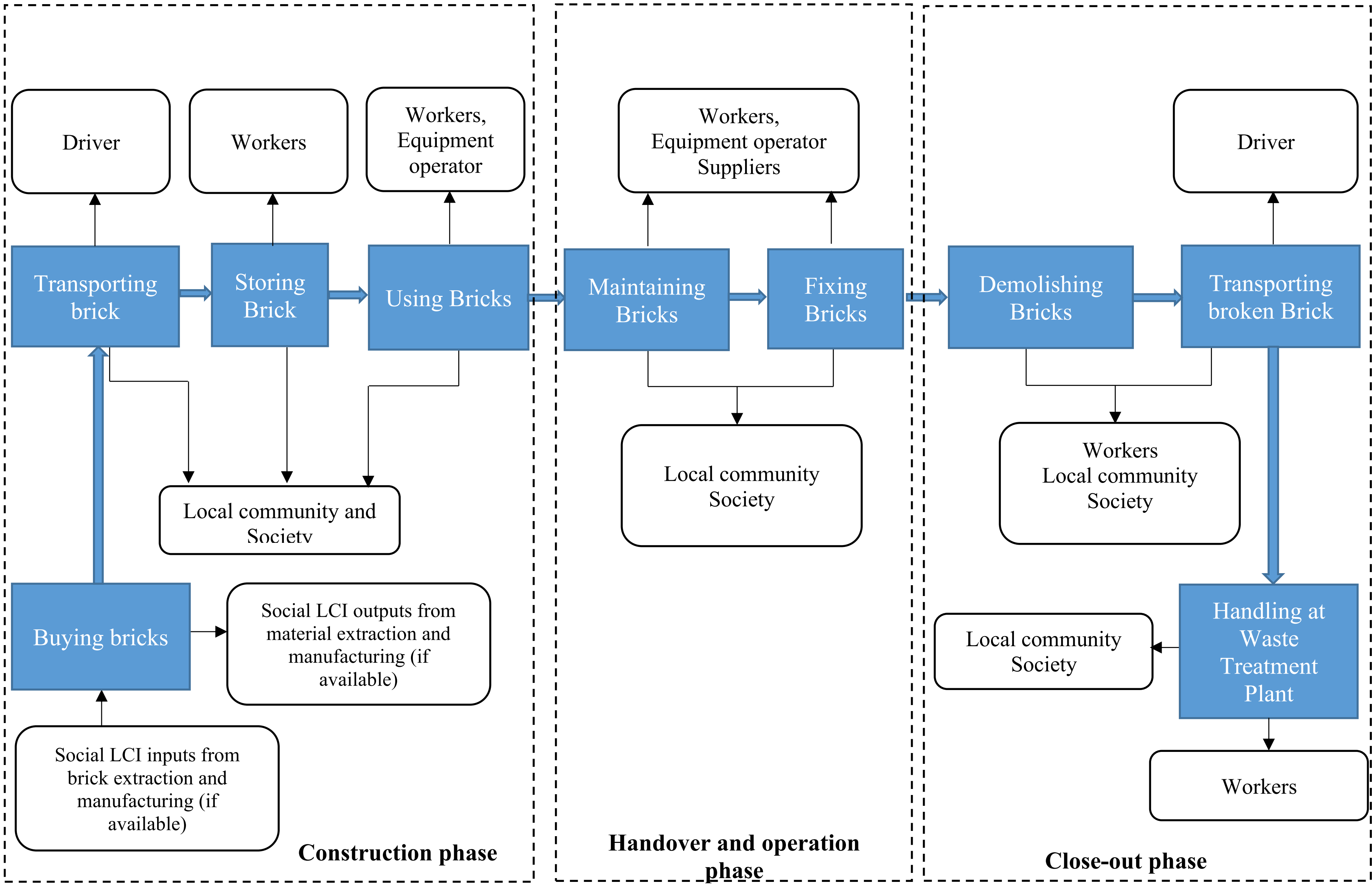


Figure 5.4. The flow chart of activities and their stakeholders for Social LCA

Next, a questionnaire form was created to assess the fulfilment of the Basic Requirements illustrated in Table 4.4. The questionnaire includes two parts (Figure 5.5). The first part introduces the personal information of respondents and their role, and the main questions are presented in the second one. The questionnaire was built according to the main content of the questionnaire in Table 4.4 and Table 4.5.

SURVEY OF SOCIAL LIFE CYCLE ASSESSMENT

Name (Optional) :

Role: **Worker of Contractor**

The project "Provincial road No207 improvement construction project from Quang Uyen to Ha Lang (km 0+00 – km 31+00)" will use concrete bricks as the main material.
This survey is carried out to evaluate the social impact of concrete bricks on the society.
Please answer questions concerning your role in the project:

Stakeholders	Subcategories	Questions	Answer (Yes/No)
Worker	Child labor	Is child labor (less than 16 years old) prohibited in brick-dependent activities?	
		(if yes) Does the organization using the bricks and executing brick-dependent activities have any supports for preventing child labor towards other construction activities?	
		(if no) Does the country have any laws preventing child labor?	
	Working hours	Do employees executing material-dependent activities must work overtime (more than eight hours per day and forty-eight hours per week)?	
		(if no) Does the organization using the material and executing brick-dependent activities have any supports for obeying maximum working hour regulations towards other construction activities?	
		(if yes) Are the working hours higher than the average number of hours in the evaluated region?	
		Do employees executing brick-dependent activities get any policies	

Figure 5.5. The survey form of social life cycle assessment

After finishing the questionnaire, it was sent to respondents. The questionnaires, accompanied by a letter and a stamped addressed return envelope, were sent to 109 selected practitioners via email. The practitioners drawing from the organization's member list have many years of experience in the construction industry (at least 5 years). A total of 81 answers were sent back after two weeks. Details regarding respondents are shown in Table 5.15.

