DEVELOPMENT OF A DECISION SUPPORT MODEL FOR BUILDING DESIGN

Based on the Cradle to Cradle® principles and the building Villa Flora

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DEVELOPMENT OF A DECISION SUPPORT MODEL FOR BUILDING DESIGN:

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Project Summary

The aim of this research is the development of a model that could guide both the design and the evaluation process of buildings according to the Cradle to Cradle® (C2C) principles. The model is suggested as a response of a lack of methods that could lead buildings towards a positive environmental impact. Agreeing with Braungart and McDonough theories, the traditional focus of *Sustainability* is only delaying the environmental damage without providing a real solution. Cradle to Cradle® represents a better approach based on eco-effectiveness, where products and systems stop being *'less bad'* and become *'good'*.

A literature review was carried out in order to identify the environmental assessment methods used in The Netherlands and the C2C guidelines for the built environment. The available environmental assessment methods, such as BREEAM and GPR, were originally designed as assessment tools. The use of these methods in the design phase was the result of a shortcoming of methods in this phase. The best way that building professionals could anticipate on the results, was by using the method itself as a design tool. This structure is used as a foundation for the model proposed in this thesis. *Chapter 3* presents the framework of the decision support model.

The model does not measure the *positive-ness* or *C2C-ness* of buildings. It only guides the transition of buildings from having a negative impact to a reference line. The reference line is allocated in the known graphic by Braungart and McDonough (2012) where the C2C approach is explained. In this proposal the reference line is described as a 'green area'. Within this area, the model is able to measure the environmental performance of buildings according to its own Key Performance Indicators (KPI's). Above this line buildings really start having a positive impact on the environment. Mondrian-like blocks are used to graphically represent the performance of buildings. *Chapter 4* illustrates the evaluation of the model through the C2C-Inspired building Villa Flora. This building was used as case to test and complement the KPI's. Villa Flora was presented as the *Greenest office of the Netherlands*. The model gives objective and quantitative information of its performance within two categories *Renewable Energy* and *Materials.*

Different opinions where found related to the measurement of the C2C features in buildings through the suggested categories and Key Performance Indicators of the model. On one hand, at the level of building designers some kind of assessment is necessary in order to make the information more clear and present the results objectively. Building professionals need tools and measurement systems in order to make objective choices during the design and operation phase of buildings. Additionally comparing and assessing buildings could help engineers and owners from a business and marketing point of view in a similar way that products are assessed through the C2C Product certification.

On the other hand providing quantitative results and comparing different buildings were the biggest criticism by the C2C experts. Their arguments were based on the fact that it is not possible to quantify the C2C features of a building. Although the model is not measuring the C2C-ness of buildings it possibly could lead to a misinterpretation by the users. Additionally the C2C experts recommended focusing on five *elements* instead of buildings as a whole, and move to *buildings* when enough *C2C-Inspired elements* are placed in the development.

Recommendations are given in this project in order to continue with this research and link the gap between the opinion of the C2C Experts and the need of a model to design, evaluate and compare C2C-inspired buildings as objectively as possible. At the end all the parties involved are unanimously working towards the same goal: *designing, constructing and using buildings with positive footprints.*

Acknowledgement

This master thesis represents all my experiences at the University of Twente. It became a beautiful opportunity to combine my two favorite topics of the master education: Cradle to Cradle and Architectural Building Components Design Engineering. I am thankful to Thonie and Jelle for their help on selecting and carrying on these topics.

As an international student I wish to thank various people for their assistance, not only during this project, but also during the complete period of the MSc. program. I am deeply thankful to my supervisor, Dr. Elma Durmisevic, for teaching me how to look at buildings as complex products and for her professional guidance during these years. I am particularly grateful with Ing. Bas Holla for giving me the opportunity to join Volantis B.V. and for all his support, inspiration, and encouragement to work on this project. The assistance provided by all my colleagues, in special Koen, Jos, Linda, Sjef, Bart, Bram and Wim, is greatly appreciated. Furthermore, the positive feedback and constructive criticisms from Dr. Tanja Scheelcaase, Bas van Westerlo and Dr. Douglas Mulhall were indispensable to find recommendations for a further development of the model. Finally, the valuable advice given by Prof. Halman and Frans Beckers always helped me in looking at the complete picture of the project.

I thank my fellow students, colleagues and all my dear friends in the Netherlands for filling these two years with multicultural experiences. It was, and still is, my pleasure to know about your traditions and sharing our different viewpoints as an international family. Additionally, I am forever indebted with my Dutch parents Frans and Annelies for their endless support and motivation to overcome difficulties; and with my fiancé Jaap for his patience, valuable and constructive suggestions.

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Andrea Herrera Jaramillo
13th August, 2013

Contents

CHAPTER 1
Introduction

This chapter presents a general description of the motivators of this thesis. It describes the environmental damage caused by the industrial activities and the building sector as one of its largest contributors. C2C framework suggests, unlike several environmental assessment methods, designing buildings with positive effects. Nevertheless there is not an integrated C2C model or method in practice that gives directions to the building professionals in designing and evaluating 'C2C buildings'. This has led to the research question: How can the Cradle to Cradle® principles be integrated into a model to guide the design and evaluation process of buildings?

1.1 Problem Description

Climate change, loss of genetic plant and animal diversity, oil crisis, and scarcity of materials; are few examples of the environmental damage due to the industrial activities of our society. Additionally some social problems have arisen such as the conflicts between nations for controlling the territories with abundant resources. Michael Braungart and William McDonough, authors of Cradle to Cradle® (C2C), have looked at the *Industrial revolution* retrospectively and described it as a system of production that:

- Puts billions of pounds of toxic materials into the air, water, and soil every year
- Produces some materials so dangerous they will require constant vigilance by future generations
- Results in gigantic amounts of waste
- Puts valuable materials in holes all over the planet, where they can never be retrieved
- Requires thousands of complex regulations not to keep people and natural systems safe, but rather to keep them from being poisoned too quickly
- Measures productivity by how few people are working
- Creates prosperity by digging up or cutting down natural resources and then burying or burning them
- Erodes the diversity of species and cultural practices
  (Braungart & McDonough, 2009)

Rachel Carson, with her book *Silent Spring*, started the *next industrial revolution* in 1962. She began revealing the abuses of the industrial system exposing the dangers of pesticides. A decade later, the Stockholm Conference triggered political and public awareness of global environmental problems. Consequently, the industry started recognizing the negative environmental impact of their activities in the early 1970's. Since then the different industrial sectors focused on reducing their negative environmental impact.

In the building sector, the professionals have paid more attention on how buildings are designed, built and operated. Several methods are used to measure the environmental performance of buildings. These methods, among them *Eco-design* and measuring techniques as *Life Cycle Assessment* (LCA), were developed with the aim of minimizing the environmental damage caused by human activity (Bor, 2011). They are based on an eco-efficiency approach which seeks to minimize the damage, and simultaneously decreasing a negative footprint.

Despite the fact that industrial companies have been committed, for more than 30 years, an environmental improvement for the future is not yet expected. The Intergovernmental Panel on Climate Change (IPCC), has predicted severe environmental damage for the upcoming years. For instance, European mountainous areas will face glacier retreat and extensive species loss up to 60% by 2080. By 2020, in some African countries, yields from rain-fed agriculture could be reduced by up to 50%. Endemic morbidity and mortality due to diarrheal disease primarily associated with floods and droughts are expected to rise in East, South and South-East Asia due to projected changes in the hydrological cycle. By 2020, significant loss of biodiversity is projected to occur in some ecologically rich sites in Australia and New Zealand, including the Great Barrier Reef and Queensland Wet Tropics. In Latin America changes in precipitation patterns and the disappearance of glaciers are projected to significantly affect water availability for human consumption, agriculture and energy generation (IPCC, 2007).

Evaluating the negative expectations for the future, it is concluded in agreement with Braungart and McDonough, that the eco-efficiency approach or the 'reducing focus' is only delaying the environmental damage without providing a real solution. Inspired by this Braungart and McDonough developed Cradle to Cradle® as an innovation platform for designing *beneficial economic, social and environmental features into products, processes and systems*. The authors encourage companies and designers not trying to merely reduce the negative environmental impact of products, but designing and producing with positive effects on the environment. Cradle to Cradle® suggests a balance between *Eco-efficiency* and *Eco-effectiveness,* based on improving product quality, by moving from simply being 'less bad' (eco-efficiency) to becoming 'good' (eco-effectiveness).

The definition of the term sustainable development released by the Brundtland Commission in 1987 is as follows: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". It is clear that Cradle to Cradle® represents a better approach to achieve a sustainable development. In theory, it does not compromise the ability of future generations to meet their own needs, and neither is it going to reverse all the damage caused by more than a century of industrial activities. Cradle to Cradle® is considered able of steadily improving products and solving today's problems (Usa Today, 2013).

Figure 1.1 compares how, in the built environment, the traditional thinking of sustainability and Cradle to Cradle® differ in targeting the *sustainable development*. The question mark (?) for C2C, under *Methods available in the built environment,* means that there is none in practice a C2C method or tool for the design and evaluation of buildings. The application of Cradle to Cradle in this sector is limited to some general guidelines, construction materials and interior design products.

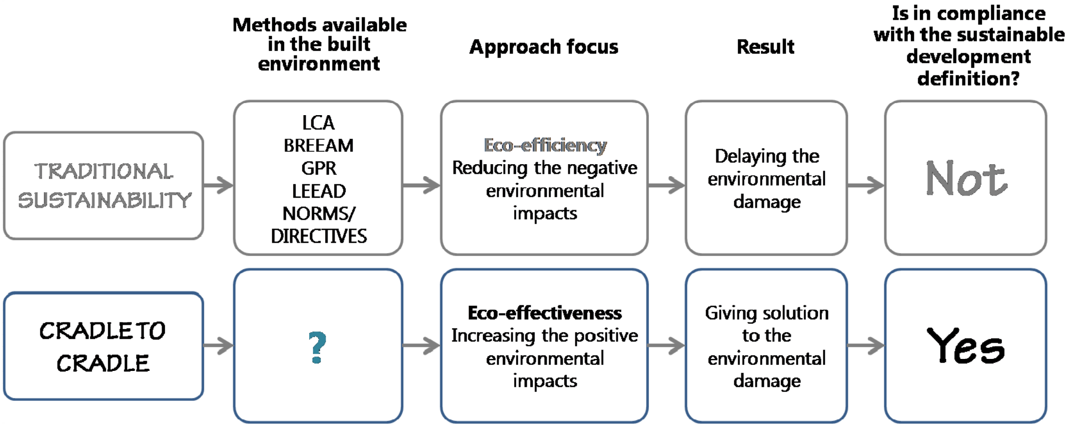

Figure 1.1–Comparison between traditional sustainability and Cradle to Cradle

1.2 Problem Statement

The different industrial sectors, among them the building sector, are large contributors of the environmental damage. When it comes to the implementation of sustainability, the building professionals are more likely to work with models and methods that give directions toward a 'sustainable' goal. A large number of environmental assessment methods such as BREEAM and GPR, are in practice to guide the design and evaluation process of sustainable buildings. The overall purpose of these methods is to reduce the negative environmental impact. Even though they are not originally intended to serve as design guidelines (Crawley, 1999), they are used in practice as such to guide the process towards a 'sustainable' result. These methods have an eco-efficiency approach.

Cradle to Cradle® presents an approach based on eco-effectiveness, where products and systems stop being designed *'less bad'* and become *'good'*. Nevertheless the implementation of

Cradle to Cradle® in buildings is limited to the use of some guidelines. There is not an integrated C2C model or method in practice, as GPR and BREEAM, which gives better directions to architects and planners in the design of a 'C2C building'.

1.3 Scope Aim

This thesis aims to set up a framework for a model that guides the design and evaluation process of buildings according to the Cradle to Cradle® principles. This model seeks to identify objectively the features of buildings that are based on the Cradle to Cradle® principles.

Figure 1.2 illustrates the model framework and the preliminary boundaries of the project. Inside the boundaries are the input and output description of the model. Usually a mathematical tool or software is used to transform input information (data) into output results (graphic results or reports). Making a mathematical model or software is out of the scope of this assignment.

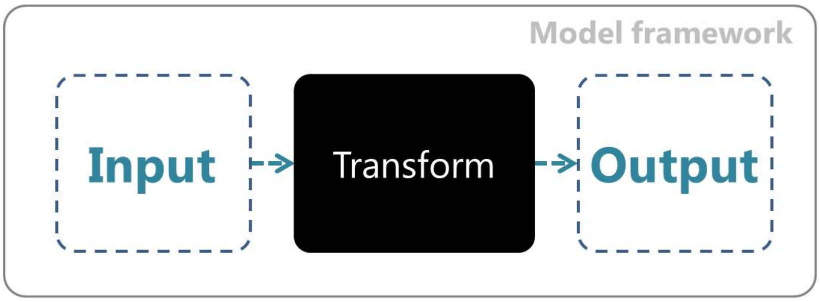

Figure 1.2–Model framework and boundaries

1.4 Research Questions and Sub-questions

The previous sections have leaded to the following research question and sub-questions:

How can the Cradle to Cradle® principles be integrated into a model to guide the design and evaluation process of buildings?

1. What environmental assessment models are available in The Netherlands to design and evaluate buildings in terms of 'sustainability'?
   To answer this question, a literature study is carried out among the environmental assessment methods/models used by the building professionals in the Netherlands. A preference is given to the models used by Volantis B.V. due to access to the information provided by the company.

2. What Cradle to Cradle® literature is related to the design process and evaluation of a building?
   The related Cradle to Cradle® publications are studied here, in order to identify the main C2C criteria for the model.

3. What are the differences between the available environmental assessment methods and Cradle to Cradle®?

An analysis is made between the literature analysis of the environmental assessment models and the Cradle to Cradle publications associated to the built environment.

4. What are the main aspects to be included in a C2C model to design and evaluate buildings?
   The previous questions should lead to the definition of the C2C aspects or criteria for the model. A special focus is given to the already defined C2C criteria and the methodology used by the environmental assessment methods.

5. How can a building be evaluated and classified in order to show its C2C features?
   A brainstorming session or literature study could be used to generate a proposal for illustrating the results of the assessment.

1.5 Research Methodology

Figure 1.3 illustrates the research methodology of this project. This methodology aims to find the answers of the research question and sub-questions. A literature study is performed at the beginning of the project. This analysis and the comparison between the environmental assessment methods and C2C will help to develop the framework for the model.

The second phase is the development of the framework itself. Additionally to the literature analysis, the C2C inspired building *Villa Flora* will be analyzed in order to identify the performance of the building according to the aspects proposed by the model. The analysis of *Villa Flora* illustrates the design process of a building. It will involve interviews, observations of the systems, review of documents among other sources that present related information.

The framework of the model will be evaluated by a panel of experts in the Cradle to Cradle field. Recommendations will be given based on their evaluation. If necessary a second building will be used to test the model.

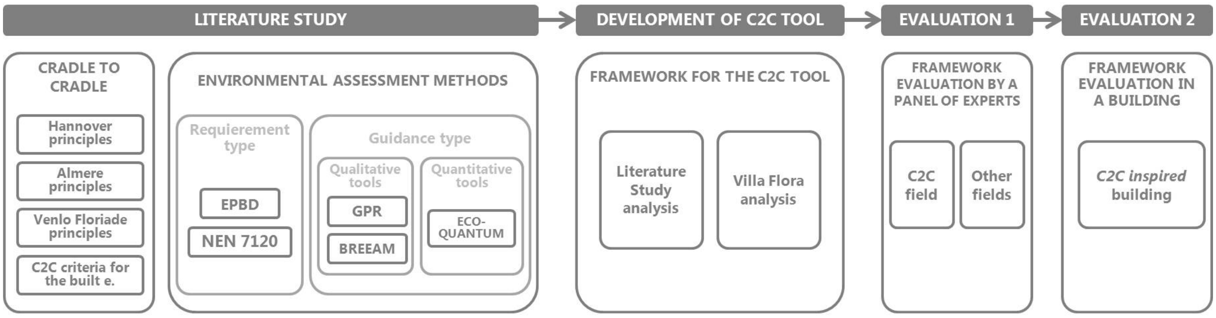

Figure 1.3–Research methodology

1.6 Research Relevance

Scientific Relevance

The Cradle to Cradle® principles have been translated into a certification program that guides designers and manufactures in creating C2C certified products. This program does not apply to buildings. It is therefore necessary to translate the C2C principles for building design, in order to make this philosophy more clear and present results objectively. A good solution could be a model that guides the building professionals in designing and evaluating buildings in terms of C2C. This model could give an objective assessment of the C2C aspects applied in buildings.

Practical Relevance

The development of a C2C model for the built environment will provide guidance to design buildings with positive environmental impacts. It can start a change in the goals that are set nowadays by the building professionals. Instead of only reducing a negative environmental impact, the C2C model can lead to a better understanding of the positive effects that a building could have. Looking at the big picture this could contribute directing the efforts toward a sustainable development.

CHAPTER 2
Literature Review

This chapter presents the analysis of five environmental assessment methods that are commonly used in the Netherlands: *Energy Label*, *NEN 7120*, *GPR Building*, Eco-quantum and BREEAM-NL. Their approaches are compared with the C2C framework. Some guidelines for the built environment have been proposed by the C2C experts, but these are generic and not measurable. Thus, one could say that the next step of the C2C criteria for the built environment is a C2C model that guides the design and evaluation process of buildings.

2.1 Environmental Assessment Methods in the Dutch Built Environment

Since 1970's companies started recognizing the negative environmental impact of their industrial activities. The building sector has tried reducing its impact focusing on how buildings are designed, built and operated (Haapio, 2008). Environmental assessment methods and tools are used to guide this process and to measure the environmental performance of buildings. The use of a specific method depends on the country and the impact to be evaluated.

Reijnders and Roekel (1999) have classified the environmental assessment instruments in two types: *Requirement type* and *Guidance type*. *Requirement type* methods are based on the law or may have a private, voluntary and contractual origin. *Guidance type* methods tend to be more comprehensive and aim at showing those involved in the building process the potential for improvement. In the Netherlands the mandatory environmental requirements are associated to energy efficiency, reuse of building wastes and some individual substances such as benzene, cadmium, formaldehyde, lead, and mercury compounds (Reijnders, 1999). No requirements are set in the Netherlands to water efficiency and building components in terms of sustainability.

Guidance type instruments can be divided in qualitative tools and quantitative tools. Qualitative tools are based on scores and criteria that indicate the relative 'environmental friendliness' using a number of building characteristics. Quantitative tools use physical life cycle assessment (LCA) with quantitative data on flows of matter and energy (Forsberg and Malmborg, 2004).

This chapter describes one directive and one norm that belong to the *Requirement type* classification. Within the group of *Guidance type* two rating systems are presented as qualitative tools and one LCA-based approach is presented as quantitative tool. Due to the high number of environmental tools available, a selection was made based on the application of these in the Netherlands and their respective representativeness within the classification.

Inside *Requirement type,* the Energy Performance of Building Directive (EPBD) and NEN 7120 are selected. The EPBD is selected for being a compulsory directive for all the EU Member States from 2006 on (Andaloro, 2010); although in the Netherlands its application is not controlled by the Dutch government nowadays. NEN 7120 is the new energy performance standard for both new and existing buildings in the Netherlands and has become compulsory since 1 July 2012 (NEN, 2013). GPR Building, the Building Research Establishment Environmental Assessment Method (BREEAM) and ECO-QUANTUM are the environmental assessment methods selected within *Guidance type.* GPR Building and BREEAM are qualitative tools used to score the 'environmental' performance of a building and ECO-QUANTUM belongs to a family of LCA-base being an example of quantitative tools.

