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Including embodied energy in the energy analysis of the Dutch built environment

MSc Thesis report

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Abstract

About 40 % of the final energy demand in Europe is related to the built environment. Therefore efforts in lowering this demand are crucial when it comes to reaching the EU ambition targets of reducing the CO_2 emissions related to energy use. Until recently these efforts have mainly been focussed on lowering the operational energy of buildings. There are, however, other important energy demanding processes involved over the life cycle of a building, which can be quantified using embodied energy (EE) analysis. The Energy Performance of Buildings Directive (EPBD) states that all new buildings in the EU must be 'nearly zero-energy buildings' by 2020 (European Commission, 2010). This prospective increase in buildings with low operational energy demand further emphasizes the importance of studying EE. However, the standardisation of EE analysis still requires improvements; Dixit et al. (2010) found that there are large variations and inconsistencies among calculated EE figures. This present research has used literature review and expert interviews to: 1) Determine to what extent EE analysis is currently implemented in the analysis of the Dutch built environment, 2) Identify possible areas for improvement, by determining how the factors identified by Dixit et al. (2010) are currently considered, and 3) Develop guidelines for an accurate EE calculation method that addresses these factors correctly, which can be used for EE analysis of the Dutch built environment.

The first part of the research has resulted in an overview of the most common methods which are used for the sustainability assessment of the Dutch built environment. The consideration of EE in these methods has been assessed and this has shown that EE is considered by using total energy demand figures to calculate the related environmental impact. EE is however not used as a separate indicator and the outcome of these sustainability assessments can therefore not be used for EE analysis. The second part of the research has resulted in an overview of the factors identified by Dixit etal. (2010), explaining the implications per factor. These factors have been used throughout this research to determine the quality of the different methods of EE calculation and sustainability assessment. The third part of the research has resulted in guidelines that recommend how a novel EE standard, focussing on the Dutch built environment, should address these factors in order to limited variations and inconsistencies. Next to these guidelines, four different pathways have been identified which can be used to calculate EE figures that represent the Dutch built environment: 1) Calculating EE figures using data from the National Environmental Database, 2) Calculating EE figures directly from Ecoinvent data, 3) Developing a novel standard and database for EE figures, and 4) Calculating EE figures from a combination of data sources. Further analysis of these pathways has showed a preference for pathway 3 and 4. It is expected that pathway 3 will result in the most accurate EE figures. However, this pathway also has several disadvantages: 1) Time-consuming, 2) Risk of doing 'double work', and 3) Expected difficulties with data collecting. Pathway 4 will be less time-consuming because it makes use of already available data. Because it is expected that most of the data is available from Dutch branch-organisations, only a small share of the data will have to be based on generic data (e.g. Ecoinvent), limiting the variations and inconsistencies.

In order to determine which pathway is best chosen further research is needed. Next to the findings from further research and the considerations discussed in this research, this decision also depends on the application of this potential EE database and the time and resources available to establish such a database.

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1. Introduction

1.1 Scientific background

About 40 % of the final energy demand in Europe is related to the built environment (European Commission, 2010). Therefore efforts in lowering this demand are crucial when it comes to reaching the EU ambition targets of reducing the CO_2 emissions related to energy use. Until recently these efforts have mainly been focussed on lowering the operational energy of buildings. Examples of these efforts are the increasing insulation standards for both newly build houses and renovation projects and the increasing energy efficiency for lighting and appliances. There are, however, other important energy demanding processes involved over the life cycle of a building. Figure 1 depicts an overview of the life cycle phases of a building. The first phase includes all the (upstream) processes involved to produce the construction materials and to transport these to the construction site. The second phase includes all the processes involved in the actual construction of a building. The third phase consists of all the processes involved when the building is used over its lifetime, including maintenance and refurbishment. The final life cycle phase of a building is the end-of-life phase which includes all the processes involved in the deconstruction of the building and treatment of this deconstruction waste. All these phases over the life cycle of a building have an energy demand and should therefore be included in the energy analysis of a building.

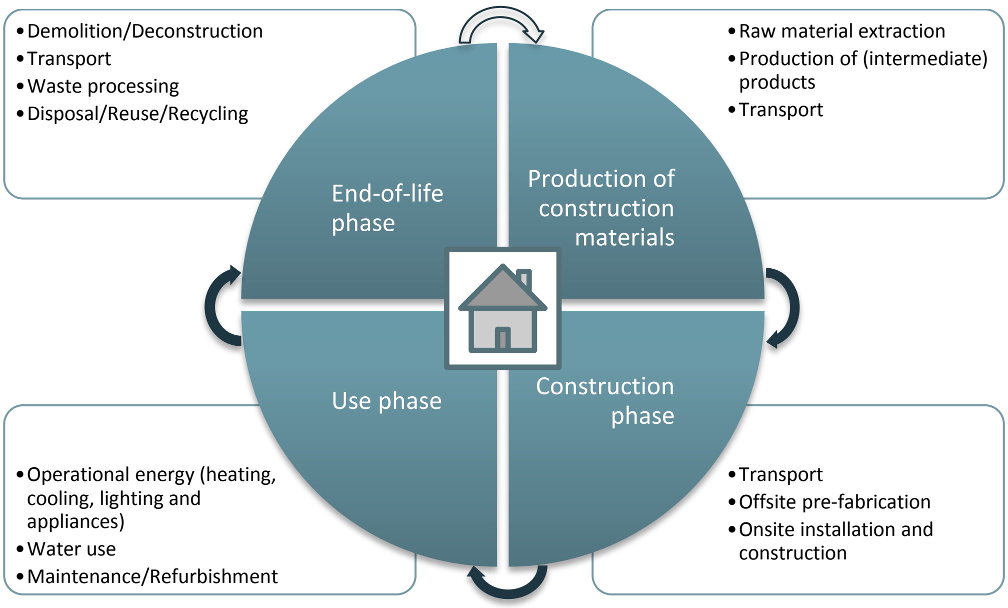

Figure 1 Life cycle phases of a building.

The Embodied Energy (EE) of a building is defined as the total primary energy requirements related to the construction process and construction materials that are used, over the complete life cycle (Jones and Hammond, 2008). Therefore, this includes all the life cycle phases depicted in Figure 1, except the operational energy demand (heating, cooling, electricity and water use). Ideally the calculation of EE would therefore include all processes in these life cycle phases, from raw material extraction until the end-of-life treatment of the construction materials.

The share of EE on the total life cycle energy demand of a building has been studied by several authors (Hall, 2011; Hestnes and Sartori, 2007; Verbeeck and Hens, 2010a). These authors argue that for buildings where little effort has been made to reduce the operational energy, by for example better insulation, this share of EE is relatively small, ranging from around 10 to 25% of the total life cycle energy demand. This lower share of EE compared to operational energy is the reason why most efforts of reducing the energy demand of buildings have been focused on lowering the operational energy. These efforts have resulted in a trend towards lower operational energy demand in buildings, which in turn has changed the relative importance of EE. It has also been argued, by the previously mentioned authors, that the share of EE over the total life cycle of buildings with low operational energy demand is much higher. For example, Verbeeck and Hens (2010b) argued that for some building designs with a low operational energy demand, the EE share could be higher than the operational energy. As a result, the relevance of the share of EE over the life cycle of a building increases. The Energy Performance of Buildings Directive (EPBD) states that all new buildings in the EU must be ‘nearly zero-energy buildings’ by 2020 (European Commission, 2010). This prospective increase in buildings with low operational energy demand further emphasizes the importance of studying EE.

Calculating EE is a complex process because of the multitude of processes involved and the lack of reliable data to base these calculations on (Langston and Langston, 2008). Dixit et al. (2010) studied the calculation of EE applied in several case studies. They found that there are large variations and inconsistencies among calculated EE figures. From this research it was also concluded that there are multiple factors that cause this variation and inconsistency; Table 1 provides an introduction to these identified factors.

Table 1 Introduction to the factors that cause variations and inconsistencies in EE calculation, as identified by Dixit et al. (2010).

Factors identified	Short description
System boundaries	Between case studies large differences in defined system boundaries can be seen, making the results incomparable.
Methods of EE calculation	Variation in the applied method (process analysis, input/output analysis or a hybrid analysis), is causing variation in the results.
Geographic location of the study	Different geographic locations can differ in raw material quality, production processes, economic data, processes of delivered energy generation, transport distances, energy use (fuel) in transport and labour, which can result in variation between EE figures.
Primary and delivered energy	To make EE figures comparable, calculations should be based on primary energy.
Age of data sources	The efficiency of (industrial) processes might change over time, therefore the age of the data sources is an important factor.
Source of data	The source of (generic) data relates to the method used for data acquisition and geographic location, therefore this can be a major contributor to the variations and inconsistencies found.
Data completeness	The completeness of (generic) data is related to the system boundaries and therefore this can also be a major contributor to the variations and inconsistencies found.
Technology of manufacturing processes	Several technologies could be available for manufacturing one material, with differences in efficiency and energy demand. The choose between technology can have a major effect on the calculated EE figures.
Feedstock energy consideration	Feedstock energy is the energy embedded in materials which are used as ingredients in the production process of a final material. Alternatively, this embedded energy could also be used for direct energy use (as fuel) or indirect energy use (electricity). Inconsistencies are found between EE studies on the consideration of feedstock energy.
Temporal representativeness	Due to data availability some studies might have to include data from old technologies, which again has an effect on the EE figures.

From the description of the identified factors in Table 1 it can be concluded that all these factors are related to data acquisition and calculation of EE figures. The identified factors require various methodological decisions that need to be made, resulting in various possible pathways for collecting data and calculating EE figures. Standardisation and the development of guidelines for calculating EE have the potential to diminish variations and inconsistencies in EE calculation (Dixit et al., 2012). The standards which are currently available for Life Cycle Assessment (LCA) (International Organization for Standardization (ISO), 2006a, 2006b) have been applied for the calculation of EE in several of the case studies studied by Dixit et al. (2010). The results of this study by Dixit et al. (2010) has shown that these standards do not solve the issue of variations and inconsistencies in EE calculation, since these standards still allow different pathways of calculating EE. An example of this are the system boundaries; this has been mentioned by various authors as an important flaw of the standards, since it has been defined in such a way that it is open for misinterpretation and does not state clear rules on what to include and exclude in the calculations (Dixit et al., 2012).

To be able to calculate accurate EE figures and apply these figures in building design analysis and energy policies, standards are needed which deal with the factors that cause variations and inconsistencies in EE calculation. These standards can then be used for the calculation of EE figures. A database with EE figures will provide possibilities for important energy analyses of the built environment, which will contribute to lowering the total energy demand related to the built environment.

1.2 Problem definition

Recent efforts in reducing the energy demand of the built environment have mainly been focused on the operational energy of buildings. With the shift towards more energy efficient buildings with lower operational energy, the relative importance of studying EE is increasing. There are however difficulties with calculating the EE of a building. Large variations and inconsistencies can be seen between studies (Dixit et al., 2010). If EE calculations are standardised in greater detail, these calculated figures can be better applied to building designs and policies. This improvement in standardisation will diminish the variations and inconsistencies in EE calculation, resulting in increased comparability between energy figures. Therefore, research is needed to 1) Optimize the methods used for calculating EE of buildings and 2) Implement EE in buildings energy analysis and policies to achieve a minimal energy demand.