Table 5.15. The respondents of the social life cycle assessment questionnaire

Phases	Respondents	Stakeholders	The number of answers
C	Drivers from suppliers to construction area	Worker	2

C, H	Local community along the transport route	Local community and society	10
C	Workers of the contractor	Worker	14
C	Representative of the contractor	All stakeholders	6
C	Equipment operator of the contractor	Worker	2
C, H, E	Local community near the construction site	Local community and society	9
C, H	Representative of the supplier	Customer	4
H, E	Workers of the owner	Worker	10
H, E	Representative of the owner	All stakeholders	6
H, E	Equipment operator of the owner	Worker	2
E	Driver from the construction area to the waste treatment plant	Worker	2
E	Local community along the waste transport route	Local community and society	8
E	Local community near the waste treatment plant	Local community and society	6
TOTAL			**81**

(Sources: author)

The questionnaires were sent directly to specific stakeholders who are assumed to be impacted by the brick-dependent activities. The respondents were identified based on the flow chart in Figure 5.5, including drivers, workers, local community near the construction site and waste treatment plant, equipment operators, and representatives of the contractor and owner. In addition, the social impacts of respondents are divided into the project life cycle in which they are affected, comprising the construction phase (C), handover and operation phase (H), and close-out phase (E). For example, the answer of "Workers of the owner" is used to assess the social performance of subcategories (child labor, working hours, health and safety, and fair salary) in the handover and operation phase and close-out phase, because the workers of owner are the impacted stakeholder in these two phases. Moreover, the respondents answer the questions related to their role among the stakeholders, which is specified clearly in the questionnaire. For example, respondents of "Local community near the construction site" only answer the question concerning stakeholders "local community" and "society" because they cannot have information concerning "workers" and "customers".

After collecting the data, the answers of each respondent were assigned and classified into the labels A, B, C, or D, according to Table 4.5. For example, the questions seeking information about the labor’s minimum age were applied to analyze the ‘child labor’ subcategory. If the organization does not hire any laborers who are below the age of 16, level A or B is assigned. In contrast to that, the response would be categorized into C or D in case of hiring laborers with an age below 16. Then, for assigning levels A or B, if the organization exhibits (or does not exhibit) proactive support in preventing child labor, it would be labelled with Level A (or B). For selecting between level C and D, level C is labelled on condition that the country does not have a policy related to ‘child labor’. The remaining case is D.

After assigning the letter A, B, C, or D to each participant's response, the social impact subcategories in project’s phases are labeled A, B, C, or D according to the aggregation of assignment’s results (see section 4.2.3). Then, A, B, C, and D levels are assigned to the numeric values in ascending order - 1, 2, 3, and 4, respectively. Moreover, all subcategories are assumed to contribute equally to the evaluation of the social performance of alternatives, so their importance weightings are the same. The social impacts of each subcategory for baked bricks and concrete bricks are presented in Table 5.16 and Table 5.17.

Table 5.16 Social LCA results of baked bricks during the project life cycle

Stakeholders	Subcategories	Construction phase				Handover and Operation phase				Close-out phase			
		Labels	Score	Weightings	Soial LCIA value	Labels	Score	Weightings	Soial LCIA value	Labels	Score	Weightings	Soial LCIA value
Worker	Child labor	A	1	1	1	A	1	1	1	A	1	1	1
	Working hours	D	4	1	4	A	1	1	1	A	1	1	1
	Health and Safety	B	2	1	2	B	2	1	2	B	2	1	2
	Fair salary	C	3	1	3	B	2	1	2	B	2	1	2
Customer	End-of-life responsibility	D	4	1	4	D	4	1	4	D	4	1	4
Local Community	Local employment	B	2	1	2	B	2	1	2	C	3	1	3
	Secure living conditions	B	2	1	2	B	2	1	2	B	2	1	2
Society	Technology development	C	3	1	3	C	3	1	3	C	3	1	3
Other actors of the value chain	Fair competition	B	2	1	2	B	2	1	2	B	2	1	2
Social LCA value for each phase		**23 points**				**19 points**				**20 points**			
Total Social LCA value		**62 points**											

(Sources: project data and calculation process)

Table 5.17 Social LCA results of concrete bricks during the project life cycle

Stakeholders	Subcategories	Construction phase				Handover and Operation phase				Close-out phase			
		Labels	Score	Weightings	Soial LCIA value	Labels	Score	Weightings	Soial LCA value	Labels	Score	Weightings	Soial LCIA value
Worker	Child labor	A	1	1	1	A	1	1	1	A	1	1	1
	Working hours	D	4	1	4	A	1	1	1	A	1	1	1
	Health and Safety	B	2	1	2	A	1	1	1	A	1	1	1
	Fair salary	C	3	1	3	B	2	1	2	B	2	1	2
Customer	End-of-life responsibility	B	2	1	2	B	2	1	2	B	2	1	2
Local Community	Local employment	B	2	1	2	B	2	1	2	B	2	1	2
	Secure living conditions	B	2	1	2	B	2	1	2	B	2	1	2
Society	Technology development	B	2	1	2	B	2	1	2	B	2	1	2
Other actors of the value chain	Fair competition	B	2	1	2	B	2	1	2	A	1	1	1
Social LCA value for each phase		**20 points**				**15 points**				**14 points**			
Total Social LCA value		**49 points**											

(Sources: project data and calculation process)

Based on the results, the total Social LCA values of concrete bricks and baked bricks are calculated by summing up the Social LCIA value of all phases during the life cycle (Table 5.18).

Table 5.18. The Social LCA results of baked bricks and concrete bricks

	Construction phase	Handover & Operation phase	Close-out phase	Total Social LCA value	Social LCA value in LCSA method
Social LCA value of baked bricks	23	19	20	62	0.5586
Social LCA value of concrete bricks	20	15	14	49	0.4414

(Sources: project data and calculation process)

According to the table, it can be seen that the Social LCA value of concrete bricks (49 points) is lower than the value of baked bricks (62 points). It means that the concrete bricks are prioritized over the baked bricks regarding social performance. The total Social LCA values are then normalized in order to enable their integration into the LCSA analysis. After obtaining the normalized values of the LCC, LCA, and social LCA results, the values can be aggregated in the LCSA equation (equation 4.43) to obtain the final LCSA result. The sensitivity analysis will be performed on all three sustainability dimensions.

5.2.5. Sustainability assessment

Integrating the LCC, LCA, and Social LCA by identifying and including trade-offs between their results is important for assessing sustainability performance. It provides a measure that considers all economic, environmental, and social aspects in a consistent way. Figure 4.2 and Figure 4.3 illustrate the procedure model that integrates the LCC, LCA and Social LCA into LCSA. Accordingly, the target value – the LCSA outcome – is evaluated after estimating the importance weightings of economic, environmental, and social aspects.