In order to compare the environmental tools described in this chapter, the evaluative framework developed by Baumann and Cowell (1999) is used. It was developed as a basis for comparing environmental management approaches and compares them regard to *Contextual and Methodological aspects*. Within *Contextual aspects* the following criteria are considered: type of decision maker, overall purpose, object analyzed, and perspective. The *Methodological aspects* included in this analysis are: investigated dimensions, basis for comparison, system boundaries, type of data, and evaluation of results. This evaluation framework is employed in this research due to the several criteria involved to compare the environmental assessment methods. It will help to identify the differences between their approaches and C2C.

2.1.2 Requirement type: EPBD and NEN 7120

This section focuses on the compulsory norms or directives that are nowadays implemented in the Netherlands regarding to *Energy efficiency*. The aim of energy performance regulations in the building sector is to reduce energy consumption in buildings caused by heating, hot water production, lighting, cooling and ventilation (Beerepoot, 2007).

Energy Performance of Building Directive

Contextual Aspects

The Energy Performance of Building Directive (EPBD) has been created as an energy policy for EU Member States to monitor and reduce energy consumption. The European Union Commission set this directive due to the high dependence on energy supplied from countries outside the EU (50% in 2000 and estimated to reach 70% in the upcoming 20-30 years) and the increase in greenhouse gas emissions (Andaloro, 2010). Therefore the *decision maker* of this directive is the EU authorities and its *overall purpose* is as strategic decision. The decision makers of the EPBD in the Netherlands are local authorities, contractors, architects and private building owners that want to communicate the energy performance of their buildings. This directive has a retrospective perspective where a building is analyzed once that it is built.

The EPBD made it compulsory for all EU Member States to introduce energy certificates from 2006 onwards. According to RICS (Royal Institution of Chartered Surveyors), in the Netherlands the certificate is called 'Energielabel' (*Energy Label* in English). This label was introduced on January 2008 for all flats and houses rented or sold, although it is up to the parties involved (buyer and seller) to have the certification. On January 2009 it became a permanent certification for public buildings.

According to Baumann and Cowell the nature of environmental approaches can be divided into *concepts* and *tools*. A *concept* is an idea about how to achieve sustainability and a *tool* consists of a systematic step-by-step procedure and a mathematical model. It could be said that EPBD is in this case a 'concept' that aims reducing energy consumption in the EU Member States, and the *Energy Label* is the tool used in the Netherlands to measure the energy performance of buildings. Tools are more structured than concepts and usually present a specific methodology. Thus the methodological aspects of the EPBD are identified through the *Energy Label*.

Methodological Aspects

The *Energy Label* is compulsory for public buildings that are not considered national heritage and have an area greater than 500m^2. This certification consists of several pages that contain the energy class of the building and recommendations to improve its energy performance. In line with Baumann and Cowell, the types of effect studied (*investigated dimensions*) with the methods can be classified into environmental, economical or social. The *Energy Label* belongs to the environmental category. The basis of comparison of the *Energy Label* is the result of a mathematical model called the Energy Index (EI) and the standard value defined for the specific function of the building. Its evaluation scale from A to G allows comparing different alternative solutions between them even when their functions differ.

The spatial boundary is defined by the geographical limitations where the method or tool can be valid. Another way of defining the spatial boundary is based on the object analyzed, for instance if the analysis is performed for a component, building, site or city. Ever since the *Energy Label* is applied only to Dutch buildings and the EI is developed under the Dutch assessment directives of ISSO and BRL 9500, its spatial boundary is the Netherlands. There are two ways of analyzing the temporal boundary. The first one is based on the time for which the results and certificate are valid, and the second one is based on the time defined by the method as the life span of the object analyzed.

The temporal boundary is related to the 10 years validation of the certification and 75 years considered as the life span of the building. The data used for the Energy Label are the quantitative measures of its thermo characteristics, mechanical and electrical installations. The result of the Energy Index is presented as a single parameter. This parameter is used to classify and compare the building according to its label class, see figure 2.1. Additionally to the EI, the energy consumption (MJ/m2) and the CO_2 (kg/m2) emissions of the building are also obtained as secondary information.

A^{++}	A^{+}	A	B	C	D	E	F	G
≤ 0.50	0.50 – 0.70	0.71 – 1.05	1.06 – 1.15	1.16 – 1.30	1.31 – 1.45	1.46 – 1.80	1.61 – 1.75	> 1.75

E
(Energie-index)

Figure 2.1 – Evaluation scale of the 'Energielabel'
Source: Energieprestatie advies utiliteitsgebouwen

NEN 7120

Contextual and Methodological Aspects

NEN 7120 is one of the norms that are part of the building regulations (Bouwbesluit) in the Netherlands. NEN 7120 contains the Dutch Energy Performance Standard and from July 1st 2012 has replaced NEN 5128 used for new residential buildings and NEN 2916 for non-residential buildings (Agentschap NL, 2012). This norm combines residential and non-residential buildings and is compulsory for all new buildings. The decision makers are the authorities, contractors and architects. The measure of energy in the NEN 7120 is expressed as Energy Performance Coefficient (EPC). The current EPC requirement for residential buildings is 0.6. For non-residential buildings the EPC depends on the building category (Agentschap NL, 2013). The overall purpose of the NEN 7120 is to set an EPC of zero by the year 2020. An EPC of zero means that the building is energy neutral or in others words that the building itself generates its own energy demand. It is intended that in the future the NEN 7120 includes also the *Energy Index (EI)* of the *Energy Label* described previously.

The energy performance in the NEN 7120 is calculated based on the sum of the energy used for heating (H), humidification (hum), ventilation (V), lighting (L), cooling (C), dehumidification (dhum), hot water (W) and the tools used for auxiliary energy (aux, to), subtracting the energy generated by the building itself (Ekerschot, 2008). The NEN 7120 has a prospective perspective, where the calculation of the EPC is made in the design phase and it is a requirement to build the building. The software *VABI Elements,* models the input data and through a mathematical model presents the EPC as an end result. The EPC is the ratio between the energy used in Mega Jules (MJ) and the allowed energy in Mega Jules (MJ). The spatial boundary of this system is the Netherlands and the implicit temporal boundary is the period for which the EPC calculation is valid. This is until the building is built or major changes are made to the different energy installations of the building.

2.1.3 Guidance type: GPR Building, BREEAM-NL and ECO-QUANTUM

GPR BUILDING

Contextual and Methodological Aspects

GPR building is a software tool that assesses and rates the environmental impact, energy performance and design quality of buildings. The first version of GPR software was developed in 1995 by the municipality of Tilburg and the Dutch consultancy company *W/E Adviseurs*. GPR software is based on the triple-P concept: People, Planet, Profit (GPR, 2013). The decision makers are public authorities and building professionals (architects and building contractors).

GPR Building can be used for both the design of new and the retrofit of existing buildings. It is suitable for residential, office and school buildings. (Van Hulten, 2010). GPR is mainly used in the design phase of a building. This tool communicates the performance of the building within different categories: Energy, Environment, Health, User Quality, and Future Value. For every category or performance indicator, the building is rated on a scale from 1 (worst) to 10 (best). This tool can be used as decision support to improve the environmental performance of the building including the best options proposed by the software. According to *W/E Adviseurs* when a building is rated as 6 on every indicator, it meets the requirements of the Dutch National Building Act 2006.

The indicators and sub-indicators are calculated on the basis of a multi-criteria analysis, except for the indicator *Energy* and the sub-indicator *Materials*. Each sub-indicator consists of several criteria, giving the user a choice between different design options. The sub-indicators have weighting values that illustrates their importance within the category, see table 2.1. *Energy performance*, *materials* and *air quality* stand out for being the most important criteria within their categories. The weighting value is divided as points among the different options for each criterion. The points are first aggregated to the level of a sub-indicator (score of 1 to 10) and then aggregated to an indicator score. Figure 2.2 is an example of the inter-phase for the indicator Future value.

Table 2.1- GPR Indicators, Sub-indicators and weighting values:

Indicator/Category	Sub-indicator	Weighting
Energy	Energy performance	750
	Additional energy measures	250
Environment	Water	200
	Environmental care	100
	Materials	700
Health	Noise	150
	Air quality	400
	Thermal comfort	350
	Lighting and visual comfort	100
User quality	Accessibility	250
	Functionality	250
	Technical quality	250
	Social safety	250
Future value	Adaptability and future amenities	333
	Flexibility	333
	Perceived value	333

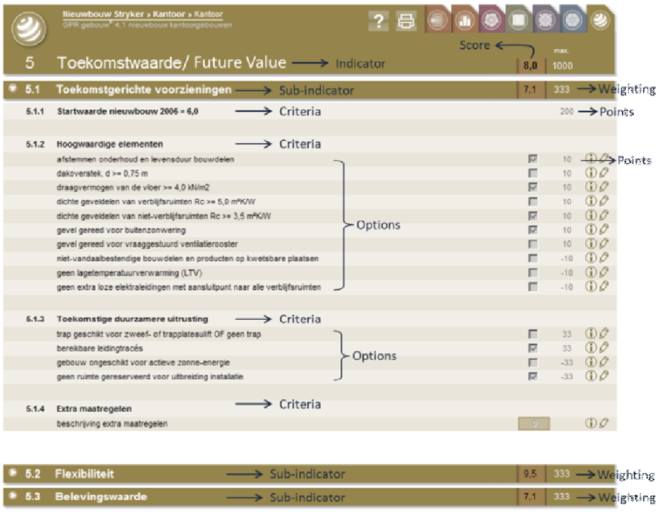

Figure 2.2 - Future Value indicator of GPR Building

The focus of the GPR analysis is the technosphere. The criteria *Materials* is evaluated according to a LCA impact assessment, composed of nine environmental impacts: depletion, global warming, ozone depletion, smog, human toxicity, ecotoxicity to water, ecotoxicity to land, acidification and eutrophication. The calculated impacts are aggregated into a single impact indicator called the *Shadow price* which is depreciated over the expected life time (75 years for residential buildings and 50 year for non-residential). The *Shadow price* is expressed in euro per square meter which is translated into 10 point scale and compared with the other criteria.

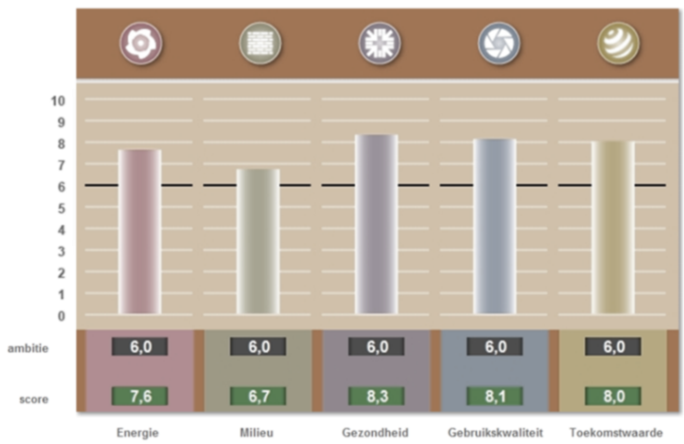

Figure 2.3 - GPR results according to its five indicators

The database used for every criterion is based on the information and regulations of the Netherlands, becoming this country the spatial boundary of the tool. The nature of the data is both quantitative and qualitative. Quantitative data is used for instance in the criteria of *Energy* where information to calculate the EPC must be provided. The main result of the GPR analysis is the performance of the building given through a score (from 1 to 10) in each of the five indicators, see figure 2.3. Additionally it presents the equivalent of *Energy Label* classification and the allocated CO_2 emissions.

Building Research Establishment Environmental Assessment Method Netherlands (BREEAM-NL)

Contextual and Methodological Aspects

BREEAM is a voluntary system which has been devised with the aim of reducing the impacts that buildings have on the environment through both their construction and use (Reijnders, 1999). BREEAM was developed by the Building Research Establishment (BRE). BREEAM-NL is the Dutch version of BREEAM and developed and managed by the Dutch Green Building Council (DGBC) licensed by BRE Global Ltd (DGBC, 2010).

Assessment is normally carried out at two stages: design stage and post construction stage. In the design stage a preliminary BREEAM-NL certificate is awarded performing a prospective analysis for a decision support. The post construction stage leads to a final certificate and unlike the design stage its overall purpose is as communication with a retrospective analysis. The temporal boundary of the preliminary certificate is until the building is built. There is not a defined temporal boundary for the final certificate therefore it is assumed that the certificated is valid until the building has a large renovation.

The building can be assessed as *Pass* (score >30%), *Good* (score >45%), *Very Good* (score >55%), *Excellent* (score >70%) or *Outstanding* (score >85%). The total score is determined by adding the preliminary scores of each category. There are some points available, the number of points varies on the building type, which the building can achieve in each category. The number of points achieved is multiplied by a weighting percentage that applies to each category, see table 2.2. The weights were defined within a research-based consensus conducted by BRE among different groups including government, suppliers, manufacturers and research institutions (Dutch Green Building Council, 2010).Energy stands out as the most important category within the method.

Table 2.2 - BREEAM categories and weighting values:

BREEAM Category	Weighting
Management	12%
Health and Comfort	15%
Energy	19%
Transport	8%
Water	6%
Materials	12.5%
Waste	7.5%
Land Use and Ecology	10%
Pollution	10%

The evaluation is based on the nine categories depicted in table 2.2. Different sub-categories are included according to international and local norms. The assessment requires qualitative and quantitative data. The data is entered into an assessment tool that translates the points achieved in every subcategory and gives a final score. The results are presented as percentage per each category and as total score. The total score is associated to the classification of *Pass*, *Good*, *Very good*, *Excellent*, and *Outstanding*. A graphic representation is given with stars, starting with one star for *Pass* and increasing in number up to five stars for *Outstanding*. The classification of the total score and energy performance expressed in MJ/m^2 are the basis for comparison between the certified buildings.

The goal behind BREEAM-NL is related to the council's mission of *drastically improve sustainability levels in the built environment, working towards climate neutral buildings that are both pleasant and healthy* (DGBC, 2010). It is promoted by the authorities but implemented voluntary by the building professionals. The main dimension is the environment and the category *Materials* is evaluated according to the following environmental impacts: Depletion of resources, Greenhouse effect, Ozone layer depletion, Smog, Human toxicity, Ecotoxicity to water, Ecotoxicity to land, Acidification, and Over-fertilization (DGBC, 2010).

ECO-QUANTUM

Contextual and Methodological Aspects

Eco-Quantum is a computer tool on the basis of LCA (Life Cycle Assessment) developed by IVAM and W/E Adviseurs. It aims to calculate the environmental effects during the entire life cycle of a building *from the moment the raw materials are extracted, via production, building and use, to the final demolition or reuse*. This includes the impact of energy and water use, the maintenance during the use phase and the differences in the durability of parts or construction needs (Kortman, 1997).

Based on an interview to Harry van Ewijk, one of the developers of Eco-quantum, the tool is not actively in practice nowadays due to the lack of financial support for its maintenance.

In spite of this, Eco-quantum is included in the current research for being a fully LCA-based tool that uses quantitative data for the environmental analysis of buildings. Two versions of Eco-Quantum were available three years ago. *Eco-Quantum Research* was a tool for analyzing and developing innovative and complex designs for sustainable buildings and offices. *Eco-Quantum Domestic* was a tool which architects could apply to quickly reveal environmental consequences of material and energy use of their designs of domestic buildings (Kortman, 1997). Consequently the decisions makers were local authorities, property developers, contractors and architects.

The overall purpose of this tool was to optimize the design of new and refurbished buildings from an environmental point of view. Therefore Eco-quantum was used as strategic decision. The focus of the decision was the technosphere emphasizing in technological systems rather than ecological but the main dimension analyzed was the environment. Eco-quantum offered different options as basis of comparison. It varied between per unit building/material component, a life cycle stage, per m^2 floor surface area, per m^3 of content, or per person depending on the object analyzed (Forsberga, 2004).

The Dutch LCA program *SimaPro 4* was used in Eco-quantum to calculate the environmental profiles per kilogram building materials and per processes (Kortman, 1997). Those environmental profiles were the input to the database *Environmental profiles* of *Eco-quantum research*. The latter prepared some standardized building components for *Eco-quantum Domestic* in the form of E*nvironmental profiles of components*. The input data is information about materials and quantities of the building component, energy and water consumption. The output is presented into four environmental indicators: resources, energy, emissions, and waste. The results are weighted based on these four indicators and represented in bar charts compared to a reference building or another alternative.

2.1.4 Comparison of the Environmental Assessment Methods

The Dutch authorities are the main decision makers of *Requirement type* methods and can influence companies to implement *Guidance type* in government-related projects. For private projects the main decision makers are the professionals in the built environment among them architects, building contractors, housing corporations and owners.

The overall purpose of the *Requirement type* methods is related to the goal of reducing CO_2 emissions and having energy neutral buildings by the year 2020. Therefore their analysis could act to support the decision makers to achieve their goals and are considered as strategic decisions. *Guidance type* methods have a communicational purpose to present the environmental performance of a building to stakeholders, government and society. One can say that these methods support decisions when they are used in the design phase and improvements can be applied to the building according to the results. In this case the overall purpose is as strategic decision.

The object analyzed identifies the focus of the decision (Baumann, 1999). The focus of the decision of all the methods presented in this section is the technosphere, focusing more in technological systems rather than ecological.

The perspective of the environmental assessment methods is related to the phase where the analysis is performed. Prospective perspective looks forward in time and aims to identify aspects for improving or selecting an alternative during the design phase. Retrospective perspective looks back in time and aims to evaluate the environmental performance of the building once that it is built. Therefore the *Energy Label* has a retrospective approach and NEN 7120 has a prospective approach. Guidance type methods can have both, prospective and retrospective approach depending on the phase where the analysis is performed.

At very general level, the types of effect studied can be classified in environmental, *economic* or *social* categories (Baumann, 1999). The main dimension of the methods analyzed in this section, is the environment. They focus on environmental effects such as global warming, depletion of resources and human toxicity. The latter is considered in this research as an environmental effect rather than social.

The basis of comparison of the methods differs from each other. Therefore it is only possible to compare alternatives using the same tool and the results from the different methods are not comparable. Additionally they can present different results even when analyzing the same aspect, as the Energy Label and NEN 7120. These requirement type methods assess the energy efficiency of a building but the results are presented in different units, Mega Jules per square meter with the EI (MJ/m^2) and a unitless value with the EPC (MJ/MJ). One could compare the secondary results of energy performance of BREEAM-NL with the EI, and the CO_2 emissions with the same result of GPR. However the data used in each method also differ from each other.

The system boundaries of the method are outlined in terms of spatial and temporal boundaries. It is only considered in this research the spatial boundary defined by the geographical limitations where the method or certificate is valid, being in this case the Netherlands for all the methods. Since the life span of the building is considered by the methods inside a range of 50 to 75 years and there is not a great difference between them, the temporal boundary specified here is based on the time for which the analysis and/or certificate is valid. This temporal boundary is only explicit for the Energy Label, being related to the expiration period of the certificate. For prospective approaches it is assumed that the temporal boundary is the period from the design phase until the building is built. After this, it is necessary to check with the building if the data entered in the calculation have not changed. For retrospective approaches, it is assumed that the analysis is valid until major changes are performed in the building.