By 2020 all new buildings in the Netherlands must be ‘nearly zero-energy buildings’, following the EU-targets (European Commission, 2010). Therefore studying EE of buildings will become increasingly important in the context of reducing the energy demand in the Dutch built environment. In this context research is needed to: 1) Determine to what extent EE is currently implemented in the analysis of the Dutch built environment, 2) Identifying possible areas for improvement, by determining how the factors identified by Dixit et al. (2010) (Table 1) are currently considered, and 3) To develop an accurate EE calculation method that addresses these factors correctly, which can then be used for EE analysis of the Dutch built environment.

1.3 Research questions

To address the identified problem the current research project has answered the following **main research question:**

How do the factors causing variation and inconsistencies in EE calculation need to be addressed in order to develop an accurate method for EE calculations used in the Dutch built environment?

To be able to answer this main research question this research has been divided into the following sub-research questions:

Sub-research question 1:
How is EE currently considered in building energy analysis in the Netherlands?

Currently EE is to some extent included in building energy analysis in the Netherlands. For example, the 2012 Dutch building decree[1] requires that starting from 2013, all permit applications for buildings larger than 100 square meter ask for an environmental performance calculation (*Milieuprestatieberekening*) (Stichting Bouwkwaliteit, 2011). This calculation includes the environmental impact of the materials used for construction. In this part of the research the role of EE within this environmental performance calculation has been determined. Also, an overview has been given of other sustainability assessment methods which are used for the analysis of the Dutch built environment, including an analysis of the consideration of EE in these methods. Current Dutch energy regulatory schemes and energy labelling schemes have also been analysed to determine the (potential) role of EE in these schemes. This gained knowledge has been used to look for improvements in the methods used for the EE calculations in the Netherlands.

Sub-research question 2:
What factors are causing the current problems with variation and inconsistency in EE calculation?

To be able to look for improvements in the methods used in the Netherlands, the first step has been to assess what problems have occurred in other studies. The factors that are involved in the found variation and inconsistency in EE figures (Table 1) have been used as guidelines for the identification of improvements in these used methods. Therefore, these factors identified by Dixit et al. (2010) have been thoroughly studied to understand the implications of each factor. This gained knowledge has then been used to determine how these factors are considered in the current building energy analysis in the Netherlands.

Sub-research question 3:
How can this gained knowledge be used to develop guidelines for EE calculations?

The gained knowledge thus far has been used to develop guidelines on how to address the factors that are causing variation and inconsistencies in EE calculation applied to analyses of the Dutch built environment.

[1] The Dutch Buildings Decree (*'bouwbesluit'*) contains the technical regulations that represent the minimum requirements for all structures in the Netherlands.

1.4 Method

An overview of the main steps that have been followed to answer the research questions is depicted in Figure 2.

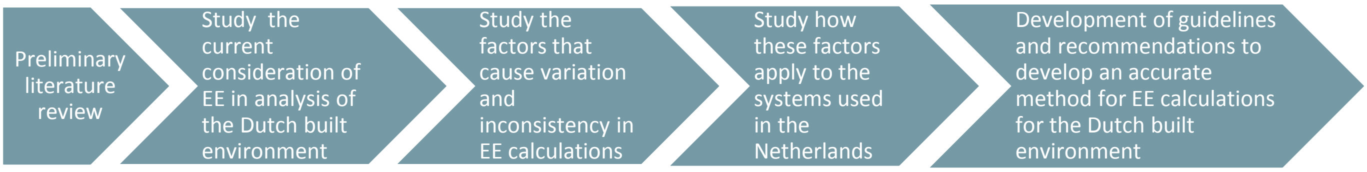

Figure 2 Schematic overview of the followed research steps

As can be seen from Figure 2, the first step of this research has been to conduct a literature review to identify the knowledge gap and the scientific background. From this preliminary literature review the research questions have been defined. The next three steps, after the preliminary literature review, have been followed to answer the first two sub-research questions. The results of this part of the research have contributed to the final research step; the development of guidelines and recommendations on how to develop an accurate method for EE calculations to be used in the Dutch built environment. These last four steps have also been used to structure the findings from the research in this report, as can be seen in section 1.5.

Throughout this research the following methods have been applied:

- Literature review
- Expert Interviews

Literature review has not only been used to identify the knowledge gap and the scientific background but has also been an important method used in all other research steps. Academic literature has been consulted throughout this research project to get a better understanding on the current knowledge about EE analysis of the built environment. For the assessment on the current consideration of EE in analysis of the Dutch built environment publicly available literature has been consulted, such as: literature from the websites of commercial sustainability assessment tools/databases and regulations regarding the Dutch built environment. **Expert Interviews** have been conducted as a second method for data collection. These interviews have been conducted with important institutions involved in sustainability assessment of the Dutch built environment. This has been done to: 1) Validate the findings from the literature review, and 2) Gain additional information and insights that can be a valuable contribution to answering the research questions. Both these methods will be further explained in the corresponding chapters, as described in section 1.5.

1.5 Structure of report

Following this introduction chapter, two theoretical chapters will describe the findings from the literature review. *Chapter 2: Consideration of EE in the (Dutch) built environment,* will report on the findings from literature review regarding the first sub-research question. *Chapter 3: Current problems with variation and inconsistency in EE calculation*, will report on the findings from literature review regarding the second sub-research question. Both these theoretical chapters start with a section explaining in detail the method used for the literature review. This will be followed by Chapter 4: Interviews. This chapter will report on the results from the expert interviews and the method which has been used to conduct these interviews. This report will end with Chapter 5: Discussion and Conclusions, this chapter will discuss the results from this research and conclude on the research questions by summarising the findings and recommendations. Figure 3 shows a flow diagram of the structure of the report.

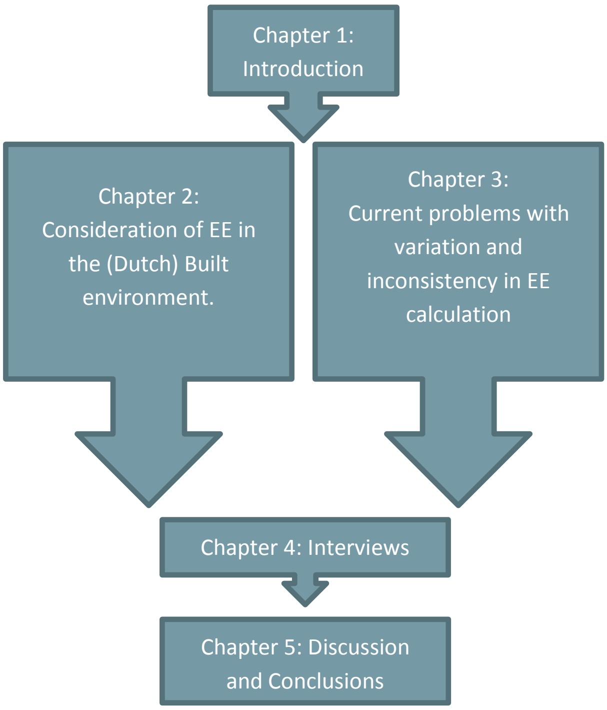

Figure 3 Flow diagram of the structure of the report.

2 Consideration of EE in the (Dutch) built environment.

This chapter gives answer to the first sub-research question: *How is EE currently considered in building energy analysis in the Netherlands?.* This chapter starts with a detailed description on how the literature review was conducted. After this the results are reported. The first section of the results lists some examples where EE has been included in the energy analysis of buildings. These examples are described in order to get a better understanding of the potential of using EE figures. In the second place, an assessment of the consideration of EE in buildings energy regulation and certification schemes is presented. The chapter ends with an overview of the current sustainability assessment methods used in the Netherlands and a discussion about the consideration of EE in these methods.

2.1 Method

The results of the literature review in this chapter have been subdivided into three result sections: 2.2) The potential of including EE figures in buildings energy analysis, 2.3) EE considerations in buildings energy regulation and certification schemes*,* and *2.4) The consideration of EE in the Dutch built environment.* The methods used are explained per result section:

Section 2.2) ***The potential of including EE figures in buildings energy analysis***

Literature review has been conducted in this section in order to give the reader an introduction of the current use of EE analysis in scientific research. The focus has been on searching for studies that show the potential of EE analysis in the context of lowering total energy demand of the built environment. This has been done by using the literature found in the preliminary literature review as a starting point to look for relevant references to other literature. Additionally, novel literature search has been conducted.

Section 2.3) ***EE considerations in buildings energy regulation and certification schemes***

In this section literature review has been conducted in order to give the reader an introduction about the consideration of EE in buildings energy regulation and certification schemes. The focus has been on assessing: 1) The current EE consideration, and 2) The importance of EE consideration in buildings energy regulation and certification schemes. This again has been done by using the literature found in the preliminary literature review as a starting point to look for relevant references to other literature. Additionally, novel literature search has been conducted.

Section 2.4) The consideration of EE in the Dutch built environment

Another approach has been used for the third result section of this chapter. The first step has been to establish a list of the most important sustainability assessment methods used in the Netherlands. This included the *milieuprestatieberekening* (as described in section 1.3), Dutch energy labelling schemes and other sustainability assessment methods. The second step has been to determine the current consideration of EE in these methods. Publicly available literature has been consulted for both these steps. This publicly available literature consisted of information from the websites of commercial sustainability assessment tools/databases and regulations regarding the Dutch built environment. This has resulted in a table listing the most important sustainability assessment methods used in the Netherlands and the consideration of EE in these methods. After this table each method is described in more detail, including a discussion about the consideration of EE. Additionally, scientific literature review has also been conducted for this section; this has been done using the same method as described for the literature review of the first two result sections of this chapter.

2.2 The potential of including EE figures in buildings energy analysis

Several authors have explored the possibilities for reducing EE in the built environment. Despite of the identified difficulties with EE calculations these studies have shown the potential of including EE in buildings energy analysis. One of the ways to reduce the EE of a building is to use low energy demanding materials. The most common materials used for the main structure of a building are concrete, steel and wood. EE analyses have been applied in several studies where these three materials have been compared (Buchanan and Honey, 1994; Upton et al., 2008). These studies show the benefits of using wood; Upton et al. (2008) argued that wood-based structures could have 15-16% less EE than steel and concrete based structures. Goverse et al. (2001) asserted that an increase in the use of wood for construction of Dutch residential buildings has the potential to reduce CO_2 emission by 50% compared to traditional construction where steel or concrete are used. A reduction in EE can also be achieved by using recycled materials for construction. Thormark (2000) asserted that EE savings of 55% are possible when recycled materials are used instead of new construction materials. The techniques used for construction also show potential for reducing the EE. Switching from traditional construction methods to modern methods of construction, which involve prefabrication and off-site assembly of components and modules, has the potential to significantly reduce the EE (Monahan and Powell, 2011). Another approach is to recover the EE of materials at the end of a buildings lifecycle. Thormark (2006) explored the possibilities for reducing EE of a low energy building in Sweden by material substitution, allowing for recycling and recovering of EE. This has shown that EE of this particular building can be reduced by 17%. It does however also emphasise that the design of a building is important for the recycle potential; buildings which are designed for disassembly have a larger potential for EE recovery. As another approach, EE figures can also be used for studying policies and regulations focussed on reducing energy consumption in the built environment. An example of this is a study conducted by Mandley in 2014. This study has explored several energy saving scenarios related to the UK built environment to determine which scenario will results in maximum energy savings.