The weightings of economic, environmental, and social aspects in road construction materials and projects were estimated in a previous paper of the author (and co-authors) (Dinh et al., 2020) by utilizing the AHP method and the Likert Scale. Firstly, they reviewed the background of integrating sustainable development into construction material selection in Vietnam. Secondly, eighteen sustainability criteria, including economic, environmental, and social sub-criteria, were selected by reviewing previous studies, and a questionnaire was established based on the criteria. The questionnaire asked the respondents to evaluate the importance of sustainability criteria in construction material selection. The response rate was 60.78 percent, with 62 useful and fully-filled questionnaires, received from respondents. A sample for a questionnaire for assessing the importance weightings is illustrated in Appendix 8.7. One hundred percent of respondents agreed that incorporating sustainability criteria into Vietnam's material selection is essential. In addition, the result demonstrated that economic criteria were more frequently considered than environmental and social criteria. The average frequency of evaluating economic criteria was 4.39, which is close to the "always" end of the scale. The figures of social and environmental criteria were 3.58 and 3.65, respectively. Thirdly, the questionnaire results were ranked and applied to estimate importance weightings according to the AHP method and the Likert scale. Two of the eighteen criteria were determined to be of "high" importance in the material selection, with relative importance indexes exceeding 0.8. The remaining criteria were ranked higher than 0.6 and marked as "higher average," indicating that they should be used to integrate sustainability into the selection of construction materials. The estimation results also indicated that the "Price of material" which is the price when the contractors or sponsors order from the suppliers had taken the highest priority among the given sustainability criteria. It is also figured out that **42.06, 29.96, and 27.98** are the weightings of the LCC, LCA and Social LCA results, respectively. The weightings were evaluated in order to be applied to the LCSA estimation (equation 4.43).

In this case, the weighting results in a previous paper of the author (and co-authors) (Dinh et al., 2020) are used since they are seen to be quite representative for the preferences of decision-makers in Vietnam. Therefore, the equation of LCSA in the case of Vietnam is proposed as below:

$$LCSA = 42.06 \cdot LCC + 29.96 \cdot LCA + 27.98 \cdot SLCA \qquad 5.6$$

The original equation of the LCSA approach (equation 3.7) evaluates the LCSA value equally. In section 4.1, it was argued that different preferences of decision-makers concerning the single dimensions might exist and should then be included in the assessment. Accordingly, here the predominant criterion is the economic value, while the contributions of environmental and social's aspects are nearly the same. In particular, the LCC value accounts for 42.06% of the LCSA result when the LCA and Social LCA figures are responsible for 29.06% and 27.98% of the LCSA result, respectively.

Based on the results of Table 5.8, Table 5.14, Table 5.18 and equation 5.6, the LCSA value is eventually determined. As a result, Table 5.19 shows the LCSA values of concrete bricks and baked bricks.

Table 5.19. LCSA values of concrete bricks and baked bricks

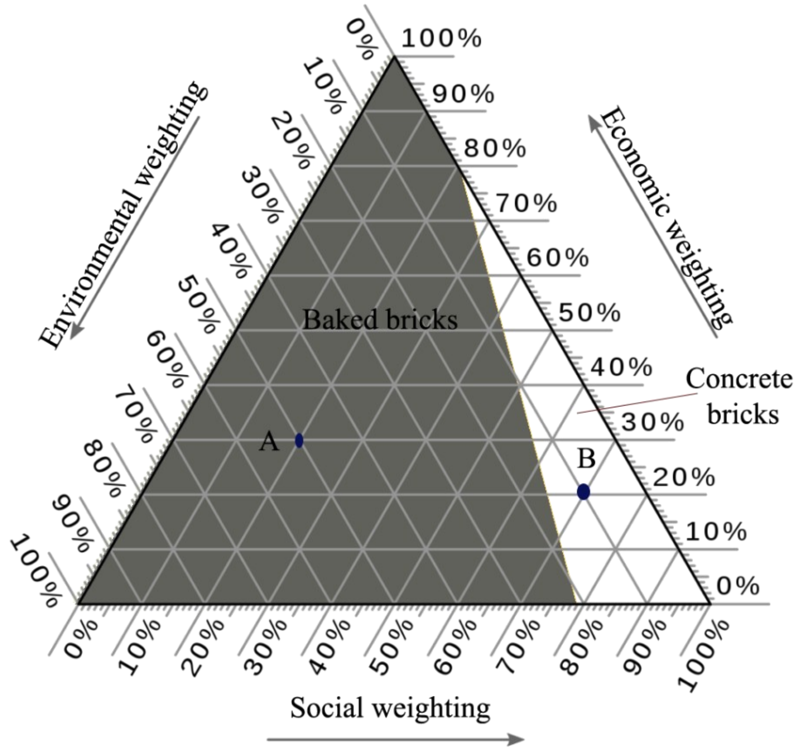
	Normalized LCC value	Normalized LCA value	Normalized Social LCA value	LCSA value
Concrete bricks	0.5146	0.7204	0.4414	55.58
Baked bricks	0.4854	0.2796	0.5586	44.42

(Sources: project data and calculation process)

In consummation, the LCSA value of concrete bricks is higher (55.58) than the figure of baked bricks (44.42). The results show that baked bricks promise a more sustainable performance compared to concrete bricks in this project. Accordingly, the baked bricks should be used to finish the task "Brick Masonry of Channel" in project "Provincial road No207 improvement construction project from Quang Uyen to Ha Lang (km 0+00 – km 31+00)".

A sensitivity analysis concerning the weightings of the sustainability dimensions can be conducted by means of a ternary diagram. A ternary diagram provides a comprehensive picture of the advantageousness of road construction materials in dependence on these weightings. The diagram displays the best alternative for each possible combination of the economic, environmental and social weightings with the weightings represented by the axes (see Figure 5.6). Thereby, the best selections are displayed according to the importance weightings given to the three perspectives of sustainability. Ternary diagrams allow a clear visualization and easy interpretation of the sustainability performance of the alternatives.