The type of data that enters in each tool is classified in this analysis as quantitative or qualitative. The requirement type methods use quantitative input data and provide quantitative output. The majority of the data used in GPR and BREEAM-NL is qualitative and the main results are presented in the same way through scores and categories. Eco-quantum uses quantitative data, although their results are presented in a qualitative way.

Each method has its own manner of presenting the results. This is the information provided after the method assesses the data. Table 2.3 presents how the methods evaluate the results. Most of them use a rating system where an alternative is classified in a category or assigned a score. Normally they present graphic representations to illustrate the performance of the building within the classification system. The contextual and methodological aspects mentioned previously are also summarized in this table.

Table 2.3 - Comparison of the Environmental Assessment Methods

EVALUATIVE FRAMEWORK		Requirement type		Guidance type		
				Qualitative tools		Quantitative tools
		EPBD 'Energy Label'	NEN 7120	GPR building	BREEAM-NL	ECO-QUANTUM
Contextual Aspects	**Decision makers**	EU commission and building professionals	Dutch authorities, building contractors and architects	Local authorities, building professionals	Building professionals	EQ-domestic: architects EQ-research: Local authorities, property developers, housing corporations
	Overall purpose	Strategic decision	Strategic decision	Communication, strategic decision	Communication, strategic decision	Strategic decision
	Object analyzed	Techno.	Technosphere	Technosphere	Technosphere	Technosphere
	Perspective	Retrospective	Prospective	Prospective and Retrospective	Prospective and Retrospective	Prospective and Retrospective
Environmental parameters		Global warming	Global warming	Global warming, depletion of resources, ozone layer depletion, smog, human toxicity, ecotoxicity to water, ecotoxicity to land, acidification, eutrophication	Greenhouse effect, depletion of resources, ozone layer depletion, smog, human toxicity, ecotoxicity to water, ecotoxicity to land, acidification, eutrophication	Greenhouse effect, depletion of resources, depletion of the ozone layer, photochemical oxidant formation, human toxicity, ecotoxicity to water, ecotoxicity to land, acidification, nitrification, energy consumption, waste, dangerous waste
Methodological Aspects	**Main dimension**	Environment	Environment	Environment	Environment	Environment
	Basis for comparison	Energy Index	EPC	CO_2 emissions	Energy performance (MJ/m^2) CO_2 emissions	Per unit building material/component, a life cycle stage, per m^2 floor surface area, per m^3 of content, or per person.
	Spatial boundary	The Netherlands	The Netherlands	The Netherlands	The Netherlands	The Netherlands
	Temporal boundary	Label: 10 years	Until construction	Until construction Until major changes	Until construction Until major changes	Until construction Until major changes
	Type of data	Quantitative	Quantitative	Qualitative	Qualitative	Quantitative
	Evaluation of results	Categories: A++ B E A+ C F A D G	EPC	Score (1-10) in each category: Energy, environment, health, user quality, and future value	Categories: Pass, Good, Very good, Excellent, Outstanding	Environmental indicators: Resources, energy, emissions, and waste

2.1.5 Conclusion Environmental Assessment Methods

A large number of environmental assessment methods are available to assess buildings in terms of sustainability. In practice, these methods are used as design guidelines to support strategic decisions in selecting or improving an alternative building solution. This chapter presented five methods that are commonly used by the building professionals in the Netherlands. The analysis was carried out at two *requirement type* and three *guidance type* methods. The latter evaluates buildings in a larger scale including additional criteria. *Requirement type methods* are norms or directives that usually evaluate a single aspect of the building. Norms that evaluate only the energy efficiency were selected for this analysis.

Since different input and output data is provided by each method, it is not possible to compare the environmental assessment methods between them. Hence the evaluative framework proposed by Baumann and Cowell was used to compare some contextual and methodological aspects.

The overall purpose of these methods is based on reducing the negative environmental impact of buildings. These methods include different environmental parameters upon which the performance of the building is evaluated. *Guidance type* methods use similar environmental parameters through the criteria of materials. The requirement type methods *Energy Label* and *NEN 7120* are based only in the global warming effect. GPR Building and Eco-quantum illustrates the results through some environmental indicators. The *Energy Label* and BREEAM-NL have different classification systems where a building is assessed according to a rating scale.

Table 2.4 below relates the different categories proposed by the methods in order to assess a building in terms of sustainability. Energy is the common category and the most important criteria in all the methods. *Guidance type* includes other categories as *health* and *user quality*. The categories are organized from quantitative (at the top) to qualitative data (at the bottom).

Table 2.4 - Categories of the Environmental Assessment Methods

	GPR	BREEAM	ECO-QUANTUM	EPBD	NEN 7120
Quantitative	Energy	Energy	Energy	Energy	Energy
	Environment	Materials	Resources		
		Water			
		Land use and ecology			
		Pollution	Emissions		
↓		Waste	Waste		
	Health	Health and comfort			
Qualitative	User quality	Transport			

2.2 Cradle to Cradle in the Built Environment

2.2.1 What is Cradle to Cradle®?

Cradle to Cradle® is an innovation platform developed by architect William McDonough and chemist Prof. Dr. Michael Braungart for designing *beneficial economic, social and environmental features into products, processes and systems.* In 2002 Braungart and McDonough published the book *Cradle to Cradle: Remaking the Way We Make Things*. Through this book the authors encouraged companies and designers not to try to reduce the negative environmental impact of products but design and produce with positive effects.

The following philosophical statement illustrates the ambition of Cradle to Cradle® related to the economical and ecological prosperity of the world: *"Our goal is a delightfully diverse, safe, healthy and just world, with clean air, water, soil and power — economically, equitably, ecologically and elegantly enjoyed."* Cradle to Cradle® suggests a balance between *Eco-efficiency* and *Eco-effectiveness*. Cradle to Cradle® is based in improving product quality by moving from simply being 'less bad' to becoming 'good' (Bolton, 2012), or in other words from eco-efficiency to eco-effectiveness, see figure 2.4.

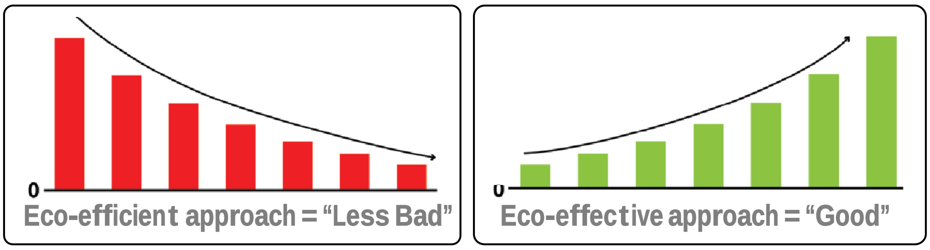

Figure 2.4 – Eco-efficiency versus eco-effectiveness.
Source: Design for a Cradle to Cradle® future

Eco-efficiency was the focus of the traditional sustainability concept created in the early seventies as a response of the awareness of the environmental damage. In the nineties, designing methods such as *Eco-design* and measuring techniques as *Life Cycle Assessment* (LCA) were developed with the aim of minimizing the environmental damage caused by human activity (Bor, 2011). The eco-efficiency approach seeks to reduce or minimize damage, decreasing simultaneously a negative footprint.

Agreeing with Braungart and McDonough the eco-efficiency approach is only delaying the environmental damage without providing a real solution. Cradle to Cradle® design aims to move from the line of *reducing and minimizing a negative footprint* which means being 'less bad' to *enhancing, maximizing a positive footprint* which means becoming 'good'. The Cradle to Cradle® approach integrates both eco-effective and eco-efficient approaches in a coherent and positive trajectory (Bolton and MBDC, 2012), see figure 2.5.

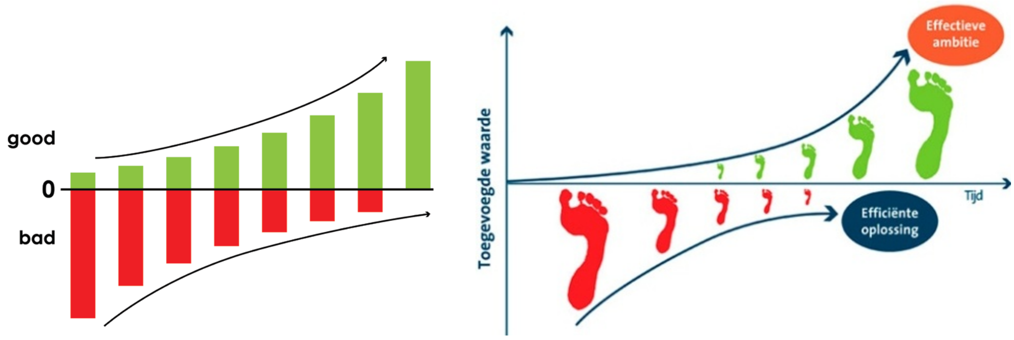

Figure 2.5 – Eco-efficiency and eco-effectiveness.
Source: Design for a Cradle to Cradle® future

When the object analyzed has a negative environmental impact, it is often related with a negative *ecological footprint*. The ecological footprint is defined as *the biologically productive land and water a population requires to produce the resources it consumes and to absorb part of the waste generated by fossil and nuclear fuel consumption* (Huijbregts, 2007).

The negative impact or ecological footprint is represented with the red bars and red footprints in figure 2.5. The traditional way of thinking of sustainability is about reducing that negative impact to zero. Cradle to Cradle® does not target the goal to zero, but to a positive footprint which is represented with the green bars and footprints in the same figure.

It could be said, based on figure 2.5, that Cradle to Cradle® complements the concept of sustainability, embracing an improvement from negative to positive and not only from negative to zero. Cradle to Cradle seeks to conceive *industrial systems* that *emulate the healthy abundance of nature*. The cherry tree is used by its authors to illustrate the design principles of the nature:

"...thousands of blossoms create fruit for birds, humans, and other animals, in order that one pit might eventually fall onto the ground, take root and grow. The tree makes copious blossoms and fruit without depleting its environment. Once they fall on the ground, their materials decompose and break down into nutrients that nourish microorganisms, insects, plants, animals, and soil... The tree's fecundity nourishes just everything around it." (Braungart, 2009)

When referring to the built environment McDonough has been saying it for years: *buildings like trees and cities like forests*. A building as a kind of tree, would purify air, accrue solar income, produce more energy than it consumes, create shade and habitat, enrich soil, and change with the seasons (McDonough, 1998).

Cradle to Cradle® principles

There are three guiding principles within the Cradle to Cradle® framework. The first one **Waste equals food** aims to apply the cycle of nutrients found in the nature, where one organism's waste becomes food for another: *A fruit tree's blossoms fall to the ground and decompose into food for other living things*. The second principle **Use of solar income** aims the use of energy that can be renewed as it is used: *a tree manufactures food from sunlight*. **Celebrate Diversity**, the third principle, seeks to celebrate diversity in means of biodiversity, cultural diversity and conceptual diversity: *A tree provides not just one design model but many, and provides an ecosystem for different species* (Braungart and Mulhall, 2010).

1. Waste equals food

This principle aims nutrients become nutrients again without the loss of quality. Here material flows can be divided into two categories: biological cycle (biological nutrients) and technical cycle (technical nutrients). Biological nutrients can be safely discarded into nature to serve as 'food'. Products within the biological cycle are called *Consumption Products* because they get consumed during their period of use. Technical nutrients are useful for the industry, and new products can be made of them. Within this cycle materials should be *upcycled* by retaining their high quality in a closed-loop (Braungart 2009). Products in the technical cycle are called *Service Products* because they do not get consumed but provide a certain desired service. Applied to architecture, these C2C nutrient cycles can serve as models for the design of materials and building systems that eliminate the concept of waste.

2. Use current solar income

This principle aims to use renewable sources powered by sun. Energy is generated by using direct and indirect solar energy and can be generated from wind, water/tidal, heat exchange or biomass. Buildings can make productive and profitable use of local energy flows, using direct solar energy collection, passive solar processes such as day lighting, wind power, among others.

3. Celebrate diversity

Diversity should be celebrated in means of biodiversity, cultural diversity and conceptual diversity. Operations and stakeholder relationships using social responsibility are an important aspect of this principle. Additionally systems and products should be beneficial and add value to all three domains: the economy, the society and the environment. In the nature photosynthesis and nutrient cycling adapt to the locality and yield an astonishing diversity of forms. In this sense professionals in the built environment can create buildings and cities that fit effectively into their own niches.

In practice these principles have been translated into a certification program for products which classifies them according to their C2C features. The Cradle to Cradle Certified program evaluates products and their manufacturers in five categories relating to human and environmental health: material health, material reutilization, renewable energy and carbon management, water stewardship, and social fairness. Product certification is awarded at five levels: Basic, Bronze, Silver, Gold, and Platinum.

This C2C Certified program does not apply to buildings. It applies to materials, sub-assemblies and finished products. The Cradle to Cradle® Certified program is used as guideline to achieve certain level of C2C. It could be said that it is the equivalent of the environmental assessment methods but applied only to products. In the built environment there is not a comparable program that could guide the design of a *'Cradle to Cradle building'*. Only some C2C criteria and examples have been provided by Mulhall and Braungart for the built environment.

2.2.2 Cradle to Cradle® guidelines for the built environment

Some C2C guidelines have been provided to the building professionals since the 1990's. Among those, published declarations such as the Hannover Principles and more recently in the Netherlands, the Almere Principles and the Floriade Venlo Principles.

The Hannover principles

The *Hannover Principles* were commissioned by the City of Hannover, Germany, when this city was selected as the site of the world exposition for the year 2000 (EXPO 2000). The theme of the EXPO 2000 was "Humanity, Nature, and Technology". The Hannover Principles aimed to provide a platform upon which designers can consider how to adapt their work toward sustainable ends (McDonough, 2000).

As it is explained in The Hannover Principles publication, these principles are a *set of maxims that encourage the design professions to take sustainability into consideration*. Following these principles are listed:

1. Insist on rights of humanity and nature to co-exist
2. Recognize interdependence.
3. Respect relationships between spirit and matter
4. Accept responsibility for the consequences of design
5. Create safe objects of long-term value
6. Eliminate the concept of waste
7. Rely on natural energy flows
8. Understand the limitations of design
9. Seek constant improvement by the sharing of knowledge

The Hannover principles were intended to be considered by designers, planners, government officials and all involved in setting priorities for the built environment. These principles, presented above, were translated into a framework based on the elements of *Earth*, *Air*, *Fire*, *Water* and *Spirit*. Earth element proposes guidelines related to materials and its proper resource management. The Air element expresses guidelines associated to air pollution, wind, noise pollution, ventilation systems and indoor air quality. Fire element is interrelated with renewable energy, energy production and energy consumption. Water element associates water use, water sources, potable water consumption, cyclical water concept and water waste. Spirit element *ensures that design will be seen as only part of the solution, never the whole*.

Even though these principles are expressed as guidelines for the built environment, their statements and descriptions are described in a generic manner. They do not specifically address the design or construction process of a building.

The Almere Principles

Almere is one of the main cities of Amsterdam Metropolitan Area. It is located in the province of Flevoland and borders with the cities of Lelystad and Zeewolde. The municipality of Almere has set some goals to growth ecologically, socially and economically. It aims to position Almere as *a national demonstration site for the large-scale implementation of sustainable systems*. The Almere Principles were defined to guide the process of achieving these goals by 2030. Following the seven principles are presented.

1. Cultivate diversity
2. Connect place and context
3. Combine city and nature
4. Anticipate change
5. Continue innovation
6. Design healthy systems
7. Empower people to make the city

Almere principles are expressed as the Hannover principles in maxims to guide the city to a sustainable development.

The Floriade Venlo Principles

Venlo is a city located in the Limburg region at the South-Eastern of the Netherlands and is nominated as '*The first Cradle to Cradle® region in the world*' by the Danish Architectural center (2012). Last year, 2012, an international horticultural exposition called *Floriade* was hosted in Venlo. Therefore the Floriade Venlo principles were created as guidance to the region and companies that were implementing C2C. The Venlo Principles are:

1. Innovate, innovate, innovate
2. Link location and context
3. Manage and appreciate food
4. Enjoy mobility
5. Let the sun shine
6. Create clean air, water and soil
7. Design with future generations in mind

The Floriade Venlo Principles are intended to inspire the design process of companies located in Venlo.

Cradle to Cradle® Criteria for the built environment

Mulhall and Braungart, through their *publication 'Cradle to Cradle Criteria for the built environment', provided planners with guiding criteria for developing a building with measurable C2C features*. It provides criteria associated to the three principles of Cradle to Cradle®. Additionally the authors recommend some tools for the C2C implementation and a method (roadmap) to measure the progress toward C2C. Table 2.5 contains the criteria defined by Mulhall and Braungart.

Table 2.5a - Cradle to Cradle criteria for the built environment:

	Criteria	Description
	1. State your intentions	*State your intentions for the building by describing your Goals and Milestones in relation to the three basic Cradle to Cradle® Principles*
C2C principle: Waste equals food	2. Define materials and their intended use pathways	*A. Use materials whose quality and contents are measurably defined in technical or biological pathways from manufacturing through use and recovery.* *B. Use materials whose impacts are measurably beneficial for human health and the environment.*
	3. Integrate biological nutrients	*Measurably recycle biological nutrients and water by integrating biomass production into buildings, landscaping, and spatial plants to generate more biomass, soil and clean water than before development of the site.*
	4. Enhance air and climate quality	*A. Measurably improve interior air quality for biological metabolisms so the air is cleaner than before it entered the building, and provides a comfortable climate for occupants.* *B. Contribute to enhancing outdoor climate by contributing air that is healthier for biological metabolisms than before it enters a building, and using climate change gases as resources through carbon management.*
	5. Enhance water quality	*Measurably improve water quality so the water is healthier for biological metabolisms than before it entered the building.*

Table 2.5b - Cradle to Cradle criteria for the built environment:

	Criteria	Description
C2C principle: Use current solar income	6. Integrate renewable energy	*Integrate renewable energy (current solar and gravitational income) into buildings and area plans so the building and site generate more energy than they use. Use exergy as a way to guide energy effectiveness*
C2C principle: Celebrate diversity	7. Actively support biodiversity	*Integrate measurable species diversity so the area supports more diversity than before development.*
	8. Celebrate conceptual diversity with innovation	*Conceptual diversity can be demonstrated measurably by focusing on special beneficial features of a building and integrating innovative components that are beneficial for the well-being of occupants and the environment.*
Stakeholder value	9. Add value and enhance quality for stakeholders	*Describe what the C2C features of a building do practically for the users.*
	10. Enhance stakeholders well-being and enjoyment	*By implementing each of the basic criteria, a C2C building enhances enjoyment by enhancing well-being. Spatial and aesthetic features that are less quantifiable can also enhance enjoyment and support diversity by demonstrating how well a building serves diverse stakeholders.*

Some of the criteria described in table 2.5 could be interpreted differently by users. Qualitative and subjective information is included. It becomes necessary to analyze how to include the subjective information into the model. For instance, how to measure objectively that *a building enhances stakeholders' well-being and enjoyment*.