2.3 EE considerations in buildings energy regulation and certification schemes

Despite the importance of including EE in buildings energy analysis, EE figures are still left out of (most) building energy regulation and certification schemes which are applied in the European Union. The primary focus of most of the buildings energy regulation and certifications systems is operational energy demand. This has the effect that these systems are not able to: 1) Reduce the total energy demand of the built environment, and 2) Reduce the negative environmental impact associated with the built environment (Casals, 2006). Not including EE figures in energy certifications schemes may have the result that buildings which are certified as being 'efficient' actually consume more energy (over its life cycle) than buildings which are not, which sends out the wrong incentive to the market. The Energy Performance of Buildings Directive (EPBD) (European Commission, 2010) obligates involved countries to implement a building energy certification scheme in their regulations; as a result numerous building energy certification schemes have been developed, using different tools and methods. The next section will elaborate on the energy certification schemes used in the Netherlands and the consideration of EE in these schemes.

2.4 The consideration of EE in the Dutch built environment

This section gives information about regulation and energy certifications schemes used in built environment of the Netherlands. Next to these obligatory schemes an overview will be given of voluntary buildings energy certification methods and life cycle assessment based methods which are available to assess the sustainability of a building. The consideration of EE will be assessed for all these available methods and energy schemes. Table 2 shows an overview of the different systems that are used in the Netherlands. Following this table, each method will be explained in more detail and the consideration of EE will be discussed.

Table 2 Overview of buildings regulation, energy certifications schemes and sustainability assessment methods used in the Netherlands.

	Description	Developers	Primary source of data	EE consideration
Energy Performance Coefficient	The EPC is an obligatory calculation of the theoretically operational energy consumption of a newly constructed building.	Dutch Government	-	no
The Energy Label	An obligatory energy labelling scheme for buildings that are constructed, sold or rented. Result is a label from A till G representing the operational energy efficiency of a building. An EPC can be converted into this Energy label and for existing buildings an EPA can be conducted to get an energy label.	Dutch Government	-	no
BREEAM-NL	BREEAM is a widely recognized system for sustainability certification of buildings. BREAAM has been first developed and applied in the UK, but now has several international versions based on the same principles, including BREEAM-NL for the Netherlands. It supports Greencalc+ and GPR-building as tools for assessment and has an own tool: The DGBC-material tool.	DGBC	National Environmental Database (NMD)	yes
Eco-quantum Research	A tool developed to lower the environmental impact of building designs. The Research version is the comprehensive version to be used for research and extensive assessments. This tool is still used, but no longer supported by the developers.	IVAM and W/E advisers	NMD	yes
Eco-quantum Domestic	This Domestic version is developed for architects to quickly assess the environmental impact of building designs. This tool is still used, but no longer supported by the developers.	IVAM and W/E advisers	NMD	yes
GreenCalc+	This tool provides the user with a single score output on the sustainability of a building: 'the environmental index'. It can also be used for other indices such as the energy label and EPC. As of the beginning of 2012 the support has been transferred to the Dutch Green Building Council (BGDC) to be developed into a BREEAM tool.	*Stichting Sureac* and DGBC	NMD + own addition	yes
GPR-Building	To be used in the design phase of a building. It can also be used for other indices such as the energy label and EPC and is supported by BREEAM-NL to be used for assessment.	Municipality of Tilburg and W/E advisers	NMD	yes
DGBC-Material tool	Based on the Greencalc method, uses the 'shadowcosts-method' to calculate and compare environmental impact. Used for BREEAM-NL certification.	DGBC	NMD	yes
NIBE Environmental classifications building materials	LCA based method used for the sustainability rating of building products. The materials which have the lowest environmental impact in a product group qualify for a 'DUBOkeur' certificate.	NIBE	NMD + own model 'TWIN2001'	yes

As can be seen from Table 2, EE is not considered in the obligatory regulations EPC and the energy label. In the voluntary sustainability assessment methods EE figures are considered. These methods make use of environmental data related to the processes involved over the lifecycle of a building, including energy demand figures of these processes. This data is then used to calculate environmental impact related to construction materials without including total EE figures as an output of these calculations. Therefore, EE is considered in these methods, but total EE figures cannot be extracted from the results.

There is also a noticeable similarity between the sustainability assessment methods; all these methods, are making use of the same database: The National Environmental Database (Dutch: *Nationale milieudatabase*[2]) (NMD). Therefore, this database plays an important role in the further development of these methods and the potential inclusion of EE figures. The NMD is further elaborated in section 2.4.2. From the section describing BREEAM-NL, it can also be seen that this sustainability certification system supports the use of three of the listed tools; Greencalc+, GPR-building and the DGBC-material tool. This suggests that there is very little variation between these sustainability assessment methods.

2.4.1 Obligatory energy and sustainability assessments of buildings

2.4.1.1 Energy Performance Coefficient

In 1995 the energy performance coefficient (EPC, Dutch: *Energie Prestatie Coëfficiënt*) was introduced in the Dutch Buildings Decree (Dutch: *Bouwbesluit*) of the Netherlands. This made it obligatory for newly constructed buildings to include an EPC calculation. The EPC is a calculation of the theoretically operational energy consumption of a building, assuming typical behaviour of residents and typical outdoor temperatures. For newly constructed buildings there is a minimum EPC that needs to be achieved in order to allow for realisation of the building project. Since the introduction of the EPC this minimum value has been adjusted several times, to account for technological developments and ensure the effectiveness of the policy. An obligatory system like this will result in a trend towards lower operational energy demanding buildings. This is important because, as described in the introduction, the highest share of the total energy demand of a building is the operational energy. However, EE also has a significant share in this. Therefore, if EE figures were to be included in the EPC, this scheme has the potential to be more effective when it comes to lowering the total energy demand of the built environment in the Netherlands.

2.4.1.2 The Energy Label

At the beginning of 2008 an obligatory energy labelling scheme for buildings was introduced in the Netherlands, as an implementation of the EPBD. This policy states that an energy label must be delivered for buildings that are constructed, sold or rented. The results are labels ranging from A to G, rating the operational energy performance of a building. Similar label schemes are used in the European Union for electrical appliances and vehicles, following European guidelines. Using a similar system has the advantage that the public is already familiar with these labels, allowing for a better understanding of its meaning than for example the EPC which has a coefficient as outcome. For newly constructed buildings the EPC results can be converted into this energy label. For existing buildings an Energy Performance Advise (EPA, Dutch: *Energie Prestatie Advies*) can be conducted. This EPA follows a similar method as the EPC and will result in an energy label. An EPA is also often conducted voluntary by building owners since not only the energy label is provided but also a list of recommendations on how to lower operational energy demand. The energy label is intended to increase the awareness of the public on the (operational) energy performance of a building. This scheme therefore has the potential to lower the operational energy demand of the Dutch built environment, for example if these labels are used by the public as criteria for selecting a building to rent or buy. However, if EE figures were to be included, this scheme has the potential to be more effective in lowering the total energy demand of the built environment in the Netherlands.

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[2] https://www.milieudatabase.nl/

2.4.1.3 Environmental Performance Calculation

The 2012 Dutch Building Decree states that starting from 2013, all permit applications for buildings larger than 100 square meter need an environmental performance calculation (Dutch: *Milieuprestatieberekening*). This calculation includes the environmental impact of the materials used for construction and should be performed following standards defined in *Bepalingsmethode Milieuprestatie gebouwen en GWW-werken* (SBK standard) (Stichting Bouwkwaliteit, 2011). Although this environmental performance calculation is obligatory, there are currently no limit values set which have to be reached for the realisation of a building project. Also, at this moment there are no penalties if this calculation is not conducted. The intention of this scheme is to introduce the construction sector to analysis of the environmental performance of building projects and to possible environmental performance demands to be set in the future. It is the first obligatory scheme introduced in the Netherlands that considers the upstream and downstream processes of a building, instead of considering only operational processes. Because of the relation between energy use and environmental impact, this scheme can eventually also result in reduction of EE demand of buildings, but this does not appear to be the primary focus. The sustainability of a building project can be assessed using various criteria, Ding (2008) for example defined ‘the sustainability index’ which considers four main criteria: 1) Maximise wealth, 2) Maximise utility, 3) Minimise resources and 4) Minimise impact. If these criteria are used, the focus of this environmental performance calculation can be categorized under the criterion of minimising impact, whilst EE analysis is more focussed on minimising resource use. Therefore, to get a more complete sustainability assessment of the upstream and downstream processes, it would be better if EE figures were to be included in the environmental performance calculation.

2.4.2 The National Environmental Database

The NMD consists of environmental profiles of building materials, which have been calculated following the SBK standard, and is set up to be used for the environmental performance calculation. This database is managed by *Stichting Bouwkwaliteit* (SBK) which also provides part of the environmental profiles. However, this database has been set up to allow external companies to deliver environmental data. The data delivered by these external companies has to be validated, following a protocol defined by SBK. The main requirement is that the delivered data has to be calculated using the previously mentioned SBK standard. Amongst other definitions, this standard states that for the data-collecting the software Simapro should be used in combination with the Ecoinvent 2.2 database and the CML-2 impact assessment method. (This SBK standard is further discussed in section 3.3.4)

2.4.3 LCA based methods for sustainability assessment of buildings

Apart from the obligatory energy labelling scheme and EPC there are multiple voluntary methods available to assess the sustainability of buildings in the Netherlands. The following sections provide the reader with a short elaboration of these sustainability assessment methods.

2.4.3.1 BREEAM-NL

This assessment method is the Dutch version of BREEAM (Building Research Establishment Environmental Assessment Method), a method developed in the United Kingdom in 1990. Internationally, BREEAM is the most widely recognized method for certifying and assessing the sustainability of buildings (Seo, 2002). The sustainability of a building is rated by comparing it to a benchmark building, which is considered to be 'sustainable'. This environmental rating uses nine categories for assessment: Management, Health and Comfort, Energy, Transport, Water Consumption, Materials, Land Use, Site Ecology and Pollution. As the result of the assessment a building gets a star rating from 1 to 5, representing: Pass, Good, Very Good, Excellent or Outstanding. The BREEAM-NL system works on harmonizing the different sustainability measurements of buildings and supports the use of two well-known tools used in the Netherlands: GPR-Building and Greencalc+. BREEAM-NL also has its own tool to be used for the assessment: DGBC-Material tool. As mentioned before, EE is considered in this method by incorporating it in the assessment of the environmental impact of building materials. However, the focus of the assessment of environmental impact is different than that of EE analysis (as discussed in section 2.4.1.1), and can therefore have different results. Using this method might not have the desired effect of lowering the total life cycle energy demand of a building, but the focus will instead be on lowering the environmental impact over the life cycle of a building (Ding, 2008). Another reason why EE might not be used to its full potential in the assessment method BREEAM is because it allows for compensation between impact categories (Casals, 2006). The nine categories that are used to assess the sustainability of a building result in one final rating and therefore it allows for compensation between these nine categories. As for EE, this can for example have the result that the environmental impact score of materials (which uses EE figures for its calculation) is compensated with the score of operational energy (Casals, 2006). This way buildings with high EE can still be rated as the (environmentally) preferable choice.

2.4.3.2 Eco-Quantum

This tool has been developed by IVAM and W/E advisers in 1999. The main purpose of this tool is to improve the environmental aspects of new building designs, before they are realised, instead of providing a score which can be used to compare with other buildings. There are two versions available; the Eco-Quantum Research which is the comprehensive version to be used for research and extensive assessments, and the second version, the Eco-Quantum Domestic which is developed for architects to quickly assess the environmental impact of building designs. This tool makes use of the Simapro software from the Dutch PRé consultants BV., and input data comes from the NMD. The environmental impact is subdivided into four assessment criteria: Natural resources (energy/materials/water), Environmental loading (emissions/waste), Land use and Biodiversity. Whilst the support from the developers has recently stopped and no new updates are provided, both versions of Eco-Quantum are still widely used. Similar to the other voluntary sustainability assessment methods, EE is considered in this method by incorporating it in the assessment of the environmental impact of building materials. Therefore, EE might not be used to its full potential in this assessment method (as discussed in 2.4.3.1).