Figure 5.6 Sensitivity analysis for life cycle sustainability assessment results in a ternary diagram



(Source: calculation from author)

Figure 5.6 illustrates the zones of advantageousness for baked bricks and concrete bricks, depending on the importance weightings given to each dimension. If the importance weightings are in the grey area, the baked bricks perform more sustainably than the concrete ones. On the contrary, if the weightings are in the white area, the concrete bricks should be chosen. For example, point A (30, 50, 20) in the grey area represents the weighting of 30% for the economic (LCC) result, 50% for the environmental (LCA) result, and 20% for the social (Social LCA) result, respectively. Accordingly, the LCSA result of baked bricks is 39.7128, which is much lower than the value of concrete ones (60.2872), so the baked bricks take priority. Meanwhile, LCSA results are 48.3973 (concrete bricks) and 51.6027 (baked bricks) for point B (20, 10, 70) in the white area. This means that concrete bricks perform more sustainably than baked bricks with respect to these weightings.

6. Conclusions and outlook

6.1. Conclusions

This thesis develops a procedure model based on the LCC, LCA, Social LCA, MCDM methods, and LCSA for assessing the sustainability performance of road construction materials in the preliminary design phase. The proposed model is intended to help designers select the most sustainable materials by addressing the issues that emerged in the preliminary design phase, as described in section 3.1.

In **chapter 1,** the challenges of road construction material selection in the preliminary design phase are introduced briefly. The challenges are pointed out in some studies, such as the lack of detailed guidelines and the negligence of cost items in the preliminary design phase (Andrade et al., 2012; Bragança et al., 2014; Jalaei et al., 2015; Fazeli et al., 2019). According to the given challenges, some practical requirements and theoretical research needs are determined. Based on that, research questions are identified. To answer them, requires some steps of investigation, which will be systematically presented in the following chapters.

Chapter 2 described the definition of some important terms, which set up a foundation for assessing the sustainable performance of road construction materials in the preliminary design phase. For example, a "road construction project" is a long-term construction process in which construction resources (e.g., materials, equipment) are placed, assembled, and transformed until obtaining the completed road (Barbu and Sandu, 2020). "Construction materials" are physical substances making up the completed construction products (Sičáková, 2015), and "Construction material selection" is defined as a process of selecting criteria-based materials (Pfeifer, 2009a). Besides, chapter 2 also describes the road construction procedure, including six main phases: (1) Initiation, (2) Planning and design, (3) Tender/Bidding, (4) Construction, (5) Handover and operation, and (6) Close-out (Netto and Raju, 2017; Trigunarsyah, 2017; Awng, 2018; Dinh and Dinh, 2021). Accordingly, the preliminary design phase is a component of the planning and design phase in which project design criteria, such as its budget and milestones, are established (Feria and Amado, 2019). Moreover, the definitions regarding sustainability are also studied to confirm that the triple bottom line (economic, environmental, and social aspects) should be assessed comprehensively (Elkington, 1999; Norouzi et al., 2017).

Chapter 3 presents and discusses current material selection methods for sustainable development in the preliminary design phase (to answer research questions 1 and 2). Initially, material selection studies conducted in the early design phase were analyzed to determine the relevant issues. The result emphasized that it is difficult to integrate sustainability into material selection in the preliminary design phase. Then, the most important sustainability criteria for selecting road construction materials were identified, covering the economic, environmental, and social dimensions of sustainability. Next, approaches which suggest the application of LCC, LCA, Social LCA, MCDM, and LCSA in road construction material selection are discussed in order to identify their limitations. Selected results are:

- Material-dependent costs, detailed equations, and a lack of information are the primary issues for LCC analysis (Andrade et al., 2012; Feria and Amado, 2019).
- The lack of information and guidelines, the inclusion of potential material-dependent activities, and case studies emerge as the primary issues for life cycle assessment (LCA) (Andrade et al., 2012; Rockizki and Peggy, 2013; Bragança et al., 2014).
- Social location-specific data, available information, and a paucity of case studies are crucial obstacles encountered by the Social LCA (Dong and Ng, 2015; Hossain et al., 2017; Zheng et al., 2020b).
- For integrating the LCC, LCA, and Social LCA into the LCSA, the consideration of trade-offs between the economic, environmental, and social dimensions is the most concerning problem (Dinh et al., 2020).

According to the problems identified in section 3, a procedure model for selecting road construction materials in the preliminary design phase was proposed **in section 4**. The most important objective of this research was the proposal of a detailed model for assessing the sustainable performance of road construction material selection in the preliminary design phase based on the LCC, LCA, Social LCA, MCDM method, and LCSA.

- *Firstly,* a procedure model for evaluating the sustainability performance of road construction materials is described. A decision theory-based procedure model is generated to support designers in making decisions. The model is divided into two levels, with the overall sustainability performance evaluation at the first level and the evaluation of the economic, environmental, and social performances at the second level. Although this procedure model demonstrates some benefits and has been utilized in some cases, the four-step LCA procedure, according to ISO 14044, appears to be more prevalent and well-established. Therefore, it is suggested here to integrate both approaches to provide a basis – the ISO 14044-based procedure model - for answering research question 3. Steps S1, S2 and S3 of the decision theory-based procedure model correspond with the first step of the LCA procedure (goal and scope definition), steps S4 and S5 with the second and third steps of LCA (life cycle inventory analysis and life cycle impact assessment) and, finally, step 6 with the fourth step of LCA (interpretation). As a result, the elements of decision theory-based procedure model (target figures, alternatives, scenarios, outcomes, etc.) are included systematically in the four steps of the ISO 14044-based procedure model. This procedure model contributes to integrating the LCC, LCA, and Social LCA (e.g. with respect to consistency of model building and data acquisition), providing a backbone for the intended development of an instrument for assessing the sustainability of road construction materials (research question 3a).

- *Secondly*, this instrument for assessing the sustainable performance of materials is further developed based on the step-by-step models of three pillars of sustainability (research question 3a). This allows for employing numerical methods from the LCC, LCA and Social LCA and thereby reducing the mistakes from the experience-based selection of designers. The proposed instrument also addresses the challenges of material selection in the preliminary design phase, as identified in section 3.
    - *The LCC* could refine all material-dependent costs incurred during the life cycle and evaluate the material alternatives' total cost. Besides, it defines long-term outcomes by dividing the material life cycle into many consecutive phases and applying the time value of money into the calculation (research question 3b). An LCC model for the economic assessment of road construction materials is developed by building LCC equations. The equations calculate the economic burdens of road construction material alternatives and, thereby, contribute to choosing the most sustainable materials in the preliminary design phase. The model involves all material-dependent activities along the material life cycle and the costs resulting from them. Two scenarios are proposed to solve the problems concerning the lack of available information in the preliminary design phase. Besides, the time

value of money is included in the equations by the usage of the NPV method and discount rate.