2.2.3 Conclusion Cradle to Cradle in the Built Environment

The previous section aimed to find the meaning of Cradle to Cradle® and the most important aspects to be included in the framework of the decision support model. First of all, the model should track the progress of buildings from negative to positive, or from being 'less bad' (eco-efficiency) to becoming 'good' (eco-effectiveness). By progress, it is meant a *process of improvement* which can take years even after the building is built. This progress could be related to the available technological and scientific developments. For instance if it is intended to use 100% of C2C certified materials in a building, it cannot be achieved with the nowadays C2C offer. Therefore some certified materials could contribute to that goal and be included perhaps several years after the construction of the building, when these become available in the market.

As mentioned in the previous sections, when it comes into the implementation of 'sustainability' in the built environment, the building professionals are more likely to work with models and methods that give directions toward a sustainable goal. The C2C criteria presented in table 2.5 is lacking in such a model especially when most of the architects and planners are not C2C experts or even familiar with its principles. Additionally the C2C criteria can guide the process of designing a 'Cradle to Cradle building' but they are still generic and not measurable. Thus, one could say that the next step of the C2C criteria for the built environment is a decision support model that guides the design and evaluation process of buildings. The model could help designing C2C buildings and quantifying the extent until which the C2C principles are applied.

Braungart stated that a building could achieve C2C if it fulfills the three basic principles. The first C2C principle 'Waste equals food' targets *nutrients become nutrients again without the loss of quality.* Therefore the model should assess materials as *biological or technical nutrients* and their *loss of quality*. By naming a material as a 'nutrient' it is implied that it is not harmful for neither the environment nor the human health. Cradle to Cradle has an ABC-X tool that evaluates the toxicity of a specific material. Additionally there is a list of banned substances according to the cycle that the nutrient will follow. The meaning of *loss of quality* is explained further in this report.

The second principle 'Use current solar income' could be measured objectively. The criteria related to this principle is lacking in defining the required data to measure this aspect. Likewise, the criteria for the third principle 'Celebrate diversity' do not clarify the terms of *conceptual diversity with innovation* and how it could be objectively assessed.

In practice the Cradle to Cradle® principles have been translated to a products certification program. It presents the requirements that must be fulfilled in other to achieve a C2C certification. It assesses products based on the following categories: material health, material reutilization, renewable energy and carbon management, water stewardship, and social fairness. The C2C certification does not apply to buildings. Even if buildings would be included, this certification program would be not feasible due to the high complexity that the process means for a building. For instance the program assesses all the products up to 100 parts per million (ppm). This would be a long term process if applied to all the materials and components used in buildings. Additionally the cost of the certification program depends on the number of ingredients used in products; in consequence it would be an expensive certification program for buildings.

The Hannover, Almere and Floriade Venlo principles are guidelines proposed for specific regions. The Hannover principles refer better to the built environment. It suggests implicitly the analysis of the following aspects associated to the design process of a building: materials and resource management, air pollution, noise pollution, ventilation systems, indoor air quality, renewable energy, energy production, energy consumption, water use, water sources, potable water consumption, cyclical water concept, and water waste.

CHAPTER 3 Decision Support Model for Building Design

This chapter presents a proposal of a decision support model for building design. It answers the research question *how can the Cradle to Cradle® principles be integrated into a model to guide the design and evaluation process of buildings?* It is intended to provide a model that the building professionals can use to implement C2C into their developments. Additionally to communicate and compare objectively the C2C features of buildings.

3.1 Model framework

As mentioned before, the built environment has been focused on reducing the negative impact of buildings since 1970's. During these years, the sector has experienced a transition between recognizing its environmental damage and trying to reduce or minimize their impact. Braungart and McDonough suggest setting the goal higher to enhance and maximize a positive impact rather than reducing a negative one. This could be called as a *second transition*, where the building sector moves from generating negative environmental impacts to positive effects. The *second transition* would probably take some decades as well, but at least it has already started.

During the *first transition*, which is still in practice, several environmental assessment methods have been employed. These methods help both, recognizing the negative impact of buildings and designing 'less bad' options. A model based on the C2C principles is proposed here as a comparable method to guide the first step in designing and evaluating buildings with positive effects. The focus of the model is to bring buildings to a reference line where they do not have a negative impact. This means for instance buildings that do not generate waste and produce their own demand of energy from renewable sources. The model is able to measure the progress of buildings towards that reference. The horizontal axis of figure 2.5 (section 2.2 Cradle to Cradle in the built environment) is considered as the baseline or reference line of the model.

Figure 2.5 has been modified into figure 3.1 to illustrate the transition from a negative impact to the reference line. The yellow bars in this figure (green bars in figure 2.5) above the horizontal axis represent the positive impact of building. The model is not able to measure the positive value above the horizontal axis, but the value of the negative impact and the reference line. The reference line is defined as a 'green area', see figure 3.2, where buildings have a neutral performance. Above the reference line is when buildings really start providing a positive impact to the environment. It could be hypothetically possible to measure the positive impacts of buildings, defining for instance some units of growth. However this is a recommendation for a further research and out of the scope of this project.

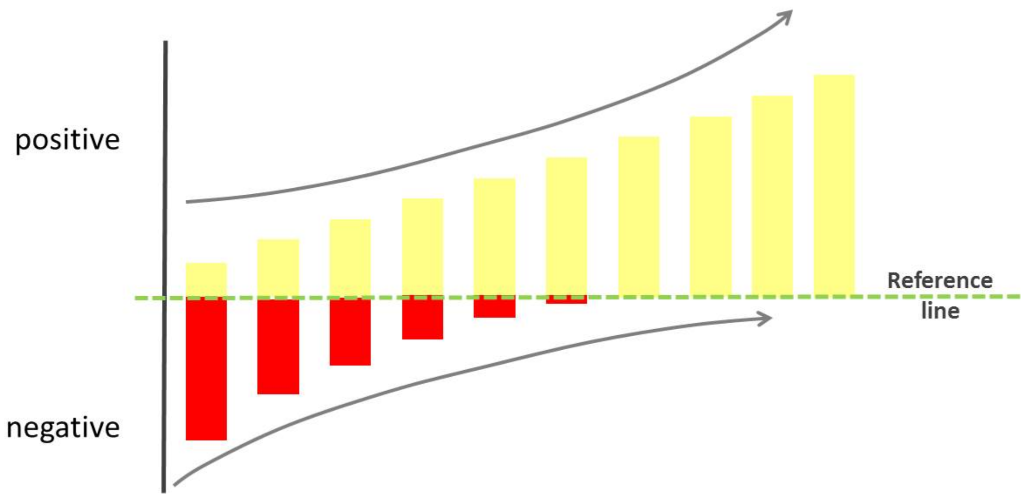

Figure 3.1- Eco-efficiency and eco-effectiveness trajectory with reference line.

Note that the yellow color in figures 3.1 and 3.2 has been selected only to make a distinction between the colors that represent the reference line and the positive impact. The green color characterizes the transition of buildings from the negative impact (red color bars) to the reference. It is considered as a first step, buildings reaching the reference line. This is associated with a 'green score' of 100. The performance of building start growing into the 'green area', while reducing the negative impact. Once buildings do not have a negative impact and have a 'green score' of 100, the focus can switch to the yellow or positive area. The measurement of the 'positive-ness' of buildings is considered as a second step and is not covered in this proposal. However buildings could start having positive impact even before reaching the 'green score' of 100. In this case, the model gives qualitative recognition of those building elements that contribute to the positive impact. For instance, if a building is producing more renewable energy than needed and that 'extra' renewable energy is exported to another building, it is contributing to a positive environmental impact. Therefore the model does not quantify the 'positive-ness' value in the environment of the produced and exported energy but it recognizes the building element. How the model makes this recognition will be explained in the following section.

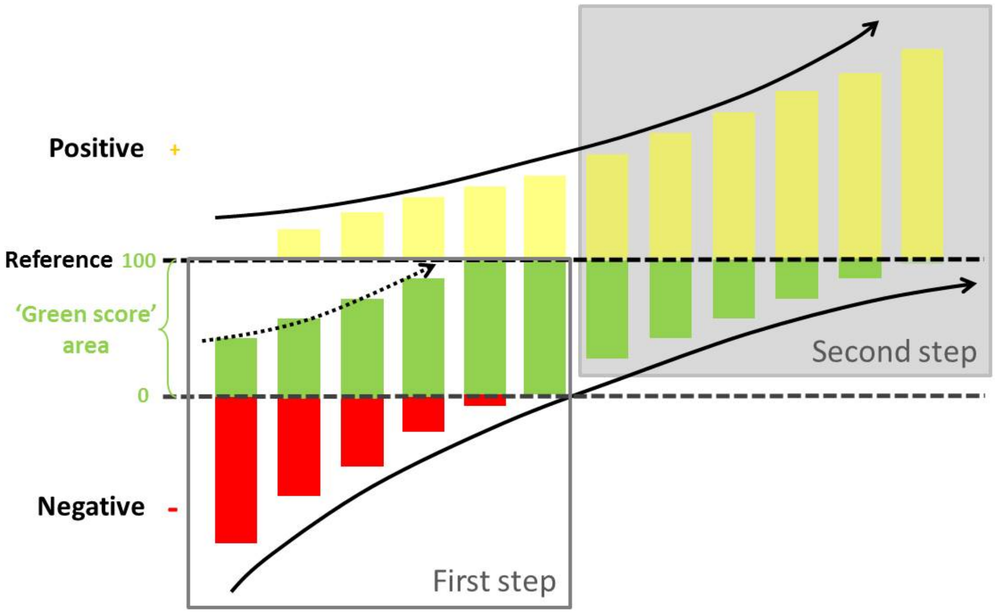

Figure 3.2- Transition from a negative impact to the 'green score' of 100

3.1.1 Measuring the transition from red to green

To guide the transition from a negative impact to the reference line, the model assesses the performance of buildings through eight categories. These categories are the result of an analysis on the C2C guidelines for the built environment and some environmental assessment methods used in the Netherlands. In the previous section it was concluded that a decision support model could be the next step of the *C2C criteria for the built environment*. Consequently, those criteria are used as baseline to create the categories.

Figure 3.3 presents the proposed categories for the model and its relations with C2C and the environmental assessment methods. The main C2C aspects from the literature analysis are listed at the left side. Additionally to the *Hannover principles*, the *C2C certification program*, and the *C2C criteria for the built environment*; the main concepts of the definition of a *C2C building* by Braungart and Mulhall is included.

*"A Cradle to Cradle building contains measurable elements that add value and celebrates innovation and enjoyment by: measurably enhancing the quality of **materials**, **biodiversity**, **air**, and **water**; using current **solar income**; being **deconstructable** and **recyclable**, and performing diverse practical and life-enhancing functions for its stakeholders."* (Braungart, 2010)

This definition aims to describe a C2C building and its measurable elements. However it is a complex definition to use. By analyzing it carefully some questions come to mind: *Enhancing the quality of materials, biodiversity, air, and water* is really *celebrating innovation and enjoyment*? Is there a standard definition of *innovation*? How does it enhance the *quality of biodiversity*? How does it perform *life-enhancing functions for its stakeholders*? It is out of the scope to find the answers of these questions. Only the following concepts of the definition are associated with the categories: Enhance *materials quality*, *biodiversity quality*, *air quality*, *water quality*, use *solar income*, and being *deconstructable* and *recyclable*.

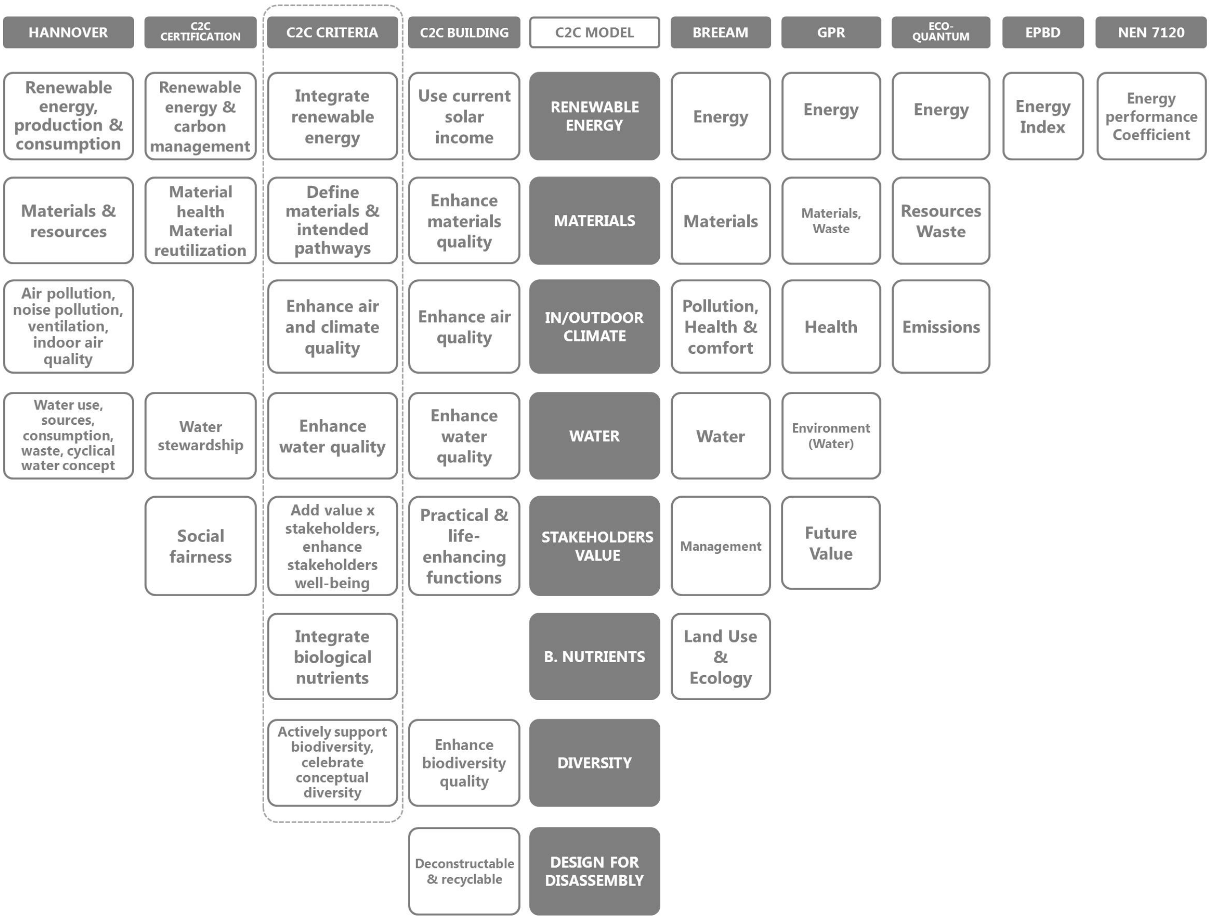

Figure 3.3 - Proposed categories and relation with literature study

At the right side of figure 3.3 are the categories of each of the environmental assessment methods. *Energy*, *Materials, In/outdoor climate*, *Water,* and *Stakeholders value* are the categories that present relations with most of the C2C and the environmental assessment methods. *Biological nutrients*, *Diversity* (biodiversity, cultural diversity, conceptual diversity), and *Design for disassembly* are mainly related to the C2C indicators. *Design for disassembly* is not a unique aspect of C2C but necessary due to the importance of measuring the disassemble potential of building components and its relation with the principle *Waste equals food*.

The categories are related to both C2C and the environmental assessment methods, but it does not mean that C2C and these methods consider buildings similarly. The main difference between them is that the environmental assessment methods do not consider a positive environmental impact as C2C does. A general name was chosen for each category due to the differences between C2C and the methods. The differences and the categories definitions are presented in this section. Since the model is based on C2C, a preference is given to this approach. For instance, in the category energy, C2C only targets *Renewable energy* to be produced and used by the building, while the methods evaluate the consumption and reduction of *Non-renewable* *energy*. So the model aims buildings that use and generate their own renewable energy (green area). The input of the environmental assessment methods in the model is related to their structure and measurement systems. The advantage of these methods is that they are used in the built environment and guide design and evaluation processes of buildings, whereas C2C provides principles and guidelines but not a comparable model or method.

3.1.2 Description of the model categories

Following a description of each category, describing the differences between C2C and the *Eco-efficiency* approach:

Renewable Energy

This category aims to identify the use and production of energy accepted by Cradle to Cradle®. The environmental assessment methods measure the energy performance of buildings and seek to reduce the consumption of non-renewable energy. Unlike, C2C suggests the use of only renewable energy and the generation of this by the building itself. It looks for buildings and areas plans generating more renewable energy than use. In addition the *energy sources*, the *material media* and the *energy effectiveness* are also important within C2C.

Materials

Within this category, materials are identified for technical or biological pathways. Their impacts should be beneficial for human health and the environment. Cradle to Cradle® identifies in detail the toxicity aspects of materials with a method called ABC-X. However assessing all the building materials through this assessment is not feasible. The environmental assessment methods *GPR* and *Eco-quantum* evaluate the impact of toxic emissions of building materials into the environment over the entire lifecycle. *BREEAM* tries to measure the reuse potential of the building façade and structure. Nevertheless these methods do not consider future reuse scenarios as C2C does.

Indoor and outdoor climate

The environmental assessment methods measure the indoor quality of buildings through different aspects such as lighting levels, natural ventilation, volatile organic compounds, thermal comfort, acoustic performance, light and visual comfort.

Cradle to Cradle® aims to enhance the interior air quality for biological metabolisms so the air is cleaner than before it entered the building and provide a comfortable climate for occupants (Braungart& Mulhall, 2010). Moreover C2C targets to enhance outdoor climate as well *by contributing air that is healthier for biological metabolisms, and using climate change gases as resources through carbon management.*

Water

GPR and *BREEAM* assess the water consumption and its use in buildings. These methods includes the analysis of aspects such as water recycling, major leak detention, irrigation systems, water savings devices, reception and use of rainwater, care and management of gray water.

While the environmental assessment methods measure only the consumption and use of water, Cradle to Cradle aims to enhance the water quality by integrating for instance water recycling systems with nutrient recycling, rainfall capture and storage, indoor plants and green walls.

Stakeholders value

The categories of *Future value* and *Management* of the methods GPR and BREEAM respectively, could be used to compare *Stakeholders value* although their criteria measure different data. This category aims to communicate the C2C features of buildings and their benefits for stakeholders. Information within this category is more qualitative than quantitative.

Additionally to the communication of the C2C features, *enjoyment* plays an important role although it is a subjective aspect. Braungart and Mulhall state that *by implementing each of the basic criteria, a C2C building enhances enjoyment by enhancing well-being*. The authors illustrate this criteria with some examples provided in table 2.5 in chapter 2. It would be necessary to provide objective aspects to measure stakeholders' value.

Biological Nutrients

This category seeks to generate more biomass, soil and clean water than before development of the site. It suggests recycling biological nutrients and water by integrating biomass production into buildings, landscaping, and spatial plans. Therefore this category enlarges the object analyzed including not only buildings but landscaping and areas. Furthermore from the C2C perspective, CO_2 is a chemical resource that is part of biological and biochemical processes. If buildings integrate those processes as well as becoming producers and users of renewable energy, they will be beneficial participants in the CO_2 cycle, in a similar way that trees are (Braungart & Mulhall, 2010).

Biological Nutrients is not a category considered by the environmental assessments methods *GPR* and *Eco-quantum* but proposed by the C2C theory. BREEAM evaluates aspects of the building that could be related to this category, such as *reuse of land*, *existing wildlife at the construction site*, and *plants and animals as co-users of the plan area*.