2.4.3.3 Greencalc+

Greencalc+ is a tool developed by *Stichting Sureac*. It provides the user with a single score output on the sustainability of a building: 'the environmental index'. This index is determined by assessing three sustainability themes: use of materials, water and energy. It can also be used for the calculation of other indices such as the energy label and EPC. As of the beginning of 2012 the support has been transferred to the Dutch Green Building Council (BGDC) to be developed into a BREEAM tool. Similar to the other voluntary sustainability assessment methods, EE is considered in this method by incorporating it in the assessment of the environmental impact of building materials. Therefore, EE might not be used to its full potential in this assessment method (as discussed in 2.4.3.1).

2.4.3.4 GPR-Building

GPR-Building has been developed by the municipality of Tilburg and W/E Advisers, to be used in the design phase of a building. Based on the EPC method, GPR-Building gives a sustainability rating from 0 to 10 and when a building is rated with at least a 7, it is considered to be 'sustainable'. It can also be used for other indices such as the energy label and EPC. Similar to the other voluntary sustainability assessment methods, EE is considered in this method by incorporating it in the assessment of the environmental impact of building materials. Therefore, EE might not be used to its full potential in this assessment method (as discussed in 2.4.3.1).

2.4.3.5 DGBC-Material tool

This tool has been developed by the DGBC for the BREEAM-NL assessment and is based on the Greencalc+ method. The environmental impact are rated using the 'shawdowcost-method', where the environmental impact are translated into monetary units; the financial needs to resolve the caused environmental effects. Similar to the other voluntary sustainability assessment methods, EE is considered in this method by incorporating it in the assessment of the environmental impact of building materials. Therefore, EE might not be used to its full potential in this assessment method (as discussed in 2.4.3.1).

2.4.3.6 NIBE Environmental classifications of building materials

NIBE (*Nederlands Insituut voor Bouwbiologie en Ecologie*) has developed this method for the sustainability rating of building materials. The results from NIBE are widely used for sustainable building projects to choose between building materials. This LCA based method applies the 'shawdowcost-method' to compare the environmental impact of materials. As an addition to the data from the NMD, this tool makes use of the TWIN2001 model to assess the noise nuisance of road transport. The environmental impact is subdivided in four categories: Emissions, Resources, Land Use and Nuisance. The materials which have the lowest environmental impact in a product group qualify for a 'DUBOkeur' certificate. Similar to the other voluntary sustainability assessment methods, EE is considered in this method by incorporating it in the assessment of the environmental impact of building materials. Therefore, EE might not be used to its full potential in this assessment method (as discussed in 2.4.3.1).

2.5 Summary

This chapter has shown the importance of EE analysis in the context of reducing the total energy demand related to the built environment. Despite this, it can be concluded from this chapter that EE is still not very well integrated in the analysis of the Dutch built environment. In the obligatory energy and sustainability schemes used in the Netherlands EE is not considered at all, whilst these schemes might have the largest potential to lower the total energy demand of the Dutch built environment. It is therefore important to assess the possibilities of including EE analysis in these obligatory schemes. In the voluntary sustainability assessment methods EE is considered by incorporating it in the assessment of the environmental impact of building materials. It would be a valuable contribution if EE figures were to be included as an outcome of these analyses. Including EE figures will increase the possible applications of these results and contribute to lowering the total energy demand of the construction sector. It has also been shown that all the sustainability assessment methods make use of the same database for the calculations; the NMD. Therefore, this database plays an important role in the further development of these methods and the potential inclusion of EE figures.

3 Current problems with variation and inconsistency in EE calculation

This chapter gives answers to the second and third sub-research question: *What factors are causing the current problems with variation and inconsistency in EE calculation?* And*, How can this gained knowledge be used to develop guidelines for EE calculations?.*

Section 3.1 of this chapter explains how the literature review has been conducted. After this, section 3.2 elaborates on the factors that cause variation and inconsistency in EE calculation, providing a detailed description and possible solutions to limit this. Section 3.3.1 consists of a literature review about the current use of standards in EE calculation. Section 3.3.2 reports on the importance of regional standardisation. Section 3.3.3 will discuss an example of regional standardisation of EE calculations: the ICE database. Finally, section 3.3.4 analyses the current use of standards in sustainability assessments of the Dutch built environment and will give some guidelines (from a theoretical perspective) for improvements.

3.1 Method

The method used for the literature review in this chapter is explained per sub-research question:

<u>Sub-research question 2:</u>
What factors are causing the current problems with variation and inconsistency in EE calculation?

An extensive literature review has been conducted to answer this research question. Using the factors identified by Dixit et al. (2010) as a starting point, the current discussion about variation and inconsistency in EE calculations has been assessed to fully understand how this applies to EE calculations in the Dutch built environment. The first step has been to study the definitions of the factors from Dixit et al. (2010). This gained knowledge was used for further literature review, in order to determine if other EE studies mentioned similar problems with variation and inconsistency of the results.

<u>Sub-research question 3:</u>
How can this gained knowledge be used to develop guidelines for EE calculations?

Dixit et al. (2012) has been used as a starting point for the literature review of the current role of standardisation in EE calculations. Additional literature review was done by: 1) Following references from Dixit et al. (2012) and 2) Novel literature search. Results of this literature review are shown in section 3.2. This has been done to determine how the current standardisation in EE calculations deals with the factors that cause variation and inconsistency in the EE figures. The identification of necessary improvements here has contributed to the development of guidelines for EE calculations.

The literature review focussed on regional standardisation has been done using the ICE database (Jones and Hammond, 2008) as a starting point. Additional literature review was done by: 1) Following references from Jones and Hammond (2008), and 2) Novel literature search. Results of this literature review are shown in sections 3.3.1, 3.3.2 and 3.3.3. This has been done to determine how other standardisations in EE calculations deal with the factors that cause variation and inconsistency in the EE figures. These examples have contributed to the development of guidelines for EE calculations.

Following this, in section 3.3.4, the current use of standards in sustainability assessments of the Dutch construction sector has been assessed. For this the SBK standard (Stichting Bouwkwaliteit, 2011) was thoroughly studied to determine how the factors that cause variation and inconsistency are considered. This has been done to identify necessary improvements if these standardisations are to be used for EE calculations.

3.2 Factors that cause variation and inconsistency in EE figures

3.2.1 System boundaries

The variation and inconsistencies found due to definition of system boundaries is a known problem in LCA (Suh, 2006). The inclusion of all upstream processes, whether this is for the calculation of environmental impact or EE, is never possible using just process data. If the processes are followed upstream the number of possible pathways will increase until an accurate calculation is no longer possible (Nässén et al., 2007). To avoid this a system boundary must be defined in the analysis to determine which processes are included and which are excluded from the analysis. However, the definition of system boundaries is not done in a consistent way between authors. The truncation error that comes with this subjective choice of system boundaries can result in the exclusion of certain important energy inputs for the calculation of EE, resulting in invalid results which are incomparable between EE studies (Suh et al., 2006) (Lenzen, 2000). To limit these variations and inconsistencies there is a need to develop a consistent system boundary selection method (Dixit et al., 2010).

3.2.2 Methods of EE calculation

There are several methods available for the calculation of EE, each method has a different way of collecting data and dealing with truncation. Therefore the method applied plays a significant role in the found variation and inconsistency between EE figures. This section will describe the most commonly used methods.

3.2.2.1 Process-based analysis

Process-based analysis is a common method used for the calculation of EE and is considered to deliver an accurate result (Dixit et al., 2010). This method calculates the energy requirements for each separate process upstream of the final product, usually including 3 or 4 orders of upstream processes. The energy requirements are usually calculated in MJ per kilogram of material produced in the upstream process and in the end this is multiplied with the total mass of that material in the final product (Bassett and Waldron, 2013). However, this method has the disadvantage that truncation of the system boundaries (as described in section 3.2.1) is inevitable. This truncation occurs because in this method each upstream process needs to be analysed separately to calculate the energy requirements, resulting in an exhaustive amount of work to include all processes in the analysis (Dixit et al., 2010). Because of this truncation the end results are often incomplete (but the results for the processes which have been included are accurate), the magnitude of this incompleteness has been estimated to be as high as 50% (Lenzen and Treloar, 2006).

3.2.2.2 Input/output-based analysis

An input/output (I/O) table maps the relationships between compartments of a system ((Miller, R.E. and Blair, 1985) as cited by (Treloar et al., 2001)). The I/O tables used for EE analysis describe economic flows between different sectors of industries for of a political region or country. Thus, with these I/O tables it can be determined how much (economic) input is required from all the different sectors to deliver one final product (with a certain economic value) produced in one specific sector. In the I/O-based analysis for EE calculations these economic flows are converted into energy flow by multiplying the cost of the product by the energy intensity of that product (Dixit et al., 2010). As a result this will give an overview of how much energy is required from each sector to produce a final product in one specific sector. This method is considered to be complete since it includes nearly all sectors within an economy and is therefore not suffering from truncation errors as much as process-based analysis. However, the literature review by Dixit et al. (2010) concludes that I/O-based analysis suffers from systematic errors such as the assumptions of homogeneity in I/O tables and errors in this economic data and the data used to calculate energy intensities. According to Bassett and Waldron (2013), using I/O-based analysis does however show benefits when it is used for a study covering a larger economic zone (such as the EU or South East Asia). These larger zones often have their own I/O table available which can be used for analysis. Using this, the analysis does not suffer from the inaccuracies caused by using several sources of data for the different countries.

3.2.2.3 Hybrid analyses

Hybrid analyses have been developed to combine the process-based analysis with the I/O-based analysis to limit the errors and combine the benefits of both methods to develop a more accurate method. The two most common hybrid analyses are described in this section.

i. Process-based hybrid

This hybrid method uses process-based analysis as the primary method for data collecting of the main production processes. However, to deal with the previously mentioned incompleteness of this process-based analysis, complex upstream processes are calculated using the I/O-based method (Dixit et al., 2010). Often the direct processes such as construction and maintenance and the downstream processes such as end-of-life treatment are calculated using process-based analysis (Suh et al., 2006). I/O-based analysis is used for the complex upstream processes such as raw material extraction and manufacturing of intermediate materials (Suh et al., 2006). Using this hybrid method does however come with the risk of double counting (Suh et al., 2006) and can be difficult for complex final products which are made from many other materials (Dixit et al., 2010).

ii. Input/Output-based hybrid

This hybrid method uses I/O-based analysis as the primary method for data collecting. Additionally process-based analysis is applied to important sectors of industries which play a significant role in the production process of the studied product (Suh et al., 2006). Nevertheless, there is a risk of double counting when this method is applied, but several solutions have been suggested on how to deal with this (Suh et al., 2006). Overall this method is considered to be complete and currently the most accurate method available for LCA and EE analysis of buildings (Crawford, 2004).

3.2.3 Geographic location of the study

Different geographic location of EE studies can be a significant reason for the found variations between EE figures; if two similar buildings in different regions are studied, there can still be a variation in EE figures. The reason for this variation between EE figures is that these regions can differ in raw material quality, production processes, economic data, processes of delivered energy generation, transport distances, energy use (fuel) in transport and labour (Dixit et al., 2010). This can result in different total energy requirements to produce a product and can therefore result in different EE figures. These differences make it difficult to compare studies from different regions; EE figures of two different building designs cannot be used to conclude which design is preferred, if there is regional variation between the studies.