- *The LCA* provides knowledge about environmental performance in the construction industry to serve as decision support in selecting road construction materials (research question 3c). In the thesis, an LCA-based methodological approach for assessing the environmental burden of road construction materials in the early design phase is developed. Two scenarios are proposed to solve the problems concerning the lack of available information in the preliminary design phase. Besides, the environmental performance of material-dependent activities, such as the usage of equipment and labor, is also considered in the method.
- *The Social LCA* analysis offers an insight into social performance of road construction materials. The thesis proposes a method based on the Performance Preference Point (PPR) approach and the Subcategory Assessment Method (SAM) method to assess the social performance of road construction materials. In the method, the Social LCI inputs and outputs are collected through a built questionnaire and compared to Basic Requirements to assess social impacts. The method also shows the potential to support the designers in selecting the most social-friendly material by considering the material-dependent activities and stakeholders (research question 3d).
- *The LCSA* is suggested as a comprehensive method for estimating and selecting objects towards sustainable development (Kloepffer, 2008; Fauzi et al., 2019). In the thesis, the LCC, LCA, and Social LCA analyses conform with the life cycle approach, so they can be integrated into the LCSA to come up with the general perspective of sustainable level. It covers all three dimensions in sustainable development during the extraction, manufacturing, construction, handover and operation, and close-out phases. The original model of the LCSA considers the economic, environmental, and social aspects equally (see equation 3.7). However, from the perspective of decision-makers, the importance level of sustainability dimensions might be different. This causes the requirement of estimating the importance weightings for the LCSA model. The study suggests applying the AHP method and Likert Scale to evaluate the weightings, then integrating them into the

LCSA model to assess the general sustainability performance of road construction materials. After that, the ternary diagram is drawn to provide a comprehensive picture of the road construction material selection in dependence on these weightings.

For **section 5,** the assessment of the two alternatives “concrete bricks” and “baked bricks” was conducted as a case study to illustrate and demonstrate the procedure model. The two alternatives are intended to be used for the task “Brick Masonry of Channel” in the project “Provincial road No207 improvement construction project from Quang Uyen to Ha Lang (km 0+00 – km 31+00)”. They were compared by applying the procedure model developed in chapter 4. Firstly, the goal, scope, and system boundary of the case study were defined. The study aims to select the most sustainable material in the project’s preliminary design phase based on the three pillars of sustainable development: economic, environmental, and social aspects. The functional unit is the whole project. Secondly, the economic, environmental, and social aspects were assessed by using the LCC, LCA, and Social LCA. For economic performance, the LCC result of baked bricks (28,448.28 Euro) is lower than the figure of concrete bricks (30,162.10 Euro). Hence, baked bricks perform more economic benefits than concrete bricks in this project. For LCA, the result shows that the summed-up LCA score of concrete bricks (7.2039 points) is higher than the baked ones (2.7961 points). It means that the baked bricks prioritize over the concrete bricks regarding environmental performance. For Social LCA, the concrete bricks prioritize over the baked bricks regarding social performance. Lastly, the LCC, LCA, and social LCA results are integrated into the LCSA by estimating the trade-offs/ weightings between each result. The AHP method and Likert scale were applied to evaluate the weightings of LCC, LCA, and Social LCA results in the LCSA equation. After that, the LCSA value was eventually determined. The LCSA value of concrete bricks is 55.58 higher than the figure of baked bricks (44.42). The results show that baked bricks provide a more sustainable performance compared to concrete bricks in this project. After that, a sensitivity analysis is conducted by using the ternary diagram. The detailed assessments are presented in section 5.

6.2. Outlook

The above section discusses the advantages of the procedure model. The model can be applied to select the road construction material in the preliminary design phase. It takes advantage of the

LCC, LCA, Social LCA, MCDM methods, and LCSA, as well as solves typical problems of the preliminary design phase.

However, the suggested instrument shows some limitations that might be overcome by future work. The "from cradle to cradle" approach is not considered in the system boundary (see section 4.1). Meanwhile, the database of similar projects is not available, especially in developing countries, similar to the latest market information concerning material-dependent activities. In addition, indirect material-dependent activities are neglected. Besides, the procedure model is built upon the LCC, LCA, and Social LCA, so it is subject to the Life Cycle approach's drawbacks.

- In the LCC, cash inflows and cash outflows are the fundamental components of cash flows, and they have to be anticipated explicitly for the whole road construction project life. However, this prediction faces some challenges due to the fact that cash flows depend on a large number of variables, such as influencing factors (environment, labor qualifications), high uncertainty, financial management, and construction conditions (Al-Issa and Zayed, 2007). Moreover, contingency costs, management costs, as well as other indirect costs, are also not featured in this model.
- The LCA method demands an excessive amount of effort in calculating (Finnveden et al., 2009), which induces a significant volume of time expense for assembling and analyzing LCI data. In addition, the estimation relies completely on the availability and completeness of LCI data (Esin, 2007), but there are significant challenges due to the complex comparative criteria or the lack of useful data (Buyle et al., 2013).
- The Social LCA performance is assessed by personal opinion in both two scenarios instead of characterization factors. So, the proposed Social LCA result depends on respondents' assessment instead of numerical calculation (Ramirez et al., 2014; Ramirez et al., 2016).
- Besides, determining the material-dependent activities is a crucial problem. Each construction item requires different construction methods leading to the difference in inputs and outputs for the procedure model. New construction methods also result in changes in material-dependent activities.

Future work can be conducted to improve the procedure model. The "from cradle to cradle" approach was not involved in this thesis due to technological limitations - some road construction materials (such as asphalt and chemical glue) do not meet its conditions (see section 4.1). However, future work should find out solutions which can comprehensively consider this approach. Meanwhile, (Llatas et al., 2020) and (Soust-Verdaguer et al., 2022) affirmed that Building Information Modelling (BIM) can be integrated into the LCSA to evaluate the sustainable performance. While BIM is widely applied in developed countries, implementations in developing countries are uncommon. BIM should be widely applied in developing countries to build a comprehensive database of construction projects. The database from similar road construction projects supports conducting dimension-specific evaluations in scenario (2). Besides, indirect material-dependent activities, such as administration costs and cleaning activities, can be added to the evaluation to improve accuracy. The sustainable performance of the indirect activities can be estimated by using indices and coefficient factors. In addition, a market information database concerning road construction materials should be established to provide the latest material-relevant information, such as the unit price of materials, labor and equipment. The identification of material-dependent activities depends on construction methods, so future work may focus on how to define material-dependent activities in new construction methods. Such future work will contribute to an instrument that enables a significant sustainability assessment of road construction materials in the preliminary design phase and in similar fields of application.