Diversity

Diversity is another category that is not covered by the environmental assessment methods but proposed by Cradle to Cradle®. One of the C2C principles itself is *celebrate diversity.* The *C2C criteria for the built environment* advocate buildings that actively support biodiversity, and celebrate conceptual diversity with innovation. This category aims to measure the goals in two sub-categories: biodiversity, and conceptual diversity with innovation. Some examples were given by Braungart and Mulhall on how to measure the goals within these sub-categories (see table 2.5).

Design for disassembly

This category aims to measure the disassembly potential of buildings. A higher disassembly potential will allow the use of materials and building components within the biological or technical cycle. Additionally buildings could perform different scenarios reducing waste or without waste at all. According to Dr. Elma Durmisevic (2006) buildings can be divided into three groups:

1. Building structures with low disassembly potential. Those are structures with standard construction waste stream (70-100% down-cycling and demolition).

2. Building structures with partial disassembly potential (30-70% of materials are down-cycled land filled or incinerated).

3. Building structures with high disassembly potential (0-30% of materials are down-cycled, land filled or incinerated).

The target for a C2C building would be group number three, seeking to have a high disassembly potential where 0% of materials are down-cycled, land filled or incinerated.

3.1.3 Sub-categories and Key Performance Indicators

The categories of the model are divided by sub-categories which contain Key Performance Indicators (KPI's). The results of the KPI's are translated into a 'green score' firstly for each subcategory, secondly per category. This score indicates the extent until which the C2C principles have been implemented in the building and its position in the 'green area'. Some relations could be found between KPI's from one sub-category with other ones of a different category.

The current graduation assignment focuses on defining the sub-categories and KPI's only for the categories *Renewable Energy* and *Materials*. These categories were chosen due to their high importance within both the environmental assessment methods and in the Netherlands. Figure 3.4 presents an overview of the model; the scope of this project is emphasized with the red lines.

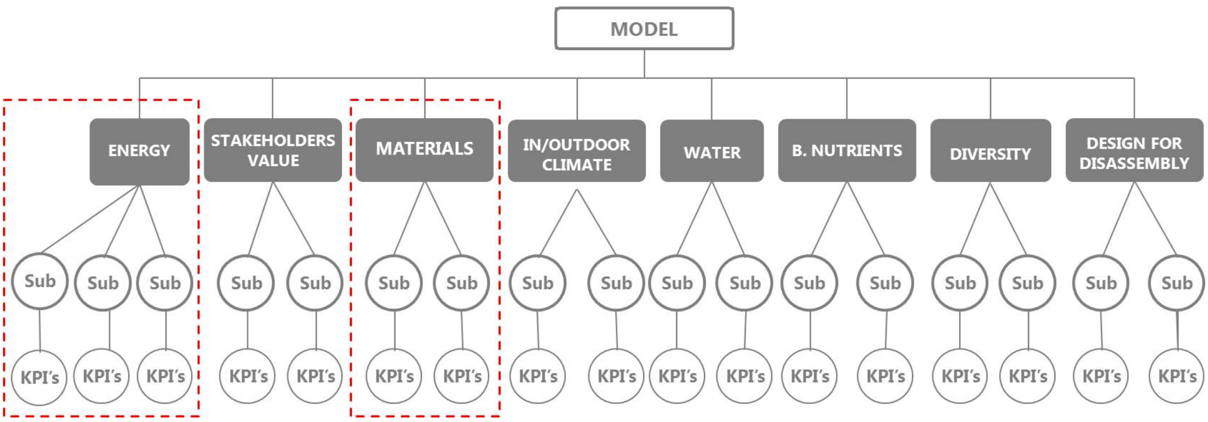

Figure 3.4 - Overview of the Model categories

3.2 Model category: Renewable Energy

3.2.1 Energy within the environmental assessment method

The EI (Energy Index) of the *Energy Label,* EPC of *NEN7120,* and the Energy categories of *GPR* and *Eco-quantum,* evaluate the energy performance of buildings according to the isolation values for the construction and the energy sources used by the installations. The methods identify the energy sources for heating, hot water, ventilation, cooling, lighting and humidification. These methods and norms present the result of the energy performance within their own classification systems and the value of the CO_2 emissions. They do not consider the CO_2 emissions as a nutrient and focus only on minimizing the energy performance.

BREEAM uses a qualitative assessment procedure to evaluate the energy performance. This method assesses building based on nine criteria among them reduction of CO_2, use of renewable energy, energy-efficient in external lighting, lifts, escalators, and thermal quality of building shell.

3.2.2 Cradle to Cradle Energy

Cradle to Cradle energy is defined as energy that is generated and applied effectively, using current solar or gravitational income, and material media that are defined as biological or technical nutrients. This C2C energy is qualified and quantified by the following three criteria: Energy sources, Material media, and Energy effectiveness. Table 3.2 presents a description of the C2C energy sources and some examples. Fossil and nuclear energy are not considered Cradle to Cradle® energy.

Table 3.2 - C2C and Energy. Source: Policy paper V.2.0 EPEA (2009)

	C2C ENERGY SOURCES	
Sources	**Examples**	**Remark**
Current Solar Income	Natural light	Primary current solar income
	Solar thermal	
	Photovoltaic	
	Photosynthesis	
	Photochemical	
	Wave and wind energy	
	Thermal mass storage	
	Heat exchange with ground, water and air	
	Respiration	Secondary solar uses
	Biomass-derived energy from: Composting, Biodigestion, Thermolysis, Hydrothermolysis, Pyrolosis, Gasification	
	Energy from fuel cells using fuel derived from biomass	
Gravitational, Kinetic	C2C energy can also be derived from gravitational energy generated by the sun, moon, and Earth, where kinetic energy is expressed for example in hydro and tidal power generation.	Consider the Third C2C principle. Tidal energy that destroys an estuary is not considered C2C. The same applies to water power when the installation of dams interrupts animal migrations.
	Kinetic energy can be C2C, depending on the primary source (solar or gravitational). Co-generation of kinetic energy from renewable sources can be C2C.	
Geothermal	In locations where geothermal energy reaches near the surface of the Earth, it is more possible to classify geothermal as C2C after materials used for delivery are qualified and quantified.	Evaluation is required of the materials and non-renewable forms of energy used to extract and convert it.
Fossil	Described as a form of renewable energy but **NOT considered as C2C energy.**	Fossil-derived energy is long-term stored energy and not replaceable in the timeframe when it is being used.
Nuclear	Described as a form of renewable energy but **NOT considered as C2C energy.**	The fusion nuclear energy on Earth can be hijacked by terrorists, is likely to accidentally explode or contaminate regions, can be used for nuclear weapons, and poses a ten or hundred thousand year waste disposal problem.

Climate change gases are seen as an abundance opportunity in Cradle to Cradle®. While the environmental assessment methods and norms, presented in chapter 2 aim at reducing CO_2 emissions, C2C uses it as a valuable nutrient for industrial and agro-industrial processes. CO_2 emissions can be used for nutrient recycling via biomass formation. The results of biomass fermentation are energy and mechanism to restore depleted soils. The further processing of formed carbohydrates as technical nutrients can contribute to build-up the technical metabolism and to reverse the greenhouse effect (Braungart & Mulhall, 2012).

3.2.3 Aim of the category Renewable Energy

The aim of the category Renewable Energy is to evaluate and monitor the progress of buildings towards *Cradle to Cradle® energy*. Therefore the following sub-categories are proposed: *Operating energy (OE)*, *Embodied energy of materials (EE)*, *Material media*, and *Energy effectiveness*. These represent the aspects for the assessment of buildings in this category.

3.2.4 KPI's of the sub-category: Operating energy

Operating energy (OE) can be defined as the energy expended in maintaining the inside environment through processes such as heating and cooling, lighting and operating appliances (Kumar Dixit, 2010). The amount and the C2C energy sources for the operation of the building are taken into account in this sub-category.

The first KPI that must be achieved in the design phase is related to the Dutch norm NEN 7120. This norm, as explained in chapter 1, states the permissible EPC for every building according to its function. The EPC is the ratio between the total primary energy used (MJ) and the total permissible primary energy use (MJ). It is expected that a C2C building is better than the norm. Therefore this KPI measures an improvement on the EPC. The following formula is used to calculate that improvement:

KPI A= (1 – EPC) * 100 [%]
KPI A = {1 - (energy used / permissible energy used)} * 100 [%]

Where:
KPI A = improvement in the Dutch energy performance indicator [%]
EPC = ratio between primary energy used [MJ] and total permissible primary energy use [MJ]

An improvement of 50% could be defined in this KPI. It is important to state that this percentage does not mean that buildings have positive effects. It only means that buildings are better than the Dutch norm. And the NEN 7120 is not based on using more renewable energy or on buildings that generate themselves their own energy. It is based on reducing the energy consumption of non-renewable energy sources. This can be seen as the first step but is under the target of Cradle to Cradle® where a building like a tree produces more renewable energy than used. Even though this KPI is not considered as a benefit within a C2C energy roadmap, it is included due to its importance inside the Dutch building regulation.

The second type of KPIs in this sub-category is correlated to the energy sources. In the design phase a feasibility and implementation study for renewable sources must be performed. As a result a KPI indicator can be specified as the feasibility and implementation study itself. Additionally this type of KPI's should identify the energy sources and quantify the energy used by the building during its operation. A prospective analysis should be carried out during the design phase. For instance a C2C goal for energy sources would be: *100% of the energy used by the building comes from renewable sources*. Different milestones with upgrading percentages can be place during the period of time helping to reach the goal. Likewise the energy sources must be in compliance with the C2C energy specified in table 3.2.

The environmental assessment methods identify the sources and the amount of energy according to the different installations for heating, hot water, ventilation, cooling, lighting and humidification. In practice these installations can have different energy sources, therefore the importance of identifying them independently. KPI's related to the percentage of renewable energy used by each installation could be defined as well.

Others KPI's should guide the progress for the generation of renewable energy by the building itself. It can be identified the amount of energy generated by the building linked to the different installations.

The amount of CO_2 emissions and their offset strategies should be included within this sub-category. A KPI identifies the CO_2 emissions and another one their positive use in a biological cycle. The offset strategies should be defined during the design phase.

Table 3.3 presents the suggested KPI's for the sub-category *OE.* These are defined as general indicators that can be used for different types of buildings. However the values and some KPI's might differ from one building to another. The building Villa Flora is used to identify values, milestones and goals associated to these KPI's.

Table 3.3 - KPI's sub-category Operating energy

Phase	#	Key Performance Indicators	Formula	Unit	Ref.
Design phase	1	X% of improvement on EPC	(1– EPC) * 100	%	>50
		Feasibility and implementation study of renewable energy sources	Results of the feasibility and implementation study. Description of the CO2 offset strategies		The building supplies its own energy
		CO2 offset strategies			
Operation phase	2	X% of renewable energy used by the building	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	100
	3	X% of renewable energy used for heating	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	100
	4	X% of renewable energy used for hot water	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	100
	5	X% of renewable energy used for ventilation	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	100
	6	X% of renewable energy used for cooling	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	100
	7	X% of renewable energy used for lighting	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	100
	8	X% of total renewable energy generated by the building	[Renewable energy generated by the building (kWh)/ energy demand (kWh)] *100	%	>100
	9	Identification of CO2 emissions		Ton	0
	10	Progress of the CO2 emissions strategies defined in design phase		%	100

3.2.5 KPI's Embodied energy of materials (EE)

Embodied energy (EE) is an assessment that includes the energy required to extract raw materials from nature, plus the energy used in primary and secondary manufacturing activities to provide a finished product. As the operating energy required for buildings declines, the embodied energy they represent becomes a more significant percentage of the total energy (Mumma, 1995).

Kumar Dixit (2010) defines EE as the energy sequestered in building materials during all processes of production, on-site construction, and *final demolition and disposal.* Some authors do not count the energy in the demolition, removal, and recycling of building materials as embodied energy. Since Cradle to Cradle® works with end-of-use scenarios, it is considered, within this sub-category, only the energy required to process and supply materials to the construction site (cradle-to-site).

Cradle to Cradle® emphasizes on the EE of the materials applied for the generation and delivering of renewable energy. It underlines that most energy generated from current solar or gravitational income does not exclusively use current solar or gravitational income. Therefore that 'embodied' energy must be qualified and quantified (Mulhall, 2009). Nevertheless the percentage of material used only for the generation and delivering of renewable energy could be insignificant compared to the total percentage of materials applied in the construction of buildings. As a result it is recommended quantify the EE of all materials included during the construction and operation of buildings. A distinction could be provided between the EE of materials used in the renewable energy systems and the rest of materials used in buildings.

Besides, not only energy but CO_2 may be regarded as being 'embodied' within materials (Hammond& Jones, 2008). Consequently materials also present 'embodied carbon' that can be quantify in this sub-category. These CO_2 emissions were already released to the environment and offset strategies are possible only for future scenarios. By knowing the EE and the 'embodied carbon' of materials, users will be more aware of the effects in selecting specific materials.

To determinate the EE and 'embodied carbon' of materials, it is recommended to use the inventory of carbon and energy database of the University of Bath. This database was developed to provide an open-access, reliable database for embodied energy and carbon associated with construction materials (Hammond & Jones, 2008). Although this database is directed towards UK construction, the material set is of quite wide application and can be used for the analysis of Dutch buildings. Additionally it was not found during this research a similar database directed to the Dutch construction industry.

The data of embodied energy is considered here to be more reliable than the 'embodied carbon'. The University of Bath included the 'best' data from foreign sources as European and worldwide for embodied energy. Whereas 'embodied carbon' uses data only from UK sources, due to national differences in fuel mixes and electricity generation. Appendix A presents some embodied energy and 'embodied carbon' coefficients that are part of this database. A Dutch database should replace the inventory of carbon and energy database of the University of Bath, when it becomes available.

Table 3.4 lists the KPI's related to both embodied energy and 'embodied carbon' of building materials. It suggests, as a first step, to identify the amount of these coefficients for the different materials used in the building. Strategies to reduce or offset these coefficients may be defined according to the building. These KPI's will allow comparing the EE and 'embodied carbon' of a building with its total operational energy and eventually with other buildings.

Some values are suggested as a reference, in table 3.4. These reference values were the results of 14 building case studies carried out by the University of Bath (Hammond, 2008). Among the cases were houses, apartments, and energy-efficient dwellings from UK and USA; some of them with multiple awards for architectural design, energy performance and sustainability. The average results, references for the model, are: EE 5340 MJ/m^2 and 'Embodied carbon' 110kgC/m^2.

Table 3.4 - KPI's sub-category Embodied Energy of materials

Phase	#	Key Performance Indicators	Formula	Unit	Ref.
Design Phase	1	Analysis and selection of materials according to EE and 'embodied carbon'	Result of analysis and strategy		None ref. found in literature
	2	Strategies to offset the EE and 'embodied carbon' of materials			
	3	Projected amount of EE of the building materials	Inventory of carbon and energy database of the University of Bath	MJ/m^2	
	4	Projected amount of 'embodied carbon' of building materials		kgC/m^2	
	5	Projected amount of EE of materials used in the renewable energy systems		MJ/m^2	
	6	Projected amount of 'embodied carbon' of materials used in the renewable energy systems		kgC/m^2	
Construction phase	7	Amount of EE of building materials	Inventory of carbon and energy database of the University of Bath	MJ/m^2	
	8	Amount of 'embodied carbon' of building materials		kgC/m^2	
Operation phase	9	Amount of EE of materials used in the renewable energy systems	Inventory of carbon and energy database of the University of Bath	MJ/m^2	
	10	Amount of 'embodied carbon' of materials used in the renewable energy systems		kgC/m^2	

3.2.6 KPI's Material media

This sub-category evaluates the defined biological or technical nutrients of materials that generates, convert and delivers energy. None of the environmental assessment methods analyzed in chapter 1 cover a similar aspect. Therefore the KPI's defined here are completely selected from the C2C literature.

An important aspect of the energy sources in order to be considered C2C is their material media. These must become nutrients for biological and technical metabolisms. The main focuses for C2C energy related to material media are:

1. Materials used to deliver energy
2. Materials resulting from energy delivery as climate change gases and polluting particulates.
3. The extent to which materials used and materials resulting can be embedded in C2C cycles.

Additionally, integrating other beneficial functions to the material media is considered an important step to C2C. This aims designing the materials media to have other positive impacts on human and environmental health.

Table 3.5 displays the proposed KPI's within this category. In the design phase of the building it is recommended to carry a feasibility and implementation study of the biological or technical metabolism of the material media. This study can be used as guideline to consider material media as biological or technical nutrients and evaluate their performance.

Similar KPI's from the design phase are proposed in the operation phase. This will allow assessing the percentage of designed material used and material resulting that really belong to a biological or technical cycle. Higher percentage of these KPI's can be placed during time to reach a specific goal as *100% of the material used for energy delivery belongs to a biological cycle.* End-of-use scenario phase is considered in this sub-category to evaluate that the material used and the material resulting from energy delivery have entered the intended cycle.

Table 3.5 - KPI's sub-category Material Media

Phase	#	Key Performance Indicators	Formula	Unit	Ref.
Design phase		Feasibility and implementation study of the energy material media for a biological or technical cycle	Results of the feasibility and implementation study		
	1	X% of designed material used for energy delivery belongs to a biological/technical cycle	[Biological cycle material media (kg) / total material media (kg)] * 100	%	100
	2.a	X% of intended biological/technical nutrients are degradable/recyclable	[TNs are recyclable (#) / total BNs (#)] * 100	%	According to building
	3.a	X% of designed material resulting from energy delivery belongs to a biological (or technical) cycle	[Biological cycle material resulting (kg) / total material resulting(kg)] * 100	%	
	4.a	Material media is designed with other beneficial functions	Explanation of the other beneficial functions		
Operation phase	2	X% of intended biological/technical nutrients are degradable/recyclable	[TNs are recyclable (#) / total BNs (#)] * 100	%	100
	3	X% of the material resulting from energy delivery belongs to a biological (or technical) cycle	[Biological cycle material resulting (kg) / total material resulting(kg)] * 100	%	100
	4	Material media provides other beneficial functions	Explanation of the other functions that material media provides		
End-of-use scenario	5	X% of biological nutrients has entered in the cycle	[Biological material media in cycle (kg) / total biological material media (kg)] * 100	%	100
	6	X% of technical nutrients has entered in the cycle	[Technical material media in cycle (kg) / total technical material media (kg)] * 100	%	100
	7	X% of biological (or technical) material resulting has entered in the cycle	[Biological material media in cycle (kg) / total biological material media (kg)] * 100	%	100

3.2.7 KPI's Energy effectiveness

The C2C effectiveness of energy can be addressed as the extent to which it is derived from current solar income or other C2C sources, and its carrier materials are either effectively replenishing biological or technical systems they are originating from or they are effectively contributing to growth of these systems (Mulhall, 2009).

The KPI's defined in the previous sub-categories are assessing the energy sources and their carrier materials. This allows evaluating the C2C effectiveness of energy according to the former description. The total percentage of C2C energy identified in the OE sub-categories is compared with the total energy demand of the building. Likewise the total percentage of carrier materials, called as 'C2C materials' in the KPI, belonging to a biological or technical cycle is compared with the total percentage of materials used in the energy systems. Efficiency could be evaluated as well within this sub-category. According to Cradle to Cradle® *it is not forbidden to make efficient use of C2C energy. This is however an economic criterion not an environmental one, unless the limits of C2C energy are exceeded through inefficiency and result in the adoption of non-C2C energy carrier materials* (Mulhall, 2009). Some KPI's are suggested in relation to the energy input and the physical unit that reflects the required end use. Economic indicators are not included for this model.