3.2.4 Primary and delivered energy

Hestnes and Sartori (2007) have shown that there is a variation between EE studies on the definition of energy (primary or delivered energy) which is used for the calculation of EE figures. Delivered energy is the energy used by the consumer, without taking into account where this energy originates from and therefore without including potential losses which might come with delivering that energy to the consumer (losses from generation/transportation of electricity). Primary energy is defined as the total energy required from nature. Therefore if calculations are based on primary energy and use of electricity is considered in the analysis, it should be calculated how much total primary energy (e.g. energy from coal or natural gas) was needed to generated this electricity. If between studies data is based on different types of energy it is obvious that this will result in variation in EE figures. It is therefore recommended to use primary energy to increase the comparability between EE figures (Treloar et al., 2001).

3.2.5 Feedstock energy consideration

Feedstock energy is the energy embedded in materials which are used as ingredients in the production process of a final material. Alternatively, this embedded energy could also be used for direct energy use (as fuel) or indirect energy use (electricity). An example of this is the use of petrochemicals like oil or natural gas as material input for a production process of for example plastics or rubber (Dixit et al., 2010). Hestnes and Sartori (2007) have shown that there are inconsistencies between EE studies on the consideration of feedstock energy. This factor again emphasises the need for standardisation; standards are needed that state when feedstock energy has to be included and when this can be excluded from the calculation, in order to limit variations between EE figures.

3.2.6 Technology of manufacturing processes

For the production of a product there are often several production technologies available. Researchers have to make a decision which production path to include in the analysis. This decision is often based on data availability instead of on a case specific decision based on technological representativeness, which can result in large variation between EE figures (Dixit et al., 2010). This factor again emphasises the need for standardisation.

3.2.7 Age of data sources

The age of data can be an important reason for incomparability between EE figures (Dixit et al., 2010). Processes involved in the production of materials tend to increase in efficiency over time, therefore if older data is used this will give different EE figures than when more recent data is used. Examples of these processes are: industrial processes for the manufacturing of (intermediate) materials, transportation processes and energy conversion processes.

3.2.8 Source of data

Just like the age of data, the source of data is also an important factor that can cause variation and inconsistencies between EE figures. There is no standardised method available which obligates researches to use one specific source of data for calculation, therefore the choice between sources is subjective and can result in variations between EE figures (Dixit et al., 2010). Standardisation of the method used for data acquisition can resolve this problem. Also, a comprehensive database is needed which offers the researchers transparent and reliable data to limit these variations and inconsistencies.

3.2.9 Data completeness

It has been argued that data which is available for researchers is often incomplete due to the method used for this data and the system boundaries which have been chosen (Khasreen et al., 2009). This incomplete data limits the researchers in delivering accurate EE figures. This therefore again requires a comprehensive database which offers the researchers transparent and reliable data.

3.2.10 Temporal representativeness

This factor again relates to the data quality available for EE analysis. Some energy studies are based on recently developed technologies, while other studies consider a mix of new and old technologies ((Curran, 2006) as cited by (Dixit et al., 2010). Again, this subjective choice that researcher have distorts the end results and emphasises the need for standardisation and a comprehensive database which offers the researchers transparent and reliable data.

3.3 Standardisation of EE calculations

As mentioned before, the standardisation and the development of guidelines for calculating EE have the potential to diminish variations and inconsistencies in EE calculation (Dixit et al., 2012). Therefore, this following section will go into more detail on the standardisation of EE calculations. This section will start with elaborating how standardisation is currently applied to EE calculations, which will be followed by a discussion on the developments of regional EE databases and corresponding standards, including some important examples. This section ends with an analysis of the current use of standards in sustainability assessments of the Dutch construction sector, including the identification of improvements which are necessary for the development of a standard focussing on EE in the Dutch construction sector.

3.3.1 Current use of standards for EE calculations

Because there is no standardised method available specifically developed for calculating EE figures, many EE studies follow LCA standards as guidelines for the calculation of EE figures. Dixit et al. (2012) has assessed several EE research studies and have shown that researchers either did not follow any standardised method or followed the LCA ISO 14040 and ISO 14044 standards in these studies. These ISO LCA standards are used because: 1) there are no standards available specifically for EE calculation and 2) because of the similarities between LCA and EE calculations. These ISO LCA standards deal with important aspects that can also be applied for EE calculations, such as system boundary definition and the methods used for data collecting. However, the effectiveness of these ISO LCA standards, when applied to LCA, has been questioned by several authors (Reap et al., 2008). Also, the variation and inconsistencies between EE figures (when these ISO LCA standards were applied) show that there is a need for a standard that limits this variation and inconsistencies in greater detail (Dixit et al., 2010).

3.3.2 Regional EE standards and databases

Efforts towards the improvement of standardisation of EE calculations have thus far mostly been focussed on the development of regional standards and databases instead of internationally applicable standards such as the ISO standards. Regional standards appear to have an advantage over international standards since these standards can better deal with the factors that cause variation and inconsistency in the results, due to fewer possible pathways of calculation. Regional standardisation could have a positive effect on the following factors:

- **Geographic location of the study.** One of the factors that cause variations and inconsistencies between EE figures is the 'geographic location of the study' (as described in section 3.2.3). By focussing on one specific region (e.g. the EU) for the development of an EE standard and database, the variations and inconsistencies caused by this factor are limited. If the development of a standard and database is focussed on an even smaller region, e.g. a specific country, the variation and inconsistency caused by this factor will be even smaller.
- **Source of data.** The number of available sources of representative data for one specific region is often limited and is therefore easier to standardise than it would be for international standards; this will results in less variation and inconsistencies caused by this factor.
- **Technology of manufacturing processes.** Regional standardisation also has a positive effect on the factor 'Technology of manufacturing processes' since a smaller region is most likely to have a lower number of available technologies to produce one material.

However, a disadvantage of regional standardisation is that EE figures can only be compared between studies that have applied the same standards, therefore global comparison of EE figures would not be possible (Dixit et al., 2010). Also, the data from a regional database cannot be used for studies in other countries; a problem which for example has been identified by Mpakati-Gama et al. (2011).

Several studies have focussed on calculating regional EE figures for construction materials. For example, Reddy and Jagadish (2003) have calculated Sri Lankan EE figures, Alcorn and Baird (1996) EE figures for New Zealand and for Spain the BEDEC database has been developed for EE figures of construction materials (Bribián et al., 2009). However, little information is available on how EE figures were calculated for these databases, and to what extent these were standardised. The most comprehensive regional database for EE figures of construction materials so far has been the development of the Inventory of Carbon and Energy (ICE) database, focused towards the UK construction sector (Jones and Hammond, 2008). This database also offers greater transparency in the used calculation method and is therefore interesting to study in the context of this present research. The ICE database will be further discussed in the next section.

3.3.3 The Inventory of Carbon and Energy (ICE) database

As mentioned in section 3.3.2, an example of a regional standard has been the development of the Inventory of Carbon and Energy (ICE) database, focused towards the UK construction sector (Jones and Hammond, 2008). In this database EE and carbon emission figures of construction materials are collected. The primary selection criterion for this data is that the methodology used complies with the ISO LCA standards. However, in order to deal with the limitations of the ISO LCA standards, three additional selection criteria are used for the calculation of EE figures. These criteria are focussed on 1) System boundaries, 2) Origin of data and 3) Age of data. These three criteria have a resemblance with the factors that cause variation and inconsistency (section 3.2). Assessing how these criteria are considered for the ICE database can be a valuable contribution for the development of guidelines and recommendations to develop an accurate method for EE calculations for the Dutch built environment. Therefore, the following sections will elaborate on the standardisation of these criteria for the ICE database.

The system boundaries criterion states that only data should be included which considers a cradle-to-gate approach and that feedstock energy should only be included for the loss of valuable resources such as fossil fuels. The developers of this database do however encourage the users to also include transport to their case specific calculations to cover the system boundaries cradle-to-site. For some of the materials in the database (mostly for metals) the recyclability has also been considered. Hammond and Jones (2011) have discussed three methodologies to account for recycling in a LCA: 1) The Recycled content approach or 100:0 method, 2) The Substitution method or 0:100 method and 3) the 50:50 method. In the recycled content approach, all the benefits of using recyclable materials are allocated to the input of the product system (thus <u>included</u> in the cradle-to-gate system boundaries). The Substitution method uses an opposite approach where the full benefits are allocated at the end-of-life stage (thus <u>excluded</u> from the cradle-to-gate system boundaries). As the name suggests, the 50:50 method is a hybrid method which allocates half of the benefits to the materials in the input of the product system and half of the benefits to the end-of-life stage. Each of these methods have their own pros and cons and which method to choose depends on the goal and scope of the research. For the ICE database the recycled content approach is the only method which has been applied (to some materials), this decision was made because the developers are convinced that this is the most suitable method for construction (mainly due to the large lifetime of buildings) and because they believe it fits in best with the primary motivation for EE/carbon assessment, which is to estimate the current impact of production (Jones and Hammond, 2008). However, it has been clearly noted when and how this recycled content approach has been applied in the ICE database, which has been done intentionally by the developers to give the researcher the possibility to correct the data according to the goal and scope of their study.

The origin of data criterion states that data originating from sources from the British Isles are preferred. Jones and Hammond (2008) do however recognise that for most materials this data is not available and in that case it is stated that best available foreign data should be used (for example European averages).

The age of data criterion states the preference to 'modern' sources of data (Jones and Hammond, 2008). However, no definition could be found on when data is considered to be 'modern', and it has also not been stated on how to proceed if data with this requirement is not available.

3.3.4 Standardisation of EE calculations in the Netherlands: Current situation and required improvements

As discussed in chapter 2, the consideration of EE in the Dutch built environmental is very limited and there is currently no robust database or standard available for EE figures. Nonetheless, first steps have been made to analyse the environmental impact over the life cycle of a building. Table 2 showed that all the methodologies available for the analysis of environmental impact of a building in the Netherlands make use of the same database, the NMD. The data delivered to this database must comply with the SBK standard[3]. This standard is a good example of regional standardisation and although it is currently only used for standardisation of LCA focussed on environmental impact, it is an example on how to deal with the factors that cause variation and inconsistency that can be used for the development of a standard for EE calculations.

The primary criterion of this SBK standard is that methodology must follow the LCA standards ISO 14040 and ISO 14044, similar to the ICE requirements (section 3.3.3). The source of data and software to be used for analysis has also been standardised in this method: It is recommended that Simapro software from PRé Consultants is to be used in combination with the Ecoinvent 2.2 database and CML-2 impact assessment method. This advice has been made because this combination is most widely used amongst LCA practitioners in the Netherlands. As it will be discussed later, it is expected that standardising these methodological steps will reduce the variation and inconsistencies between the results. Next to this some other aspects have also been standardised, for example on how to deal with transportation and the consideration of capital goods, infrastructure and waste. For transportation it has been stated what (average) distances are to be used for the supply of construction materials from national and international origins. The inclusion of infrastructure and capital goods has also been standardised. If Ecoinvent data is used then these processes should be included, for other sources of data (e.g. branch or product specific data) this only needs to be included if the expected contribution is more than 10 percent. As for waste, some waste percentages, which describe how much material is lost in the construction process, are stated and should be used for calculations.

[3] *Bepalingsmethode Milieuprestatie gebouwen en GWW-werken* (Stichting Bouwkwaliteit, 2011).