7. References

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8. Appendix

Appendix 8.1. Recent studies for integrating sustainability into the preliminary design phase

References	Research object	Research method	Contributing to integrate sustainability into the preliminary design phase
(Lucchini et al., 2012)	Predict the energy and environmental performances, and their influences in buildings in Italy	Literature review	Establish a simplified method to predict the energy and environmental performances focusing on ventilation, heat recovery, thermal bridge, and solar.
(Andrade et al., 2012; Bragança et al., 2014)	Develop Sustainability indicators for comparing and evaluating the consequences of different building design solutions	Literature review	Set out sustainability indicators for early design phases that contain core indicators (economic and environmental indicators) and additional indicators (economic, social, and environmental indicators)
(Stanescu et al., 2013)	Present a simplified optimization method for heating, ventilation, and air conditioning systems	Literature review and case studies	Provide an optimization method for the preliminary design phase in arranging the heating, ventilation, and air conditioning system by using the zone's daily profile loads

(Kanters et al., 2014)	Identify barriers of existing tools and methods for solar system design	Survey (350 respondents) and interview (23 semi-structured interviews).	Highlight the importance of the solar aspect in the preliminary design phase
(Gharzeldeen and Beheiry, 2014)	Green Design Parameter (GDPs) and their application in UAE construction projects	Survey (a questionnaire consisting of 21 questions was designed and 112 professional engineering respondents resent the questionnaire.	Propose Green Design Parameter (GDPs) that could be applied in the early design phase; these parameters cover green performances, such as CO_2 emission, wastes, and energy consumption
(Zanchetta et al., 2014)	Apply Building Information Modeling into conducting energy simulations	Literature review	Analyze the role of Building Information Modeling as a tool to conduct energy simulations in the schematic design phase (e.g., Revit)
(Rodrigues and Rocha, 2015)	Confirm the importance of the maintenance perspective	Literature review	Confirm the importance of considering the maintenance perspective in the preliminary

			design phase and provide a sustainability guideline from the maintenance perspective.
(Bertoni et al., 2015)	Combine Value-Driven Design and Lean Product Service Development and its application in aerospace product development	Literature review and case studies	Combine Value-Driven Design and Lean Product Service Development Lean Product Service Development in the schematic design phase.
(Grosso et al., 2015)	Use climatic and microclimatic analysis as a tool to optimize the environmental performance of future buildings.	Literature review	Build a guideline supporting designers and suggest climatic and microclimatic analysis to evaluate the environmental performance
(Pancovska et al., 2017)	Analyze the elements impacting the sustainable assessment of the preliminary design phase	Literature review and survey	Identify six important factors for the preliminary design phase's sustainable assessment
(Dong et al., 2016)	Collaborate Building Information Modelling method and explore their application in an ecological sponge exhibition center	Literature review and a case study	Propose technical routes for integrating Building Information Modelling into the preliminary design phase. Establish a guideline for energy conservation design, sunlight analysis, energy efficiency evaluation, natural ventilation design, heating, ventilation, and air conditioning design

(Nesticò et al., 2017)	Build a model to estimate the construction cost and apply the model into estimating the construction cost of a building	Literature review and case studies	Propose a three-step model to estimate the construction cost during the preliminary design phase
(Gültekin et al., 2018)	Build a comprehensive theoretical framework and its relevant criteria.	Literature review	Build a comprehensive theoretical framework regarding dimensions, strategies, criteria, and procedures focusing on sustainable design
(Favi et al., 2019)	Build a data framework relating to the environmental performance of the welding process	Case study	Build a structured data framework for comparing the environmental performance of welding processes in the preliminary design phase
(Bergquist et al., 2019)	An innovative process is developed to bridge the gap between sustainability theory and practical design	Literature review and case studies	Establish an innovative measure for bridging the gap between sustainability theory and practical design in the preliminary design phase. This method focuses on providing a landscape integrating ecological principles, stakeholder perspectives, and practical design strategies
(Marta et al., 2019)	Integrate Building Information Modelling into sustainability assessment in design	Literature review and case studies	Integrate Building Information Modelling into sustainability assessment in design

	processes to address energy and environmental problems. A rail construction project is assumed as a case study.		processes to address energy and environmental problems
(Jin et al., 2019)	Conduct analyses to integrate Building Information Modelling into Building Performance Analysis	Bibliometric analysis, Content analysis, Qualitative discussion	Integrate Building Information Modelling into Building Performance Analysis in the project life cycle and the preliminary design phase to fill the gap between 'as-designed' building performance and 'as-built' performance
(Moghtadernejad et al., 2020)	Provide a new and simplified guideline for designers to achieve a high-performance façade system regarding solar system alternatives. The guideline is applied into a two-story commercial building to be built in Montreal's downtown	Case studies and literature review	Provide a list of criteria to select solar system alternatives in the preliminary design phase.

(Sources: author)

Appendix 8.2. Recent studies for material selection in the preliminary design phase

References	Proposed Method	Advantages	Disadvantages
(Deng and Edwards, 2007)	Reviewing supporting tools in the preliminary design phase	There are several tools supporting the selection	Fewer supporting tools for selecting materials in comparison with the later stages
(Andrade et al., 2012)	set out sustainability indicators comparing different construction solutions, including main materials	Sustainability criteria were proposed	Detailed guidelines for the criteria assessment were not provided
(Rockizki and Peggy, 2013)	Combine technical and environmental dimensions into the material selection	Identify obstacles in the combination. Integrate sustainability in selecting materials.	Social aspects were still neglected.
(Bragança et al., 2014)	Critical indicators were applied to compare material alternatives in the preliminary design phase	Providing economic criteria and environmental criteria	Social criteria are neglected
(Jalaei et al., 2015)	Integrate decision support system (DSS), building information modeling (BIM) and life cycle cost method.	Properly define the energy consumption and its cost during the operation phase Define the alternatives based on owner's priorities and sustainability criteria	Mostly focus on the operation phase The other environmental problems excluded energy consumption,