Exergy is an important comparative measure of energy effectiveness between energy generating methods (Mulhall, 2009). Exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy is a measure of the potential of the system or flow to cause change, as a consequence of not being completely in stable equilibrium relative to the reference environment. For exergy analysis, the state of the reference environment, or the reference state, must be specified completely. This is commonly done by specifying the temperature, pressure and chemical composition of the reference environment (Rosen & Dincer, 1999).

Rosen and Dincer express the exergy Ex contained in a system as:

$$Ex = S\,(T - T_0) - V\,(p - p_0) + N_k\,(\mu_k - \mu_{k0})$$

Where the intensive properties are temperature, *T*, pressure, *p*, and chemical potential of substance *k*, μk, and the extensive properties are entropy, *S*, volume, *V*, and number of moles of substance *k*, *Nk*. The subscript "0" denotes conditions of the reference environment.

The previous formula could be used as KPI's to quantify the exergy of a system. However a general energy balance analysis is suggested instead, due to the time consuming and the lack of information available to calculate exergy according to the formula of Rosen and Dincer. The energy balance analysis aims to find the amount of work being waste to bring systems into a state of equilibrium.

The KPI's within this sub-category should be calculated during the design phase in other to compare different options for energy delivery, but controlled and improved during the operation phase.

Table 3.6 - KPI's sub-category Energy effectiveness

Phase	#	Key Performance Indicators	Formula	Unit	Ref.
Design/ Operation phase	1	COP of technical installations	Comparison with a standard COP of heat pumps	COP	>3 to 5
	2	X% of C2C energy used by the building	[total C2C energy (MJ) / total energy demand (MJ)] * 100	%	100
	3	X% of C2C materials as energy carriers	[C2C materials as energy carriers (kg) / total carrier materials (kg)] * 100	%	100
	4	Amount of work being waste to bring systems into a state of equilibrium.	Energy balance analysis	%	0

3.3 Model category: Materials

3.3.1 Materials within the environmental assessment methods

The analysis of materials within the environmental assessment methods has a retrospective perspective. It analyses the sources, embodied energy, function and potential reuse of materials but does not track the pathway of materials after their use. Different sub-criteria are used by the methods to evaluate buildings materials.

ECO-QUANTUM and GPR perform a LCA and present the results according to the environmental effects (*Environmental parameters)* listed in table 2.3. *Materials* is one of the sub-indicators of the category *Environment* within the method GPR. It shares the category with *Water* and *Environmental Care*. However, *Materials* is more representative than the other two sub-criteria. More weighting points are aggregated to this sub-indicator (700) than to *Water* (200) and *Environmental Care* (100). It identifies the amount (lengths, areas or parts) of materials and type of elements used in foundation, floors, facades, interior walls, roofs, staircase, lifts, installations, and devices (kitchen, shower, sinks). The total score is presented as shadow price.

BREEAM has five criteria to evaluate building materials. One of those is *Materials specification*, whereas LCA should be carried out by an external method to identify the construction materials with low environmental impact over the life cycle of buildings. The other criteria target the reuse of building façade, reuse of existing structures, and design for robustness to minimize the frequency of use and replacement of materials. An additional criterion evaluates the sources of materials. It looks at the main building elements such as structural frame, ground floor, upper floors, roof, external walls, internal walls, foundation, structure, and staircase. And it defines eight types of materials to assess their sources, among them: brick, resin-based composites, concrete, glass, plastics and rubbers, metals, and timber. Even though this green system assesses the reuse of materials, it does not include the analysis of the quality of them. As a result, it could be awarding materials that are downcycled instead of upcycled.

3.3.2 Cradle to Cradle Materials

C2C works with end-of-use scenarios and not with end-of-life scenarios as the environmental assessment methods (Bor, 2011). The first C2C principle *Waste equals food*, seeks designing materials for a biological or technical cycle. Materials as biological nutrients provide nourishment for nature after use. Materials as technical nutrients circulate through industrial systems in closed-loop cycles of production, recovery and remanufacture. All materials can be seen as nutrients that flow in natural or designed metabolisms, see figure 3.5.

Figure 3.5 - C2C Biological and Technical nutrients.
Source: EPEA, 2012

McDonough and Braungart are proposing a strategy that will transform architecture into *a celebration of a human ecological footprint with positive effects*. This becomes into a necessary strategy nowadays because, as the authors claim, none of the materials used to make contemporary buildings is specifically designed to be healthful for people. For instance the use of polyvinyl chloride (PVC) is a common ingredient for building components, but its formulation contains plasticizers and toxic heavy metals such as cadmium and lead. Plasticizers are suspected of disrupting human endocrine systems, cadmium is known to be carcinogenic and lead is a neurotoxin. In addition, the globalized depletion of material resources is driving industries and governments to compete for limited supplies. Instead of disrupting economies, the scarcity of materials should lead to innovation where materials are designed for ongoing use rather than being wasted after their first use (McDonough & Braungart, 2003).

3.3.3 Aim of the category Materials

The available environmental assessment methods use normally a LCA database where some 'less bad' options are recommended in order to reduce the negative environmental impact of buildings. By analyzing the use of these methods, one can conclude that planners and architects implement the recommendations that the methods provide. These are recommendations based on negative attributes of materials. Therefore it is important to include positive recommendations, for instance through a *Positive Materials Database*; a database that could lead the building professionals to the implementation of Cradle to Cradle® and materials with positive effects.

Consequently, this category suggests creating a *Positive Materials Database (PMD)* that building professionals can use to choose C2C certified materials and products. All the building materials, C2C certified or not, could be classified as intended nutrients within a biological or technical cycle. This includes materials and products such as furniture and office equipment that move through buildings. Additionally it is important to identify their quality level seeking to keep them at the same or higher quality. As a result, building materials could be assessed according to the following sub-criteria: *Material Inventory*, *Intended pathway*, and *Quality content*.

3.3.3 KPI's Material Inventory

The Cradle to Cradle CertifiedCM Product Standard assesses product materials under two categories: Material health and Materials reutilization. Within the first category the generic materials used in the product are listed in a Bill of Materials. The intended cycle, biological or technical, and the recycle content are identified for each homogeneous material. These data is then classified according to the Cradle to Cradle® ABC-X rating system. The material assessments combine chemical hazard ratings, potential exposure information, and material cyclability information into a single ABC-X assessment for each material in the product. The results are illustrated through a "traffic-light" hierarchy that uses the colors GREEN, YELLOW, RED, and GREY (MBDC, 2012), see table 3.7.

Table 3.7 - ABC-X Material Assessment Rating System. Source: MBDC, 2012

A	The material is ideal from a Cradle to Cradle perspective for the product in question.
B	The material largely supports Cradle to Cradle objectives for the product.
C	Moderately problematic properties of the material in terms of quality from a Cradle to Cradle perspective are traced back to the ingredient. The ingredient is still acceptable for use.
X	Highly problematic properties of the material in terms of quality from a Cradle to Cradle perspective are traced back to the ingredient. The optimization of the product requires phasing out this ingredient.
GREY	This material cannot be fully assessed due to either lack of complete ingredient formulation, or lack of toxicological information for one or more ingredients.
Banned	BANNED FOR USE IN CERTIFIED PRODUCTS This material contains one or more chemicals from the Banned List and cannot be used in a Cradle to Cradle Certified^{CM} product.

Several requirements in accordance with the C2C ABC-X material assessment and reutilization score are defined for the different levels of the product certification: basic, bronze, silver, gold, and platinum. It is out of the scope to assess all the chemicals included in the building materials with a C2C ABC-X rating system because of the large among of chemicals involved and the complexity of the process. However C2C certified materials and products which have already been assessed with this rating system could be included in the building development. It is a responsibility of planners, architects and designers to use materials that are safe for humans and nature. By implementing C2C certified materials and products is a way of assuming this responsibility.

Accordingly, this sub-category suggests creating a *Positive Materials Database* where building professionals can identify and classify safe materials during the design and evaluation phase. All building materials and their respective amounts can be recognized here forming a *Material Inventory* of buildings. This is similar to the *Bill of materials* of the product certification system. Due to the complexity of a building, it is suggested in this sub-criteria categorize the different building parts. Stewart Brand for instance had divided them into the following classification: *structure*, *skin*, *setting*, *systems*, and *stuffs*. Figure 3.6 presents an alternative to guide the inventory process of building materials. The first column at the left represents Brand's classification, the second column the generic building components, the third column the parts that conform the component and fourth and fifth column their respective materials and amounts.

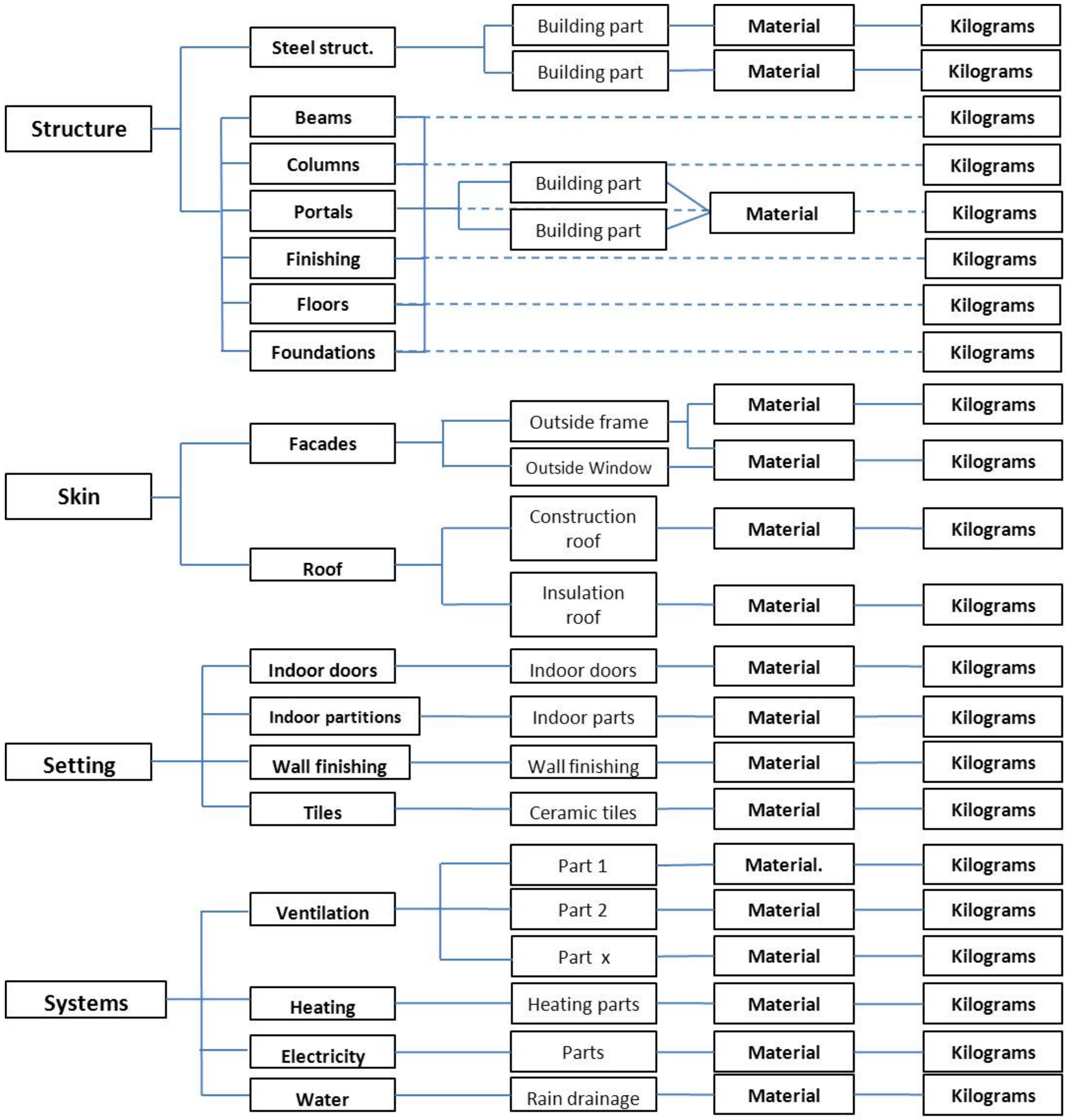

Figure 3.6 Inventory process of building materials

The C2C-centre (www.c2c-centre.com) is an open online platform that gathers and shares information on Cradle to Cradle®. It provides already a product catalogue that could be used for the *Positive materials database*. Approximately 39 certified building materials and 71 interior design products (C2C-centre, 2013) could form up the options for the database. Appendix B exemplifies how the available information from the C2C-center can be used as an input to make this *PMD*.

The KPI's for the sub-category *Materials inventory* identify all the building materials, including those that are C2C certified. The C2C certified materials provide already information about their pathway and positive features, see appendix B: *Positive Materials Database*. Therefore KPI's to identify the type and amount of only non C2C certified materials are suggested as well. This information will be the input for the other sub-categories. Table 3.8 presents the KPI's according to the buildings parts of Brand's classification. This sub-category aims implementing the KPI's at early stage of the design process and review their real results during the operation phase once that all materials have been employed.

Table 3.8 - KPI's sub-category Material inventory

Phase	#	Key Performance Indicators	Formula	Unit	Ref.
Design/ Operation phase	1	X% of building materials belongs to the *Positive Materials database*	[Building materials of the PMD (kg) / total building materials (kg)] * 100	%	50
	2	X% of the *structure* materials belongs to the PMD	[Structure materials of the PMD (kg) / total structure materials (kg)] * 100	%	50
	3	X% of the *skin* materials belongs to the PMD	[Skin materials of the PMD (kg) / total skin materials (kg)] * 100	%	50
	4	X% of the *setting* materials belongs to the PMD	[Setting materials of the PMD (kg) / total setting materials (kg)] * 100	%	50
	5	X% of building materials is known	[Building materials known (kg) / app. total building materials (kg)] * 100	%	100
	6	X% of the *structure* materials is known	[Structure materials known (kg) / app. total structure materials (kg)] * 100	%	100
	7	X% of the *skin* materials is known	[Skin materials known (kg) / app. total skin materials (kg)] * 100	%	100
	8	X% of the *setting* materials is known	[Setting materials known (kg) / app. total setting materials (kg)] * 100	%	100

3.3.4 KPI's Intended Pathway

The information gathered in the former sub-category is use here to determinate the intended use and pathway of materials. The C2C certified materials have been already designed for a specific pathway: biological or technical. See description of the C2C principle *Waste equals food* in section 2.2.1, which gives a general explanation about materials as biological and technical nutrients. The C2C certified product standard defines these nutrients as follow:

Technical Nutrients (TNs)

• Materials or products that are capable of "feeding" technical systems: they may be dismantled and reused, or physically or chemically transformed, but are not consumed (i.e., materials that do not enter the biosphere).
• Materials or products that generally cannot be processed by biological systems.
• Materials or products that are items used as Products of Service. A Product of Service is a material or product designed to provide a service to the user without conveying ownership of the materials.
• Metals and plastics are examples of TNs. Bio-plastics, although they are from the biosphere, may be designed as TNs (i.e., kept in technical cycles).

Biological Nutrients (BNs)

• Materials or products that are usable by living organisms to carry on life processes.
•Materials or products that are items used as Products of Consumption, which are typically changed biologically, chemically, or physically during use and therefore enter the biosphere either by nature or human intention. Such products should be designed for the biological system and thus are categorized and evaluated as biological nutrients. For

example, brake pads, which abrade into the environment upon use, should ideally be designed for the biological cycle and will be reviewed with that intention in mind.
• Cleaning products, cosmetics, personal care products, and paper are examples of BNs.

These descriptions help identifying the intended pathway of the building materials. In either pathway, materials get in contact with the environment and humans. It could be said that one of the conditions for materials to be called ‘nutrients’ is that they are not harmful for neither the environment nor the human health. Therefore C2C seeks the implementation of safe materials and some substances are banned for the Cradle to Cradle Certified^{CM} Products Program. Appendix C presents the C2C Banned List of Chemicals. This list may be used in this sub-category to identify those banned chemicals that are present in building materials. Some substances are banned for one cycle but not for the other. For instance lead and cadmium are allowed to be (safely managed) in technical cycles where exposure to humans or the environment is highly unlikely to occur.

Table 3.9 lists the KPI’s for this sub-categories. Three aspects are assessed here:

1. Building materials are intended or designed to follow a biological or technical pathway.
2. The substances in the materials are not part of the C2C banned chemical list.
3. At the end-of-use scenario or ‘first cradle’ the intended BNs and TNs have entered to the cycle or ‘second cradle’.

Table 3.9 - KPI’s sub-category Intended Pathway

Phase	#	Key Performance Indicators	Formula	Unit	Ref.
Design Phase	1	X% of building materials belongs to either biological or technical pathway	[Building materials as TNs or BNs (kg) / total building materials (kg)] * 100	%	50
	2	X% of the *structure* materials belongs to either biological or technical pathway	[Structure materials as TNs or BNs (kg) / total structure materials (kg)] * 100	%	50
	3	X% of the *skin* materials belongs to either biological or technical pathway	[Skin materials as TNs or BNs (kg) / total structure materials (kg)] * 100	%	50
	4	X% of the *setting* materials belongs to either biological or technical pathway	[Setting materials as TNs or BNs (kg) / total structure materials (kg)] * 100	%	50
	5	X% of biological nutrients are not part of the C2C Banned list	[BNs are not part of banned list (#) / total BNs (#)] * 100	%	100
	6	X% of technical nutrients are not part of the C2C Banned list	[TNs are not part of banned list (#) / total TNs (#)] * 100	%	100
End of use scenario	7	X% of intended biological nutrients are following the cycle	[BNs are in the second cradle (#) / total BNs (#)] * 100	%	100
	8	X% of intended technical nutrients are following the cycle	[TNs are in the second cradle (#) / total BNs (#)] * 100	%	100

3.3.5 KPI’s Quality Content

This sub-category aims identifying the recycling potential of building materials. Recycling in C2C is defined as *recovering and reusing materials at a similar level of quality by defining their content, as compared to “downcycling” where materials are recovered and reused at a lower quality level.* In the previous sub-categories the content of materials where defined in *Materials Inventory* and the intended use in *Intended Pathway*. As a result this third sub-category assesses the level of quality of the nutrients. The following definitions, provided by the Cradle to Cradle Certified^{CM} Product Standard within the *Cyclability Assessment* of materials, are used to classify the nutrients:

Recyclable: A material that may be recycled into a material of similar quality and/or value.

Partially Recyclable: A material that is only downcyclable. Resulting material is of lower quality and/or value; resulting material will most likely be land filled at the end of use. For example, the options for recycling of thermosets are very limited.

Not Recyclable: Material is not downcyclable. Materials that cannot be separated may not be recyclable. For example, in the case of foam glued to a fabric, each may be recyclable on their own, but because they cannot be separated, neither is recyclable.

Rapidly degradable: Materials that degrade completely in an industrial composting facility within a prescribed time frame.