The results of this preliminary analysis of the SBK standard have been used to determine how the factors that cause variation and inconsistencies between EE figures are considered in the SBK standard (from a theoretical perspective). On overview of these findings is shown in Table 3.

Table 3 Current consideration of the factors that cause variation and inconsistencies between EE figures, in the SBK standard.

Factor	Consideration of the factor in the SBK standard (Yes/Limited/No)	Elaboration on the consideration of the factor in the SBK standard.
System boundaries	Limited	Primary criterion of this standard is compliance with the ISO LCA standard, which is referred to for the primary system boundary definition. As an addition to the ISO LCA standard, it has been defined how and when infrastructure and capital goods have to be included. However, it has been argued that following the ISO LCA standards still allows for significant variation in EE calculations (section 3.3.1).
Methods of EE calculation	Limited	The SBK standard advises the use of the Ecoinvent database. This database primarily makes use of data based on process-analysis. However, since this is only an advice, other methods can also be used for calculations.
Geographic location of the study	No	The SBK standard is an example of regional standardisation, focussing on the Dutch construction sector. However, since there are no data available specifically for the Dutch built environment the SBK standard advises the use of Ecoinvent data. However, for construction products and processes the Ecoinvent database primarily includes data from European averages or data representing Switzerland.
Primary and delivered energy	No	No clear definition on how to consider delivered energy.
Age of data sources	Limited	It has been defined in the SBK standard that ‘recent’ data should be used. However, it has not been clearly defined when data is ‘recent’, and also no alternative procedures or corrections are described if ‘recent’ data is not available.
Source of data	Limited	The SBK standard advises the use of the Ecoinvent database, which offers an extensive amount of data. However, it has not been mentioned in the SBK standard how to consider processes not included in the Ecoinvent database.
Data completeness	Limited	The SBK standard advises the use of the Ecoinvent database, which offers an extensive amount of data. However, it has not been mentioned in the SBK standard how to consider processes not included in the Ecoinvent database.
Technology of manufacturing processes	Limited	It has been defined in the SBK standard that technological representative data should be used. However, no alternative procedures or corrections are described if technological representative data is not available.
Feedstock energy consideration	No	No clear definition on the consideration of feedstock energy
Temporal representativeness	Limited	It has been defined in the SBK standard that technological representative and ‘recent’ data should be used. However, no alternative procedures or corrections are described if this data is not available.

None of the factors appear to be sufficiently considered in the SBK standard, the factors that have been labelled to have ‘limited’ or ‘no’ consideration, require more attention for the development of an EE standard. ‘Limited’ means that the factor has not been sufficiently considered and that there are possibilities for improvement. ‘No’ means that the factor has not been considered at all. Therefore, it was needed to analyse how the standardisation in the SBK standard can be improved to develop an accurate standard for EE calculations. This has been done by analysing how the factors in the SBK standard are best addressed; the results of this analysis are shown in Table 4.

Table 4 Guidelines, from a theoretical perspective, on how the factors in the SBK standard are best addressed to develop an accurate standard for EE calculations.

Factor	Guidelines (from a theoretical perspective) on how these factors are best addressed
System boundaries	If only Ecoinvent data are used the system boundaries are static, but since this SBK standard also allows the use of other sources of data, this can potentially result in the use of different system boundaries. One way of addressing this would be to define in the standard how data from other sources needs to be corrected in order to cover the same system boundaries as data from Ecoinvent. Additionally an EE standard should also include definitions on how to incorporate the benefits of recyclable materials.
Geographic location of the study	The Ecoinvent database primarily includes data from European averages or data representing Switzerland. Using this data for the calculation of Dutch EE figures will cause a significant inaccuracy in the results (as described in section 3.2.3). This therefore emphasises the need for a Dutch EE database. Or alternatively an EE standard should include definitions on how to correct the data from Ecoinvent to values which are more accurate for the Netherlands.
Methods of EE calculation, Source of data and Data completeness	By using only data from the Ecoinvent database, these three factors are considered. However, since this is only an advice, LCA practitioners can choose to use data from other sources. To further improve the consideration of these factors, the source of data could be standardised in greater detail. This can be done by recommending the use of one primary source of data and defining an alternative procedure/database for processes which are not included in this primary database.
Age of data sources, Technology of manufacturing processes and Temporal representativeness	To further improve this standard and make it applicable for EE calculations, better definitions are needed that specify the required data quality and on how to proceed if the available data is not of required quality (by for example correcting for this). These factors require extensive analysis on how this is best applied to the Dutch situation and depends largely on the availability of data that represents the Dutch construction sector.
Primary and delivered energy	It is recommended that primary energy data is used for the calculation of EE figures since this has shown to deliver more consistent results for EE calculations (Hestnes and Sartori, 2007).
Feedstock energy consideration	It needs to be stated in an EE standard when feedstock energy has to be included and when this can be excluded from the calculation, in order to limit variations between EE figures.

These guidelines show that additional standardisation is needed, on several aspects, if the SBK standard is to be used for calculating EE figures. The most important improvements which are required, as can be seen from Table 4, are related to the current standardisation regarding the source of data.

3.4 Summary

In this chapter the current discussion about variation and inconsistency in EE calculations has been assessed in order to answer the second sub-research question: *What factors are causing the current problems with variation and inconsistency in EE calculation?.* This has resulted in an overview of the factors, including the definitions from Dixit et al. (2010) and a summary about the discussion of these factors in (other) scientific literature.

The second part of this chapter has contributed to answering the third sub-research question: *How can this gained knowledge be used to develop guidelines for EE calculations?.* This has been done by performing a literature review focussed on: 1) The current role of standardisation in EE calculations, 2) The importance of regional standardisation, including the some important examples, and 3) The current use of standards in sustainability assessments of the Dutch construction sector, including the identification of improvements which are necessary for the development of a standard focussing on EE in the Dutch construction sector. This has shown that the current standards available for EE calculations insufficiently address the factors that cause variation and inconsistency in the results. Therefore improvements are needed. This chapter has also shown that regional standardisation could have a positive effect on a number of factors. Therefore, to be able to implement EE in the energy analysis of the Dutch environment, and possibly in the Dutch energy regulations, a standard is needed specifically developed for the calculation of EE for the Dutch construction sector. The SBK standard can be used as a good foundation for the development of such a standard. However, for further development of an EE standard more research is needed on how to address the factors that have thus far not been considered sufficiently in the SBK standard. The standardisation which is used for the ICE database has also been assessed in this chapter. Because this regional EE standardisation also addresses some of the factors, this assessment has been a valuable contribution for the development of guidelines and recommendations to develop an accurate method for EE calculations for the Dutch built environment.

4 Interviews

Interviews have been conducted to: 1) Validate the findings from the literature review, and 2) Gain additional information and insights that can be a valuable contribution to answering the research questions. These interviews have been conducted with institutions which have been selected on the basis of their involvement in sustainability assessment of the Dutch built environment. These institutions are well known stakeholders involved in the sustainability assessment of the Dutch building sector. Section 4.1 elaborates on the method which has been used for conducting these interviews. After this, section 4.2 gives an overview of the findings from the interviews. This chapter ends with section 4.3, discussing the validity and reliability of this method.

4.1 Method

The interviews have been conducted following a semi-structured approach. A semi-structured interview is guided by several topic areas, which are introduced to the interviewee by asking for their views on that specific topic (Flick, 2009). For this specific research the majority of the topics have been introduced following a 'theory driven' approach[4]; the questions related to the topics were asked based on the researcher's theoretical presumptions (Flick, 2009). This open question approach has been chosen in an attempt to maximise the information collected from the interviews. Because of the expertise of the interviewees a more standardised approach might limited the information collected, since it is difficult for the interviewer to anticipate the knowledge the interviewee has on the subject. This open question approach allowed the interviewer to change the direction of the interview based on the replies of the interviewee, allowing for a more open discussion.

The results from the four interviews have been reported following the three interview topics which are discussed in section 4.1.2. The interviews were either voice recorded or notes were taken by the interviewer. As a first step all the findings from the four interviews were transcribed and translated from Dutch to English. These findings were then subdivided into the three interview topics. After this, the important findings (which can contribute to answering the research questions) were selected, and these were compared with the findings from the other interviews. In the results section of this chapter (section 4.2) the analysis of these findings are reported, subdivided into the three interview topics. The focus here has been on looking for similarities between the four interviews.

4.1.1 Sampling

There are several actors involved in the (development of) sustainability assessment of the Dutch built environment. An overview of the actors involved is provided in Table 5, including a short elaboration on the role of these actors. The four institutions that have been chosen for interviews are mainly involved in conducting sustainability assessments and in the research towards improving the current sustainability assessments. Therefore the four institutions that have been chosen for the interviews can be considered as actors in the categories 3 and 5 in Table 5.

[4] 'Theory-driven, hypotheses-directed questions are oriented to the scientific literature about the topic or are based on the researcher's theoretical presuppositions. In the interview, the relations formulated in these questions serve the purpose of making the interviewees' implicit knowledge more explicit. The assumptions in these questions are designed as an offer to the interviewees, which they might take up or refuse according to whether they correspond to their subjective theories or not' (Flick, 2009)

Two of the four institutions, which have been chosen for interviews, are mainly involved in conducting sustainability assessments related to the Dutch built environment. Therefore the interviews with these institutions have mainly been used to gain more information regarding the current role of EE in sustainability assessment of the Dutch built environment and on how the factors that cause variation and inconsistency in EE figures are considered in the sustainability assessments (section 3.2) . Additionally these two interviews have been used to gain information about the views of the demand side of sustainability assessment of the Dutch built environment.

The other two institutions that have been chosen for interviews are, next to conducting sustainability assessments, also involved in further development of the methodology used for sustainability assessment of the Dutch built environment. Therefore the interviews with these institutions have mainly been used to gain more information regarding further developments of the sustainability assessment methods and the possibilities for EE analysis of the Dutch built environment. In this report the four interviews will be referred to as:

- Interview A: Sustainability assessment practitioner 1
- Interview B: Sustainability assessment practitioner 2
- Interview C: Methodological development 1
- Interview D: Methodological development 2

The third column of Table 5 shows an overview on how the four interviews have been intended to cover all actors involved in the (development of) sustainability assessment of the Dutch built environment.

Table 5 Overview of the actors involved in the (development of) sustainability assessment of the Dutch built environment.