			and social aspects were not paid attention.
(Zhong et al., 2016)	- Build a model to select materials based on economic sustainability, environmental sustainability, and constructability considerations.	Suggest using structural frame material (SFM) score	Social aspects were neglected.
(Fazeli et al., 2019)	A BIM-integrated TOPSIS-Fuzzy framework	Consider sustainability criteria weights Assess sustainability performance	Mainly focus on building construction projects Effectively applied only in developed countries due to the requirement of BIM and sufficient database.
(Feria and Amado, 2019)	Conducting a survey and proposing a guideline	emphasizing the importance of integrating sustainability into material selection in the early design phase	The guideline was too general without detailed instructions.
(Soust-Verdaguer et al., 2022)	Researching on the preliminary design phase and the detailed design phase	Finding the gap in available data between the early design phase and following design phase. they proposed integrating LCSA and Building	A case study is not conducted, and it is only applicable to developed countries which can apply BIM in the construction industry

		Information Modelling (BIM0	

(Sources: author)

Appendix 8.3. The costs of concrete bricks in the handover and operation phase

Year	Unit Price (Euro/block)	The amount of new materials (blocks)	Unit Price of mortar (Euro/ m^3)	The amount of mortar (m^3)	Maintenance cost (Euro)	Present Maintenance cost (Euro)
1	0.07029	1536	8.94	1.00	116.95	105.36
2	0.07486	1536	9.52	1.00	124.55	101.09
3	0.07972	1536	10.14	1.00	132.65	96.99
4	0.08491	1536	10.80	1.00	141.27	93.06
5	0.09043	1536	11.50	1.00	150.45	89.28
6	0.09630	1536	12.24	1.00	160.23	85.66
7	0.10256	1536	13.04	1.00	170.64	82.19
8	0.10923	*6146*	13.89	4.01	726.94	315.44
9	0.11633	1536	14.79	1.00	193.55	75.66
10	0.12389	1536	15.75	1.00	206.13	72.60
11	0.13194	1536	16.78	1.00	219.53	69.65
12	0.14052	1536	17.87	1.00	233.80	66.83
13	0.14965	1536	19.03	1.00	248.99	64.12
14	0.15938	1536	20.27	1.00	265.18	61.52
15	0.16974	1536	21.58	1.00	282.41	59.03
16	0.18077	*6146*	22.99	4.01	1,203.09	226.53
17	0.19253	1536	24.48	1.00	320.32	54.34
18	0.20504	1536	26.07	1.00	341.14	52.13
19	0.21837	1536	27.76	1.00	363.32	50.02
20	0.23256	1536	29.57	1.00	386.93	47.99
21	0.24768	1536	31.49	1.00	412.08	46.05
22	0.26378	1536	33.54	1.00	438.87	44.18
23	0.28092	1536	35.72	1.00	467.40	42.39
24	0.29918	*6146*	38.04	4.01	1,991.10	162.68
25	0.31863	4609	40.51	3.01	1,590.39	117.07
26	0.33934	4609	43.15	3.01	1,693.77	112.32
27	0.36140	4609	45.95	3.01	1,803.86	107.77
28	0.38489	4609	48.94	3.01	1,921.12	103.40
29	0.40990	4609	52.12	3.01	2,045.99	99.21
30	0.43655	4609	55.51	3.01	2,178.98	95.18

31	0.46492	4609	59.11	3.01	2,320.61	91.33
32	0.49514	10755	62.96	7.01	5,766.72	204.45
33	0.52733	4609	67.05	3.01	2,632.10	84.07
34	0.56160	4609	71.41	3.01	2,803.18	80.66
35	0.59811	4609	76.05	3.01	2,985.39	77.39
36	0.63699	4609	80.99	3.01	3,179.44	74.25
37	0.67839	4609	86.26	3.01	3,386.10	71.24
38	0.72249	4609	91.86	3.01	3,606.20	68.36
39	0.76945	4609	97.83	3.01	3,840.60	65.58
40	0.81946	10755	104.19	7.01	9,543.89	146.83
41	0.87273	4609	110.97	3.01	4,356.11	60.37
42	0.92945	4609	118.18	3.01	4,639.25	57.93
43	0.98987	4609	125.86	3.01	4,940.80	55.58
44	1.05421	4609	134.04	3.01	5,261.96	53.33
45	1.12273	4609	142.75	3.01	5,603.98	51.16
46	1.19571	4609	152.03	3.01	5,968.24	49.09
47	1.27343	4609	161.91	3.01	6,356.18	47.10
48	1.35620	10755	172.44	7.01	15,795.10	105.44
49	1.44436	4609	183.65	3.01	7,209.34	43.36
50	1.53824	4609	195.58	3.01	7,677.94	41.60
Total present maintenance cost						***4,328.86***

(Source: calculation process)

Appendix 8.4. LCI inputs and outputs for the proposed LCA analysis of concrete bricks

Unit process	LCI Input			LCI Output		
	Name	**Unit**	**Total LCI input value**	**Name**	**Unit**	**Total LCI output value**
Brick transportation	*Short-haul truck (from supplier):*			*Short-haul truck (from supplier):*		
	-Fuel consumption	litre	14256	-Emission (CO_2,NO_2)		
				CO_2	kilogram	9,626.76
				CO	kilogram	23.56
				HC+NO_x	kilogram	16.83
				PM	kilogram	2.02
				-Loss Bricks	m3	1.61
Storing in the warehouse	*Land use*	m^2	100.00			
	Light					
	-Electricity consumption	kWh	21.12	Loss bricks	m3	0.96