Slowly degradable: Materials that come from the earth and may be returned to the earth but are not biodegradable may receive this designation (e.g., clay, natural stone).

Not degradable: Material is not biodegradable and cannot be returned safely to the biosphere.

See table 3.10 for the definitions according to the ABC-X rating system.

Table 3.10 Source: MBDC, 2012.

b	Biological cycle: rapidly degradable. Technical cycle: recyclable
c	Biological cycle: slowly degradable. Technical cycle: partially recyclable
x	Biological cycle: not degradable. Technical cycle: not recyclable.

Table 3.11 presents the KPI's for the category Quality Content. These are related to the cyclability rating system of the Cradle to Cradle Certified[CM] Product Standard. Only the highest goal (100%) in the KPI's was defined for *Optimizing* materials (denomination 'b' of table 3.10). The KPI's in the design phase seek to find the percentage of rapidly biodegradable and recyclable substances of the total BNs and TNs. The KPI's defined for the end-of-use scenario seek to lead the nutrients to the second cradle. Non KPI's were defined for the other definitions (slowly degradable, partially recyclable, not degradable and not recyclable) because these do not represent the highest goal in C2C. However they may be controlled and assessed by the suppliers, aiming to make a transition from 'x' (not acceptable) and 'c' (tolerable) to 'b' (Optimizing).

Table 3.11 KPI's sub-category Quality Content

Phase	#	Key Performance Indicators	Formula	Unit	Ref.
Design phase	**1**	X% of intended biological nutrients are rapidly degradable	[BNs are rapidly degradable (#) / total BNs (#)] * 100	**%**	100
	2	X% of intended technical nutrients are recyclable	[TNs are recyclable (#) / total BNs (#)] * 100	**%**	100
End of use scenario	**3**	X% of rapidly degradable biological nutrients are following the cycle	[Rapidly degradable BNs are in the second cradle (#) / total BNs (#)] * 100	**%**	100
	4	X% of recyclable technical nutrients are following the cycle	[Recyclable TNs are in the second cradle (#) / total BNs (#)] * 100	**%**	100

3.4 Weighting factors

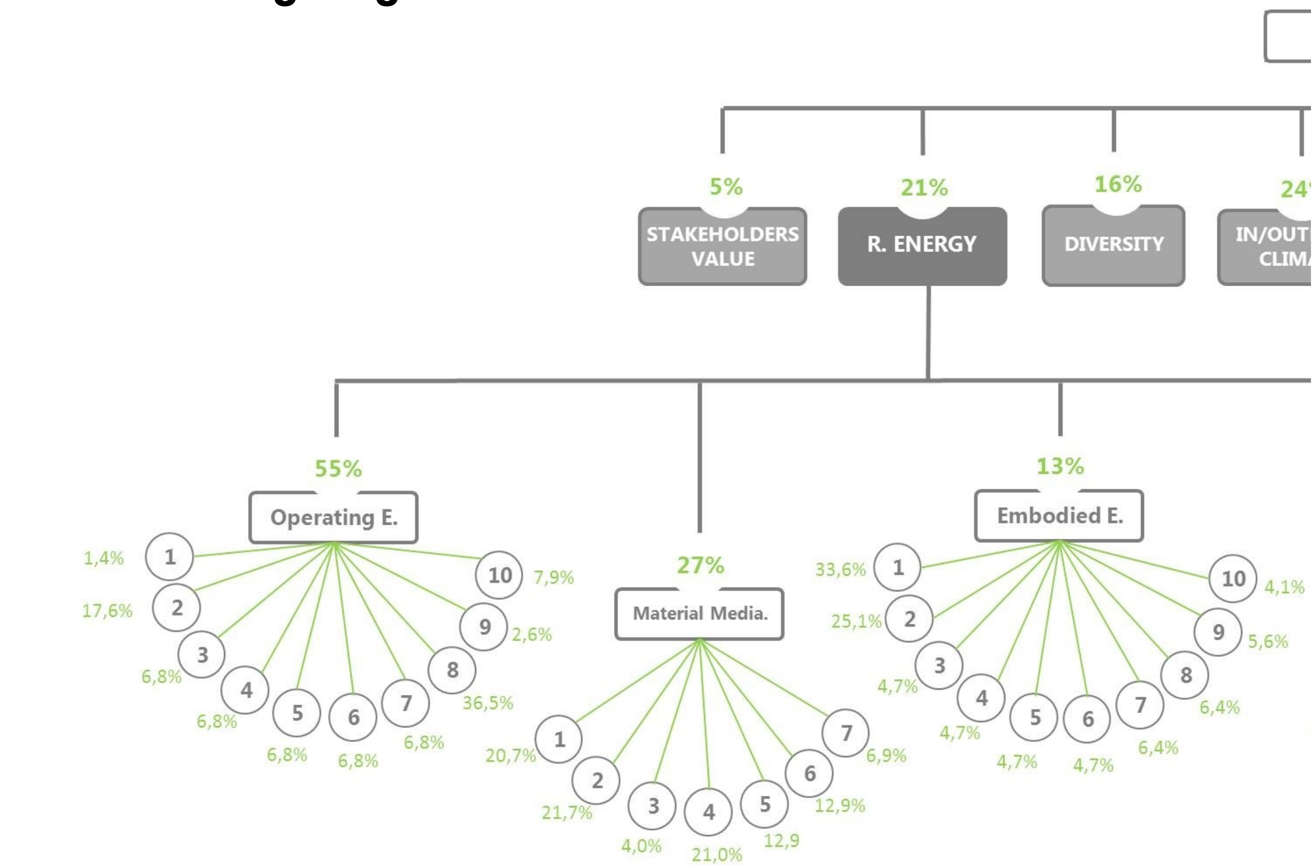

Figure 3.7a - Pair wise comparison matrix for the Model categories

Three members that are familiar with the C2C philosophy determinate the Weighting Factors for the categories of the model. It is not likely that two or more participants evaluate the categories with the same importance. Even ranking several criteria, is an arduous task for each individual. Nevertheless, a consensus is needed in order to clarify the goals. According to Thomas L. Saaty (1990), the most effective way to concentrate judgment is to take a pair of elements and compare them on a single property without concern for other properties or other elements. The Analytic Hierarchy Process (AHP) was used to determinate the relative importance of the categories of the model, see appendix D. The objective was to obtain the relative importance of each category according to the C2C principles. The members selected the most important category of each pair (A or B) and evaluated how much more important it was on a scale of 1-9. This hierarchy is suggested for the model categories.

Matrix		Renewable Energy 1	Materials 2	Design for disassembly 3	In/Outdoor climate 4	Water 5	Stakeholders value 6	Biological Nutrients 7	Diversity 8	0 9	0 10	normalized principal Eigenvector
Renewable Energy	1	-	2 2/5	3 2/5	1/2	3 5/9	3	5 5/8	8/9	-	-	20,61%
Materials	2	2/5	-	3/4	1/2	3 5/9	3	5	4/5	-	-	13,12%
Design for disassembly	3	2/7	1 1/3	-	1/2	1 1/2	2 2/3	4 3/5	1/2	-	-	11,06%
In/Outdoor climate	4	2	2	2	-	3 3/8	2 7/8	5 1/4	2 1/6	-	-	23,78%
Water	5	2/7	2/7	2/3	2/7	-	3	3	3/8	-	-	7,18%
Stakeholders value	6	1/3	1/3	3/8	1/3	1/3	-	1	1/3	-	-	4,63%
Biological Nutrients	7	1/6	1/5	2/9	1/5	1/3	1	-	1/5	-	-	3,15%
Diversity	8	1 1/8	1 2/9	2	1/2	2 5/8	3 1/3	5 1/3	-	-	-	16,48%
0	9	-	-	-	-	-	-	-	-	-	-	0,00%
0	10	-	-	-	-	-	-	-	-	-	-	0,00%

Figure 3.8 - Pair wise comparison matrix for the categories

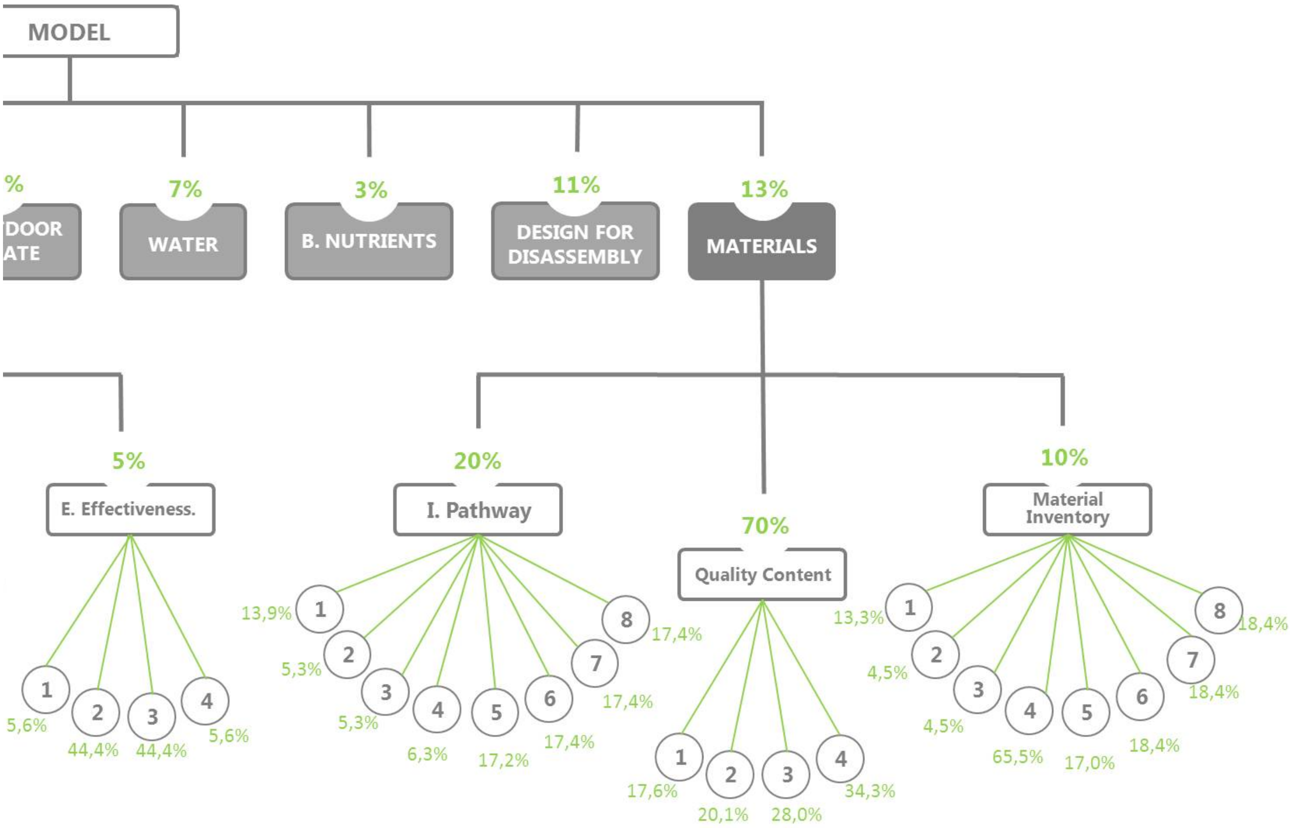

Figure 3.7b - Pair wise comparison matrix for the Model categories

Figure 3.7 presents the WF in percentages for the first level (categories), second level (sub-categories) and third level (KPI's) of the model. Figure 3.8 illustrates the Pair wise comparison matrix for the first level of the model. *In/Outdoor climate* and *Renewable Energy* are the categories with the highest weighting factors, followed by *Diversity*, *Materials*, *Design for disassembly*, *Water*, *Stakeholders value*, and *Biological Nutrients* respectively. Similarities are found only with the results of the category *Renewable Energy* and the environmental assessment methods. *Energy* is seen as the most important criteria by BREEAM and GPR. The hierarchy of the other categories differs from those given by the environmental assessment methods.

3.5 How does the model communicate the results?

A difference between this decision support model and the environmental assessment methods is the use of the model itself. In every building category, the model seeks to track and guide an improvement of the building. At this stage an improvement from a negative profile to the reference line.

Three Mondrian-like graphs (red, green and yellow) have been allocated in strategic places of figure 3.2 to explain the relation of the KPI's with the transition to the 'green area', see figure 3.9. The red Mondrian-like graph represents buildings with negative environmental impacts. The green graph typifies neutral buildings. And buildings with positive environmental effects are represented by the yellow graph.

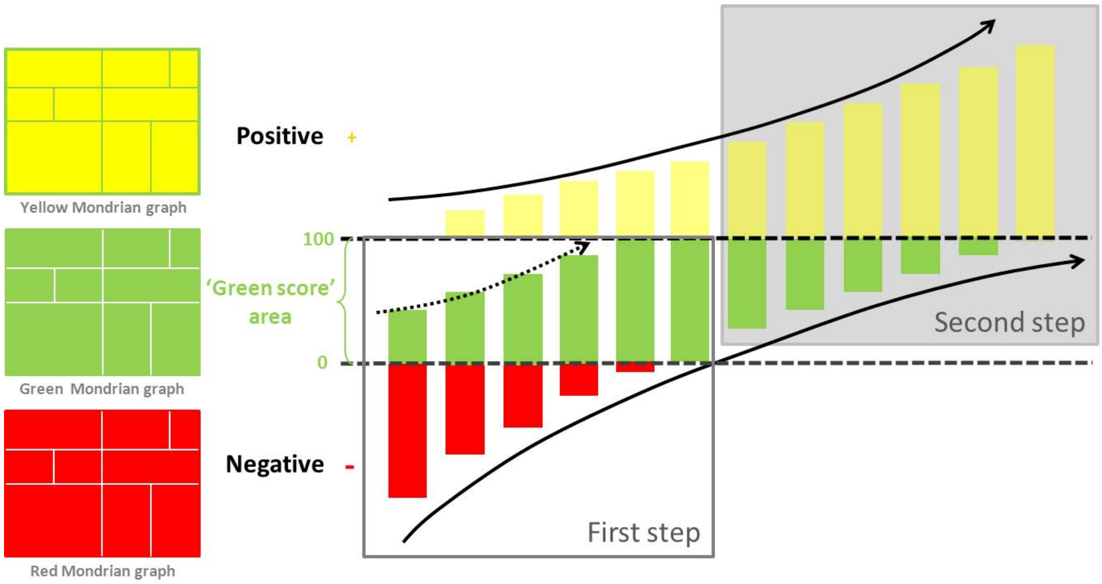

Figure 3.9 Mondrian-like graphs with the Eco-efficiency and eco-effectiveness trajectory

The decision support model illustrates the results of the KPI's through a combined Mondrian-like graph. The red and green graphs are combined in one to communicate the negative impact and the 'green score' of buildings, see figure 3.10. Each of the categories and sub-categories of the model are represented by a block inside the Mondrian-like graph. The size of the square denotes the relative importance of the category within the model. This graph allows the visualization of results per categories and sub-categories. It is intended, by using the Mondrian-like graph, to provide a complete picture of the performance of buildings. Buildings reach the reference line and complete the first step, when the Mondrian-like graph is totally green. This means that buildings have a 'green score' of 100%.

Figure 3.10 Example of a Mondrian-like result for a building

Buildings with a score higher than 100% are already providing a positive environmental impact and they are above the reference line. As mentioned formerly the model cannot quantify this 'positive-ness' value, but it recognizes it. This qualitative recognition is made, adding a 'smiley' in the subcategory where it belongs. The purpose of this smiley is to focus the attention of users on it and provide the information about the positive effect. It allows building professionals becoming aware of the positive features of buildings on the environment instead of only the negative impacts. An example of this quality recognition is provided in the following chapter with the building Villa Flora.

Additionally to the Mondrian-like graph, the model presents the 'green score' of buildings per category. Figure 3.11 is an example of a nonexistent building, where every category has a percentage related to the results of the KPI's of each sub-category. Weighting factors are included to calculate the scores. Likewise a total 'green score' is given according to the results and weighting factors of every category.

The total 'green score' allows predicting the position of buildings in the modified *Eco-efficiency and eco-effectiveness trajectory*. For instance, Beta is placed in figure 3.12 according to its total 'green score'. Since the model is measuring only the green area above the line '0', it is assumed that the subtraction between the 'green score' and 100% is the value of the negative impact.

Figure 3.11 Representation of the green score

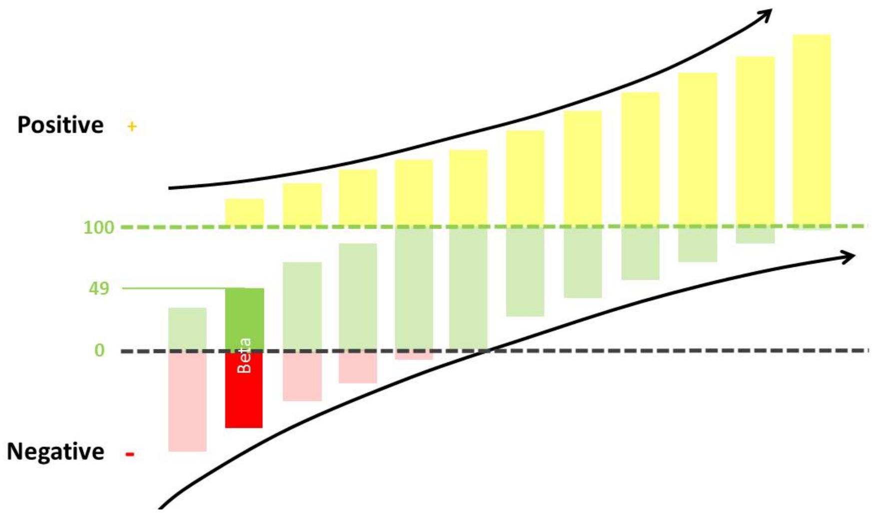

Figure 3.12 Position of Beta in the Eco-efficiency and eco-effectiveness trajectory

3.5.1 Comparison of several buildings

The previous Mondrian-like graphs could be used as well to compare several buildings. This comparison would help for instance selecting the best alternative during the design phase. The results of two or more alternatives are compared through three diagrams. Figure 3.13 illustrates the results for two buildings: Beta and Demo. The Mondrian-like graphs give qualitative information about the negative impacts (red), 'green scores' (green) and positive elements (smiley). The graphic that displays the 'green scores' allows comparing the quantitative results of the KPI's for each building. Finally the positions of both buildings are displayed in the modified *Eco-efficiency and eco-effectiveness trajectory.*