Actor	Role of the Actor	Views of actor covered by interviews
1.Government/Municipalities	The main role of this actor is policy development related to the sustainability assessment of the Dutch built environment (national government). Another example of the role of the national government is overseeing the developments related to this, by providing (financial) resources and overseeing knowledge development. Municipalities play a role in enforcing the policies developed by the government.	A,B,C,D
2. Demand of sustainability assessments	The demand side of the sustainability assessments, mainly including contactors, architects and homeowners.	A,B,(C),(D)
3.Sustainability assessments practitioners	Professionals that conduct the sustainability assessments.	A,B,(C),(D)
4.Suppliers of LCA data	An important part of the sustainability assessments is the supply of data. This group of actors include: the institutions responsible for the management of LCA databases (such as Ecoinvent) and for example branch-associations overseeing the production of certain construction materials (which can supply branch-specific LCA data).	C,D,(A),(B)
5.Researchers involved in the development of sustainability assessment methods	Actors involved in the further development of the methodology used for sustainability assessment of the Dutch built environment.	C,D,(A),(B)

As can be seen from Table 5, the views of all actors involved have been covered by the four interviews. The following section will elaborate on how, and by which interview, these actors are covered:

- **Government/Municipalities.** All the four institutions that have been chosen for interviews have, to some extent, provided their views on the role of this actor. The *milieuprestatieberekening* policy and the overseeing governmental control regarding the development of the sustainability assessment methods related to this policy are important for all the four institutions which have been chosen for the interviews.
- **Demand of sustainability assessments.** The four institutions all conduct sustainability assessments and therefore have a close working relation with this actor. Interviews A and B have resulted in most of the findings regarding the views of this actor because these institutions are primarily focussed on conducting sustainability assessments.
- **Sustainability assessments practitioners.** All the four institutions that have been chosen for interviews are actors in this category. Interviews A and B have resulted in most of the findings because these institutes are primarily focussed on conducting sustainability assessments.
- **Suppliers of LCA data.** All the four institutions that have been chosen for interviews have a close work relation with this actor. One reason for this work relation is that conducting sustainability assessments requires LCA data. More importantly, further development of the methodology used for sustainability assessment requires research to determine what sources of LCA data are available and regarding the quality of this data. Therefore, because the institutions of C and D are more involved in further development of the methodology used for sustainability assessment, these interviews have resulted in more findings.
- **Researchers involved in the development of sustainability assessment methods.** All the four institutions that have been chosen for interviews are actors in this category. Interviews C and D have resulted in most of the findings because these institutes are to a greater extent focussed on conducting sustainability assessments than A and B.

4.1.2 Interview guide

As described in section 4.1, the interviews have been conducted following a semi-structured approach. Therefore, the interviews did not follow a concrete list of questions, but instead aimed on having an open discussion about pre-defined interview topics. The topics which were used as guidelines for the interviews follow the sub-research questions of this present research. The aims and guidelines used for these interview topics are described below:

Topic 1:
EE and the current consideration in the sustainability assessment of the Dutch built environment

This topic relates to the first sub-research question: *How is EE currently considered in building energy analysis in the Netherlands?.* The aim of this interview topic was to gain information and insights regarding the current role of EE in sustainability assessment of the Dutch built environment. Firstly, the interviewees were asked about their current knowledge of EE analysis and their opinions regarding the importance of including this in the sustainability assessment of the Dutch built environment. The previously described 'theory driven' approach has been used to gain information regarding this topic. The knowledge acquired from the literature review regarding this topic was checked with the interviewee.

Topic 2:
The consideration of the factors, that causes variations and inconsistencies in EE calculation, in the current sustainability assessment methods used in the Netherlands.

This topic relates to the second sub-research question: *What factors are causing the current problems with variation and inconsistency in EE calculation?.* The aim of this interview topic was to gain information and insights regarding the consideration of the factors that cause variations and inconsistencies in EE calculation in the current sustainability assessment of the Dutch built environment. This was again done by following a 'theory driven' approach. The factors were briefly introduced to the interviewee. The interviewees were asked if they have experienced similar problems with the sustainability assessment method the interviewee is involved in. Additionally, questions were asked about parts of the method which were unclear to the interviewer and about parts of the method that were expected to cause variations and inconsistencies (presumptions based on literature review).

Topic 3:
Pathways towards an EE database for the Netherlands.

This topic relates to the third sub-research question: *How can this gained knowledge be used to develop guidelines for EE calculations?.* The aim of this interview topic was to gain information and insights on how the factors that cause variations and inconsistencies should be addressed in order to calculate accurate EE figures, either by improving current calculation methods or by discussing the possibilities for a novel method. This topic aimed at finding possible pathways towards the calculation of novel EE figures representing the Dutch built environment. The interviewees were also asked about their views regarding possible sources of data which could be used for the calculations.

4.2 Results

Topic 1:
EE and the current consideration in the sustainability assessment of the Dutch built environment

This topic is related to research question: *How is EE currently considered in building energy analysis in the Netherlands?*. All the interviewees were familiar with the concept of EE. However, EE figures are used as a data input rather than as a separate analysis or analysis output. Total energy demand figures are used to calculate the environmental impact in the (already well established) sustainability assessments conducted by the different interviewed institutions. This confirms the findings from the literature review conducted in chapter 2. This literature review has also shown that in the voluntary sustainability assessment methods EE is considered in this method by incorporating it in the assessment of the environmental impact of building materials (section 2.4). All of the interviewees initially questioned the need for EE analysis. In this context interviewee D said: *'Why do we need additional EE analysis, if these figures are already included in the environmental impact results?'.*

The institutions had received little requests for EE analysis or figures from their clients (mainly contractors and architects). However, interviewees B and C have received requests from research projects about EE analysis of the built environment. Interviewee B is involved in a European project which aims at reducing EE in the built environment by using bio-composite materials. Interviewee C has been involved in a project aiming on unifying European sustainability assessments methods used in the built environment. Interviewee C mentioned that in many European sustainability assessment methods EE is used as an indicator, therefore studying EE has been an important part in this project. This shows that although EE analysis is still not very well integrated in the analysis of the Dutch built environment, the concept of EE analysis is known and applied by Dutch researchers.

All of the interviewees acknowledged, to some extent, the benefits of using EE as an (extra) indicator in sustainability assessments. This has been acknowledged because energy is already a well-known indicator to the public (and probably better to understand than environmental impact indicators) and because of the extra analyses that can be done using EE figures. In this context interviewee C said: *'EE is a concept that people can easier relate to..'*. An example of an extra analysis possible with EE figures is the comparison between operational energy and EE of a building. However, interviewees C and D mentioned that such a comparison can also be made using carbon emission figures or by comparing the complete results of environmental impact.

<u>Topic 2:</u>

The consideration of the factors, that causes variations and inconsistencies in EE calculation, in the current sustainability assessment methods used in the Netherlands.

This topic relates to research question: *What factors are causing the current problems with variation and inconsistency in EE calculation?.* The sustainability assessments conducted by the interviewed institutions make use the NMD. This confirms the findings from the literature review (section 2.4). This database primarily makes use of data from Ecoinvent, which primarily consists of data based on European averages or Swiss calculations. It was expected by the interviewer that this parts of the calculation would cause variations and inconsistencies, related to the factor **'Geographic location of the study'**. Interviewee B replied that data from Ecoinvent is corrected to better represent the Dutch situation. This done by: 1) Using Dutch electricity generation data for the calculation of primary energy requirements and related emissions from these electricity generation processes, and 2) Using Dutch waste treatment scenarios for the calculations, since in most cases these are more efficient in the Netherlands than for Swiss or European average scenarios. This way, part of this Ecoinvent data is corrected to the Dutch system, and the factor 'Geographic location of the study' is not considered to be a problem in the sustainability assessments. This has been confirmed by interviewees C and D.

Regarding the factor **'Source of data',** Interviewee A recognizes that standardisation could be improved; in this context Interviewee A said: *'...it would be ideal if all data in the NMD made use of the same database'*. Ecoinvent is used as the main source of data for the NMD, but when required data is not available in Ecoinvent, other sources are used. The SBK standard could be improved by stating in greater detail how to proceed if Ecoinvent data is not sufficient, or better, if data is missing from Ecoinvent, efforts should be made to include this data in Ecoinvent.

None of the interviewees showed large concerns regarding the variations and inconsistencies caused by the factor '**System boundaries'**. In this context interviewee C said: *'The system boundaries are static because of the methodological choices that have been made in Ecoinvent..'*. This has been confirmed by the other interviewees; the data from Ecoinvent is for the largest part calculated using standardised system boundaries, therefore the interviewees do not expect that this will result in large variations and inconsistencies.

Topic 3:
Pathways towards an EE database for the Netherlands.

This topic relates to the research question: *How can this gained knowledge be used to develop guidelines for EE calculations?.* The interviewees identified four possible pathways towards an EE database for the Netherlands:

1. Calculating EE figures using data from the National Environmental Database.
2. Calculating EE figures directly from Ecoinvent data.
3. Developing a novel standard and database for EE figures.
4. Calculating EE figures from a combination of data sources.

1. Calculating EE figures using data from the National Environmental Database

All the interviewees agree that using data from the NMD for the calculation of EE figures has the advantage that this is already a well-established method; the construction sector is already familiar with using this database. Interviewee C also mentioned that the NMD is likely to become more important in analysis of the Dutch built environment when the policies around the environmental performance calculation are changed to a more mandatory approach. However, a disadvantage of using this method, as mentioned by all interviewees, is that the NMD provides very little transparency. If this data is to be used for the calculation of EE figures, more transparency is needed on the methods and sources of data that are used to calculate the final energy figures which are reported in the NMD. The publicly available data from the NMD does not currently provide this transparency; it might however be possible to contact SBK to gain access to more detailed data. Another disadvantage, as mentioned by interviewee B, is that the NMD is only nationally recognized. If these EE figures are to be used for research purposes, it might be better if the figures are calculated using an internationally recognized database, such as Ecoinvent.

2. Calculating EE figures directly from Ecoinvent data.

Using Ecoinvent as a source of data for the calculation of EE has the advantage that this source is internationally recognized. It is also the most widely used source for scientific research related to life cycle assessment (Interviewee B). A disadvantage however is the consideration of the factor **'Geographic location of the study'**. If Ecoinvent is to be used for the calculations of EE it should be determined what the effect of this factor is. Interviewee D expected that for some construction materials the difference between European average data and Dutch specific data is very small. An example of this is the steel industry, which is a large scale industry where the steel is produced in one location and transported to the country where the demand is. Therefore using European average data from Ecoinvent for steel production is likely to give a representative result. However, the production of other materials, such as concrete, is more regionalised and therefore larger differences can be seen between countries. Interviewee D therefore suggested that for each individual construction material it should be determined whether Ecoinvent data can be used directly or if a correction of this data is necessary.

3. Developing a novel standard and database for EE figures.

Developing a novel method, where process data is collected according to a newly developed standard, has been identified as the third potential pathway. This method has the advantage that it will be specifically developed for EE calculation representing the Dutch system, and is therefore expected to result in the most accurate EE figures. However, as mentioned by all interviewees, there is a significant risk of doing 'double work'. Similar data might already be available from other sources (from databases such as Ecoinvent or data from industry). Therefore, all interviewees agreed that it would be better to calculate EE figures using already available data. An additional problem has been mentioned by interviewee B. It might be difficult to introduce a new method and corresponding database and get it accepted in the Dutch system. Using the NMD is already a well-established and accepted method for calculating the sustainability of buildings in the Netherlands, and it will be difficult to convince the actors involved that there is a need for an improved method and extra indicator. However, this does not apply if this EE database is to be used as a standalone database for research purposes.

4. Calculating EE figures from a combination of data sources.

Because of the differences between the production of the construction materials, interviewee D argued that using a combination of data sources for the calculation of EE figures might be the best option. If such an EE database is to include numerous different construction materials, it is recommended that a combination of methods and data sources should be used for calculations. In this context interviewee D said: '*…this depends on the scale of the database, if many different construction materials are to be included, this would require different methods of data collecting.'.* Interviewee D also mentioned that in the Netherlands the production of several important construction materials (e.g. steel and concrete) are represented by branch-organisations. It is expected that these branch-organisations already have data available for their products, which can be used to calculate EE figures. It is therefore suggested that the preference is given to data from these branch-organisations and as a secondary method other databases such as Ecoinvent should be used (if necessary by correcting these data to better represent the Dutch situation).

Table 6 shows a summary of the results from the third interview topic. It summarizes the advantages and disadvantages of the four pathways which have been identified for calculating an EE database for the Netherlands.