Construction	*Related material:*			*Waste Materials*	m3	4.82
	-Water	m3	109,226.89	*Short-haul truck (to waste treatment plant):*		
	-Sand	m3	30.06	-Emissions (CO_2, NO_2)		
	Equipment (mortar mixer 80l)			CO2	kilogram	48.62
	-Electricity consumption	kWh	189.37	CO	kilogram	0.12
	Short-haul truck (to waste treatment plant):			$HC+NO_x$	kilogram	0.09
	-Fuel consumption	litre	72.00	PM	kilogram	0.01
Operation and Maintenance	*Related material:*			*Damaged bricks*	m^3	395.05
	-Water	m^3	134,349.08	*Short-haul truck (from supplier):*		
	-Sand	m^3	36.98	-Emissions (CO_2, NO_2)		
	Short-haul truck (from supplier):			CO_2	kilogram	14,586.00
	-Fuel consumption	litre	21,600.00	CO	kilogram	35.70
	Equipment (mortar mixer 80l)			$HC+NO_x$	kilogram	25.50
	-Electricity consumption	kWh	232.92	PM	kilogram	3.06
	Short-haul truck (to waste treatment plant):			*Short-haul truck (to waste treatment plant):*		
	-Fuel consumption	litre	7,200.00	-Emissions (CO_2, NO_2)		
				CO_2	kilogram	4,862.00
				CO	kilogram	11.90
				$HC+NO_x$	kilogram	8.50
				PM	kilogram	1.02
Close-out phase	*Short-haul truck (to waste treatment plant - 20% is recylced)*			*Short-haul truck (to waste treatment plant - 20% is recylced)*		
	-Fuel consumption	l/km	3,801.60	-Emissions (CO_2, NO_2)		
				CO_2	kilogram	2,567.14
				CO	kilogram	6.28

				$HC+NO_x$	kilogram	4.49
				PM	kilogram	0.54

(Sources: data from the project and stakeholders)

Appendix 8.5. LCI inputs and outputs for the proposed LCA analysis of baked bricks

Unit process	LCI Input			LCI Output		
	Name	Unit	Total LCI input value	Name	Unit	Total LCI output value
Brick transportation	*Short-haul truck (from supplier):*			*Short-haul truck (from supplier):*		
	-Fuel consumption	litre	234.00	-Emission (CO_2,NO_2)		
				CO_2	kilogram	158.02
				CO	kilogram	0.39
				$HC+NO_x$	kilogram	0.28
				PM	kilogram	0.03
				-Loss Bricks		1.61
Storing in the warehouse	*Land use*	m^2				
	Light					
	-Electricity consumption	kWh		Loss bricks	m^3	
Construction	*Related material:*			*Waste Materials*		4.82
	-Water	m^3	116,578.70	*Short-haul truck (to waste treatment plant):*		
	-Sand	m^3	32.09	-Emissions (CO_2, NO_2)		
	Equipment (mortar mixer 80l)			CO2	kilogram	48.62
	-Electricity consumption	kWh	203.50	CO	kilogram	0.12
	Short-haul truck (to waste treatment plant):			$HC+NO_x$	kilogram	0.09
	-Fuel consumption	litre	72.00	PM	kilogram	0.01
Operation and Maintenance	*Related material:*			*Damaged bricks*	m3	558.85
	-Water	m^3 per m^3 cement	202,846.95	*Short-haul truck (from supplier):*		

	-Sand	m^3 per m^3 cement	55.83	-Emissions (CO_2, NO_2)		
	Short-haul truck (from supplier):			CO_2	kilogram	364.65
	-Fuel consumption	l/km	540.00	CO	kilogram	0.89
	Equipment (mortar mixer 80l)			$HC+NO_x$	kilogram	0.64
	-Electricity consumption	kWh	354.09	PM	kilogram	0.08
	Short-haul truck (to waste treatment plant):			*Short-haul truck (to waste treatment plant):*		
	-Fuel consumption	l/km	10,800.00	-Emissions (CO_2, NO_2)		
				CO_2	kilogram	7,293.00
				CO	kilogram	17.85
				$HC+NO_x$	kilogram	12.75
				PM	kilogram	1.53
Close-out phase	*Short-haul truck (to waste treatment plant):*			*Short-haul truck (to waste treatment plant):*		
	-Fuel consumption	l/km	4,680.00	-Emissions (CO_2, NO_2)		
				CO_2	kilogram	3,160.30
				CO	kilogram	7.74
				$HC+NO_x$	kilogram	5.53
				PM	kilogram	0.66

(Sources: data from the project and stakeholders)

Appendix 8.6. The characterization factors of midpoint impact categories

ID	Midpoint impact category	Unit	Characterization factor	Inverventions	CF value
1	Terrestrial acidification	kg SO_2 eq.	Terrestrial acidification potentia	SO_2	1
				NO_x	0.36
2	Landuse	annual crop eq.	Land transformation/ occupation	pasture and meadow	0.55
3	Climate change	kg CO_2 eq.	Global warming potential	CO_2	1
				CH4	84

4	Fossil resource scarcity	kg oil-eq.	Fossil depletion potential	Raw Coal	0.42
				Fuel Oil	1
5	Water depletion	m3	Water depletion potential	Water consumption	1
6	Photochemical oxidant formation: Human health	kg NO_x eq	Human health ozone formation potential	NO_x	1
				CO	0.0456
				NMVOC	0.18
7	Photochemical oxidant formation: Terrestrial ecosystems	kg NO_x eq	Ecosystem ozone formation potential	NO_x	1
				CO	0.0456
				NMVOC	0.29
8	Fine particulate matter formation	kg PM2.5-eq	Particulate matter formation potential	Particulate matter	1
9	Ozone depletion	kg CFC-11 eq/kg	Ozone depletion potential	N_2O	0.007
10	Mineral resource depletion	kg CU-eq	Surplus ore potential	Lime	0.012

(Sources: (Goedkoop et al., 2009; Huijbregts et al., 2017; RIVM, 2020))

Appendix 8.7. The form of questionnaire for estimating the importance weightings

QUESTIONNAIRE FOR SUSTAINABILITY CRITERIA IN CONSTRUCTION MATERIAL SELECTION IN VIETNAM

The following questions ask you about your experience in construcion material selection.
Please circle (O) the best suitable answer

	Question	1 = Low; 2 = Lower average; 3 = Average; 4 = Higher average; 5 = High				
	Evaluate the importance of these sustainable criteria when you select the material in Vietnam?					
A	**Economic criteria**	**1**	**2**	**3**	**4**	**5**
A1	Price of materials	1	2	3	4	5
A2	Cost of the material transport	1	2	3	4	5
A3	Cost in the construction phase	1	2	3	4	5
A4	Cost in the operation and maintenance phase	1	2	3	4	5
A5	Cost in the demolition phase	1	2	3	4	5
B	**Environmental criteria**	**1**	**2**	**3**	**4**	**5**
B1	Energy consumption	1	2	3	4	5
B2	Water consumption	1	2	3	4	5

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Chemnitz, 11.2022

Trong Hung Dinh