Table 6 Summary of the interview results from Topic 3

Pathways towards an EE database for the Netherlands	Advantages	Disadvantages	Additional remarks
1. Calculating EE figures from NMD data.	Already a well-established database. NMD is likely to become more important in the future.	NMD provides very little transparency. NMD is only nationally recognized.	
2. Calculating EE figures directly from Ecoinvent data.	Ecoinvent is internationally recognized.	Consideration of the factor 'Geographic location of the study'.	
3. Developing a novel standard and database for EE figures.	Expected to result in the most accurate EE figures.	Risk of doing 'double work'. Time consuming	All interviewees agreed that it would be better to calculate EE figures using already available data.
4. Calculating EE figures from a combination of data sources.	Best Consideration of the factor 'Geographic location of the study' from already available sources of data.	It is expected that collecting novel data (pathway 3) will result in more accurate results.	Combination of branch-specific data and other databases such as Ecoinvent (if necessary by correcting these data to better represent the Dutch situation).

4.3 Validity and reliability of the results

Four interviews have been conducted in this research, representing two actors (of the five identified (Table 5)) which are involved in the sustainability assessment of the Dutch built environment. It is however anticipated that information on the views of the other actors in this field has been gained through these four interviews, because of the close work relationship between the interviewees and the other actors in this field. Therefore it is expected that these four interviews have given a representative view on the subject, despite the limitation that not all actors in this field are interviewed. However, additional interviews with other actors involved could have resulted in a more complete picture of the (potential) role of EE in the sustainability assessment of the Dutch built environment. The interviews have been conducted using a semi-structured approach which has resulted in an open discussion with the interviewees. Using this approach has several advantages in the context of this research (as discussed in section 4.1). This approach however has the disadvantage that not all the findings of the interviews could be compared amongst each other, because no specific list of questions has been used to guide the interviews. The discussions with the interviewees were guided based on their role and knowledge regarding the research subject. Another limitation related to the methodology has been the limited feedback of the interviewees regarding the factors that cause variations and inconsistencies in EE results. The interviewees did not recognize all factors and only three of these have been discussed in the interviews. However, because the interviews have been used as an addition to the results from the literature review and theoretical analyses, these limitations are not expected to have caused uncertainties in the results. The conclusions and recommendations made in this research are not solely based on the interviews; the interviews have been used to confirm the theoretical findings and to provide new insights into this topic.

5 Discussion and Conclusions

This research has been conducted because of the increasing importance of EE analysis in the context of lowering the energy demand of the built environment (as discussed in Chapter 1). Literature review has shown that the standardisation of EE analysis requires improvements. In order to improve this standardisation, this research has focused on developing guidelines for an accurate EE calculation method to be used in the Dutch built environment. Literature review and expert interviews have been used in this research to answer the research question: *How do the factors causing variation and inconsistencies in EE calculation need to be addressed in order to develop an accurate method for EE calculations used in the Dutch built environment?*.

This chapter has been written to discuss the results from this research and to conclude on the research questions by summarising the findings and recommendations made throughout this report. Section 5.1 discusses each research question separately. After this, section 5.2 presents the limitations of this research. Section 5.3 provides the recommendations for further research. Finally, some concluding remarks are made in section 5.4.

5.1 Discussion and conclusions per research question

Sub-research question 1:
How is EE currently considered in building energy analysis in the Netherlands?

The literature review conducted in this research has shown the importance of EE analysis in the context of reducing the total energy demand related to the built environment. It has also resulted in an overview of the most common methods which are used for the sustainability assessment of the Dutch built environment. The consideration of EE in these methods has been assessed and this has shown that EE is considered by using total energy demand figures to calculate the related environmental impact. EE is however not used as a separate indicator and the outcome of these sustainability assessments cannot be used for EE analysis. Additionally it has been shown that the interviewees, who are involved in the current sustainability assessment methods, question the need of including EE analysis in these assessments. Therefore it is recommended that a stand-alone EE database is developed which can be used for scientific research, rather than including these figures in already available sustainability assessment methods.

Sub-research question 2:
What factors are causing the current problems with variation and inconsistency in EE calculation?

The literature review presented in chapter 3 has resulted in an overview of the factors identified by Dixit etal. (2010), explaining the implications per factor. These factors have been used throughout this research to determine the quality of the different methods for EE calculation and sustainability assessment. Three standards have been analysed in order to determine how these standards consider the factors that cause variations and inconsistencies: 1) ISO 14040/14044, 2) The SBK standard, and 3) The ICE standard. The findings from these theoretical analyses have contributed to: 1) the identification of the factors that are causing variation and inconsistency in EE calculations that follow these standards, and 2) answering the third sub-research question, because the findings from these analyses have been used to develop guidelines for EE calculations.

__Sub-research question 3:__
How can this gained knowledge be used to develop guidelines for EE calculations?

The findings from the theoretical analyses of the three previously mentioned standards, in combination with the findings from the interviews, have resulted in guidelines that recommend how a novel EE standard, focussing on the Dutch built environment, should address these factors in order to limited variations and inconsistencies. An overview of these guidelines is shown in Table 7.

Table 7 Guidelines for a novel EE standard focussed on the Dutch built environment

Factor	Guidelines for a novel EE standard focussed on the Dutch built environment
System boundaries	It is recommended that an approach similar to the ICE standard is used. The system boundaries should be defined as cradle-to-gate including additional data to include the benefits of recyclability (section 3.3.3). This allows the researchers to adapt the EE data according to the scope of their study.
Methods of embodied energy calculation	It is recommended that the method chosen for this novel standard should be based on data availability. It can be argued, based on the interviews, that consistency in the method used is more important than the decision of which method is used.
Geographic location of the study	The intention of this novel standard is to focus specifically on the Dutch built environment. Therefore calculations are expected to be based on direct process data and/or branch-specific data. If however additional generic data has to be included, this standard should include definitions on how to limit the differences between the sources of data. The method which is currently used for the correction of Ecoinvent data for the NMD database (section 4.2) can be used as an example for this.
Age of data sources, Technology of manufacturing processes, Temporal representativeness	Similar to the standard used for the ICE database, this novel standard should include a definition about the age of data sources and the quality of the data related to these other factors. This should include definitions about the required quality of the data and should include alternative procedures or corrections if data of this quality is not available.
Source of data , Data completeness	Similar to the standard used for the ICE database, this novel standard should include a definition about the source of data. This should include definitions about the main source of data and include alternative procedure if this source is not sufficient. The variations and inconsistencies caused by this factor can be limited by: 1) Including as little sources of data as possible, and 2) Including a correction method that defines how to correct data to limit the variation between sources.
Primary and delivered energy	It is recommended that primary energy data is used for the calculation of EE figures since this has shown to deliver more consistent results for EE calculations (Hestnes and Sartori, 2007).
Feedstock energy consideration	It is recommended that it is stated in this novel EE standard when feedstock energy has to be included and when this can be excluded from the calculation, in order to limit variations between EE figures.

How the guidelines from Table 7 can be applied depends largely on what sources of data are available for the calculation of EE figures for the Dutch built environment. For this reason, four different pathways have been identified, next to the guidelines, which can be used to calculate EE figures that represent the Dutch built environment:

1. Calculating EE figures using data from the National Environmental Database.
2. Calculating EE figures directly from Ecoinvent data.
3. Developing a novel standard and database for EE figures.
4. Calculating EE figures from a combination of data sources.

Further analysis of these pathways has showed a preference for pathway 3 and 4, because of the disadvantages of the first and second pathways (section 4.2). It is expected that pathway 3 will result in the most accurate EE figures. However, this research has also shown that this pathway has several disadvantages: This pathway is very time consuming, because it involves collecting novel process-based energy demand data and the development of a corresponding novel standard. This research has also shown that there is a risk of doing 'double work'; data of similar quality might already be available (e.g. branch-specific data), or generic data (e.g. Ecoinvent data) could be corrected to represent the Dutch construction sector. This pathway is further complicated by the expected difficulties that come with introducing a novel method next to the already well-established methods based on the NMD. For this same reason it is expected that the willingness of industries to provide data might be low; these parties will need to be convinced about the need for a new database/indicator. Pathway 4 will be less time-consuming because it makes use of already available data. Also, because it is expected that most of the data is available from Dutch branch-organisations, only a small share of the data will have to be based on generic data (e.g. Ecoinvent), limiting the variations and inconsistencies caused by the factor 'Geographic location of the study'. Both pathway 3 and pathway 4 require the development of a novel standard. Based on this research it is recommended that the guidelines, defined in Table 7, are followed for the development of these standards.

Main research question:

How do the factors causing variation and inconsistencies in EE calculation need to be addressed in order to develop an accurate method for EE calculations used in the Dutch built environment?

The findings from the three sub-research questions have all contributed to answering the main research question. Summarizing the answer to the main research question, it is recommended that the factors causing variation and inconsistencies in EE calculation are addressed following the guidelines which have been developed in this research. Additionally, four different pathways have been identified which can be followed to calculate EE figures for the Dutch built environment.

5.2 Limitations of the study

It was expected that the literature review conducted in this research would have resulted in more findings on research towards the standardisation of EE calculations. This was expected because preliminary literature research showed references to a multitude of EE databases. However, most of these databases provided very little transparency in the used method and standard and could therefore not be included in the theoretical analyses of this research. This has resulted in a limitation of this research because only three standards have been analysed and compared, from a theoretical perspective. Analysis of additional standardisation could have contributed to the development of the guidelines that address the factors that cause variation and inconsistencies in EE calculation.

There are also some limitations regarding the methodology used for this research, which have been discussed in section 4.3. The main limitation regarding the methodology is that four interviews have been conducted in the research, representing only two actors (of the five identified (section 4.1.1)) which are involved in the sustainability assessment of the Dutch built environment. It is expected that these four interviews have given a representative view on the subject, despite the limitation that not all actors in this field are interviewed. However, additional interviews with other actors involved could have resulted in a more complete picture of the (potential) role of EE in the sustainability assessment of the Dutch built environment.

Due to the limited time available for this research project some additional analyses, which could have resulted in a more complete picture of the (potential) role of EE in the sustainability assessment of the Dutch built environment, have not be conducted. This has resulted in recommendations for further research, which are discussed in the next section.

5.3 Recommendations for further research

It is recommended that further research is conducted to determine the availability of energy demand data from branch-organisations that are overseeing the production of construction materials in the Netherlands. It needs to be determined if this branch-specific data is of sufficient quality to be used for EE calculations. This research will be important for the decision on which pathway is best chosen for the calculation of EE figures that represent the Dutch built environment. Additionally, it is recommended that regional data (e.g. branch-specific data) and generic data (e.g. Ecoinvent) are compared, in order to determine how significant the differences are between these sources of data. This will also be important for the decision of which pathway is best chosen. If this research shows that for certain construction materials these differences are small, using generic data (e.g. Ecoinvent) for these construction materials might not significantly increase the variations and inconsistencies.

Furthermore, if EE figures that represent the Dutch built environment are available, additional research is needed on how to implement this in buildings energy analysis and policies in the Netherlands in order to achieve a minimal energy demand.

5.4 Concluding remarks

This research has provided guidelines which are recommended to be followed for the calculation of EE figures that represent the Dutch built environment. Additionally, four different pathways have been identified which can be followed to calculate these EE figures. However, in order to determine which pathway is best chosen further research is needed. Next to the findings from further research and the considerations discussed in this research, this decision also depends on the application of this potential EE database and the time and resources available to establish such a database. The findings from this research have shown the importance of studying EE in the context of lowering the final energy demand of the (Dutch) built environment. Further research towards developing an EE database, with corresponding standard, is therefore considered to be of major importance in the context of minimizing the energy demand of the built environment.

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