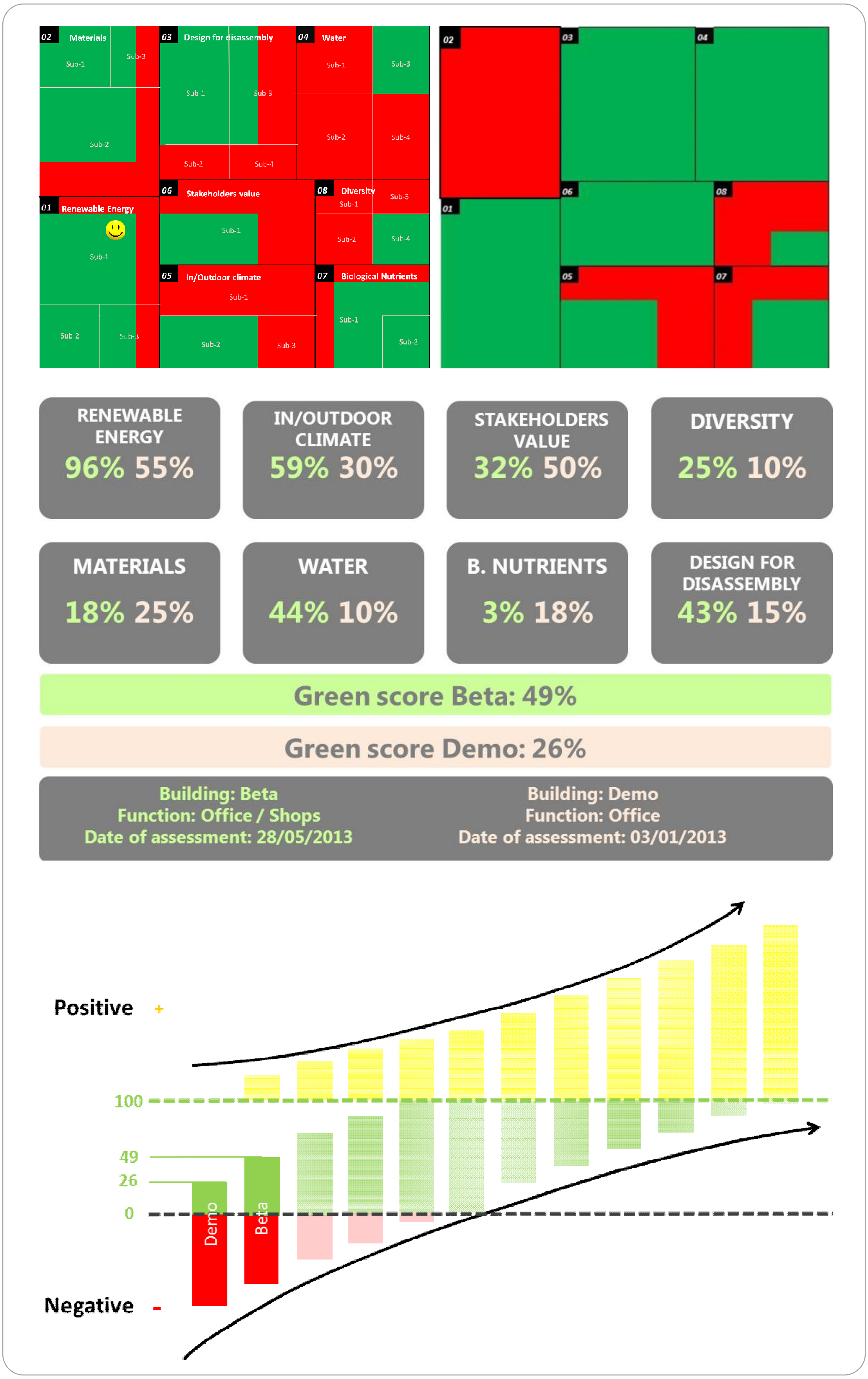

Figure 3.13 Comparison of two buildings through the three diagrams of the model

CHAPTER 4
Villa Flora

This chapter describes the main features of the building Villa Flora, building presented as the g*reenest building of the Netherlands*. The decision support model gives objective and quantitative information of the features of Villa Flora within two categories: *Renewable Energy* and *Materials*. The information of the building is used as a case to test and complete the KPI's of these categories. Quality recognition is given to the building due to its positive impact on the environment producing 283% of renewable energy for heating during the year 2012.

4.1 Villa Flora Features

4.1.1 Cradle to Cradle® and Villa Flora

Cradle to Cradle® plays an important role in the Netherlands especially in Venlo, a city located in the Limburg region at the South-Eastern of the country. Venlo is nominated as *the first Cradle to Cradle® region in the world* (Danish Architectural center, 2012). *Floriade,* the World Horticultural Exposition that takes place in the Netherlands every decade, was hosted in Venlo in the year 2012. Therefore different companies collaborated with this exhibition and implemented the Cradle to Cradle® principles. Over two million visitors were registered in *Floriade 2012*.

Kristinsson Architectural Engineers in cooperation with *Volantis B.V.* designed the building *Villa Flora.* Villa Flora is one of the two iconic buildings of *Floriade 2012.* Its design was inspired by the central Floriade theme *'Be part of the theater of nature; get closer to the quality of life!'* and the C2C principles. Although a 'C2C model' is not available to guide the design process of a 'C2C building', the studies of the architect Jon Kristinsson in sustainable design are in line with the C2C philosophy. For instance: the production of renewable energy by the building itself and the closed-cycle of materials as biological and technical nutrients.

The method BREEAM-NL was used in the design process, and GPR evaluated the building after its construction. *Volantis B.V.* calculated a preliminary BREEAM-NL score of 72.5%, which means a result of 'Excellent' within this classification system. In general, the aim of the designers and engineers was to create a self-sufficient building by implementing sustainable technologies and innovations. The target was a building that produced its own energy, was CO_2 neutral, recycled organic waste in a sustainable way, allowed flexibility for different scenarios, and was demountable. Villa Flora was presented as *the greenest building in the Netherlands* at the World Sustainable Building Conference 2008.

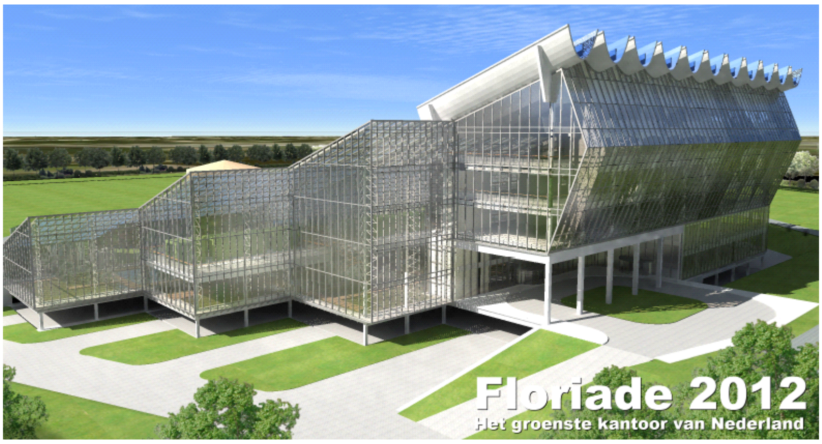

Figure 4.1. - Villa Flora. Source: Volantis B.V.

The building consists of modular components predominantly made of glass, steel, concrete and wood that can be used in another building after their use in Villa Flora. These components form two parts: a greenhouse and an office building. The energy-producing greenhouse is the main feature of Villa Flora representing the larger greenhouses, the economy and the highly developed logistics industry of the region. Two scenarios where designed for the greenhouse: *Phase 1* and *Phase 2*. The first is the use-scenario during Floriade on which the greenhouse serves as exhibition hall. *Phase 2* is the use-scenario after Floriade, where it can be used for multiple and flexible solutions. A possible scenario for the upcoming months is a 'Food drome' including a Kids University of Cooking. The office building is rented by small and medium companies during both *Phase 1* and *Phase 2*.

At Villa Flora heating and cooling is produced with low-temperature systems and seasonal storage of heat and cold in the second underground aquifer. Additionally it has a yield improvement on the heat pump to supply the heat to the offices. Organic waste is fermented into biogas for the production of hot water. Various types of glass control the light and the radiation of the sun. Green plants and partition panels improve acoustics and windows provide a pleasant climate in the workplace (Volantis, 2008). Additionally in the original design of Kristinsson it was intended the use of a parabolic solar collector roof with a mirrored coating. This would enable harvesting boiling water and PV electricity (Kristinsson, 2012). However not every aspect of the original design was realized. The roof kept the form but not the intended function.

4.1.2 Location

Villa Flora is located in the area development *Venlo Green Park* which is a major, independent part of the regional development of Greenport Venlo. The last one is the second largest concentration of horticulture in the Netherlands. It aims a unique cooperative venture in the field of agribusiness between the public and private sectors, science, education and the local residents (Venlo Green Park, 2013). *Venlo Green Park* is located close to the Zaarderheiken A67/A73 junction in North-Limburg, see figure 4.2.

The access to the building is by car and through a pedestrian and cycle bridge that goes over the A73 motorway. During *Floriade 2012* public vehicles transported visitors from the Venlo train station to the exhibition, a distance of 10 km approximately. Nevertheless, after Floriade there is not any public transportation available to the building. The closest bus stop is located 30 minutes away by foot. More than hundred parking places are available for visitors and tenants of the building.

Figure 4.2. Villa Flora Location. Source: Home page Venlo Green Park

4.1.3 Technical features

Villa Flora is a greenhouse building characterized by office workplaces in green surroundings. It offers 4,000m^2 of floor area for open offices and 7,500m^2 for exhibition in the greenhouse. A low glasshouse roof on the south side climbs up till six floor of office on the north side, see figure 4.3. The transparency of the building is a reference to the greenhouses of Venlo (Kristinsson, 2012). Solar modules on the pergola of the greenhouse supply up to 138kWp of power. Two elevators in the office building feed additional power into the network when they travel downward.

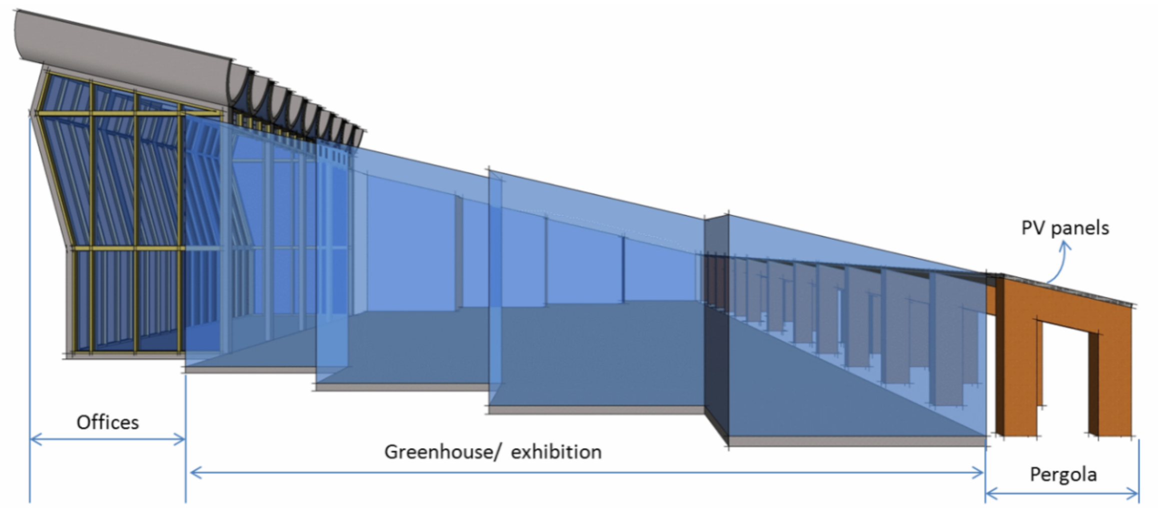

Figure 4.3 - Villa Flora

Heat and Cold storage

The excessive heat generated in the greenhouse is stored underground in an aquifer. Cold from nightly radiance to the sky is also stored in this system. At Villa Flora, warm water (in summer) has to be pumped into one well and extracted from another. This extraction takes place at a meticulously calculated location where the heat stored in summer will have flowed to in six months' time, by a speed of 50-75 m/year. Likewise, the cold is injected into a second, deeper aquifer layer and extracted at a point further down the groundwater stream. A heat pump brings the warm water to desired level of 30° C. The heat pump has an efficiency COP of 7 to 10 (usual value 3 to 5). This means that for every income unit the heat pump produces 7 to 10 units' outcome. Simultaneously, cold water from this heat pump and from colder external sources is injected into the deeper aquifer for use in summer.

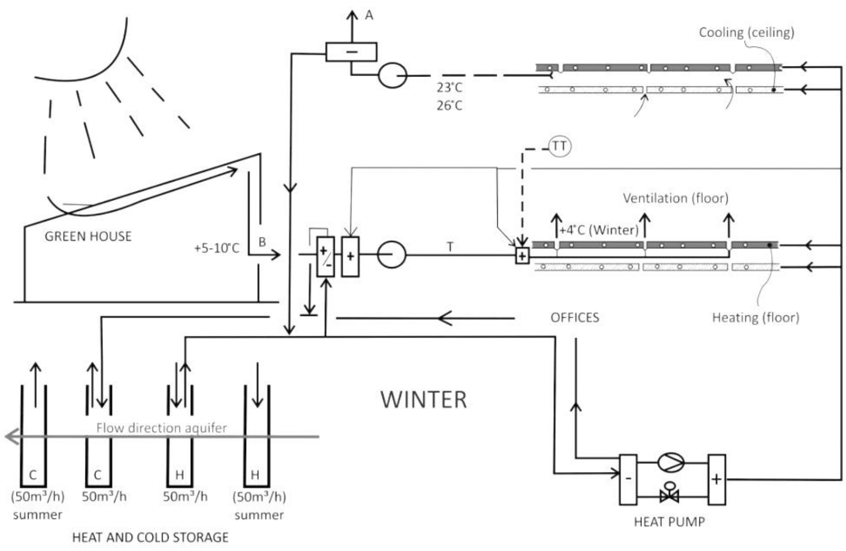

Figure 4.4 - Heat and Cold Storage at Villa Flora

The two parts of Villa Flora, greenhouse and office building, complement themselves. Air handling units supply oxygen-rich-air as needed from the greenhouse to the offices. Heat from solar energy is collected in the greenhouse, stored into the wells units and supplied to the offices with the aid of the heat pump. This heat production is even sufficient to cover the requirements of another building: *Innovatower*. The design included fine-wire heat exchangers to heat and cool air efficiently. Additionally they absorbed the excess heat and carried off to the heat and cold storage aquifer. Nevertheless these heat exchangers were removed in February 2013 due to maintenance and technical performance.

Concrete floor and structure

Concrete and glass are the representative materials of the structure of Villa Flora. The concrete floor and structure was supplied by Holcon B.V. The concrete structure has a high disassemble potential. Its components act as ‘Lego blocks’ that can be reused in another location or building. The modular floor can span 18 meters. This dimension formed the basis of the structural pattern at Villa Flora where some slots where considered for the replacement and maintenance of piping and wiring, see figure 4.5. Additionally the ventilation system is placed between the floor and ceiling.

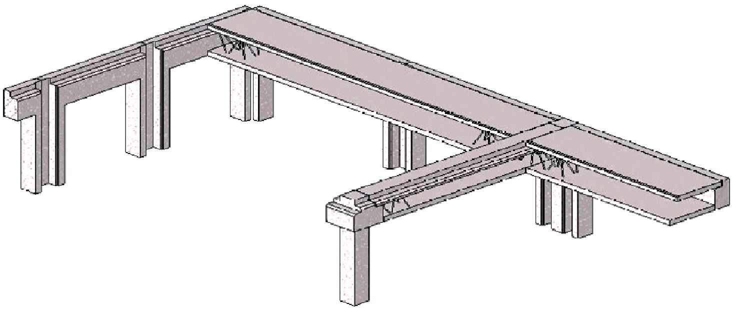

Figure 4.5 - Holcon floor at Villa Flora

Table 4.1 lists the different concrete elements and their respective amount used at the Greenhouse (Expo) and the office building. In total 3.667 tons (3.326.646 kg) of concrete were used at Villa Flora. Additionally an amount of approximately 2.250.000 kg of concrete was used in the foundations of the building.

Table 4.1. Concrete elements at Villa Flora

Element	Quantity (Parts)		Volume (m^3)		Weight (tons)	
	Expo	Office	Expo	Office	Expo	Office
Portals	36	21	118.00	274.43	295.00	686.07
Finishing	36	85	56.56	28.71	141.40	71.78
Floors	64	176	311.94	660.00	779.85	1650.00
Beams		6		12.98		32.45
Columns		4		4.48		11.20
Total	136	292	486.50	980.60	1216.25	2451.50

Scheuten Glass was the supplier of the glass used in the greenhouse and the office building. For the office part *Scheuten* supplied 2.400m^2 of insulating glass with sun proof and neutral coating. An amount of 9.900m^2 of insulating glass in two different compositions was supplied for the greenhouse (Scheuten, 2013). Considering a density of 2.500 kg/m^3 and 4 mm of thickness, a total amount of 123.000 kg of glass were used in Villa Flora.

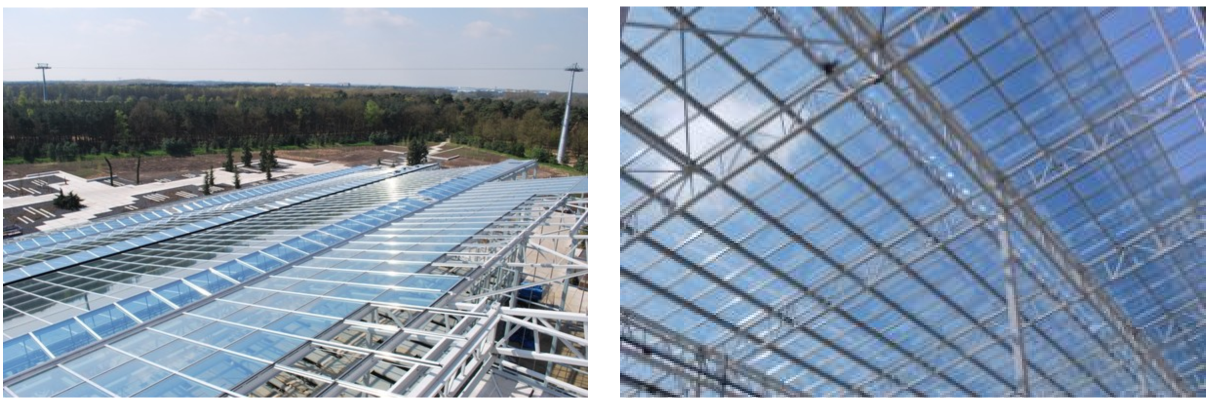

Figure 4.6 - Greenhouse glass. Source: Scheuten Glass website

Thermal Concrete Core Activation

As mentioned formerly, the heat collected in the greenhouse is stored in an aquifer at a depth of approximately 80 meters. The heat and cold is supplied to the offices through a Concrete Core Activation system. The concrete core is thermally activated by oxygen-tight heating pipes in the floors and ceilings.

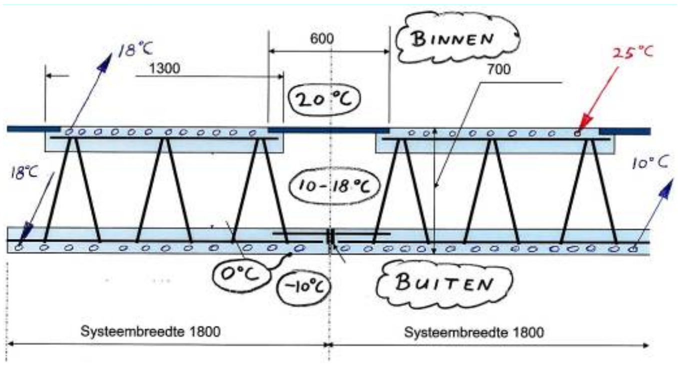

Figure 4.7. Smart Skin Villa Flora. Source: Volantis B.V.

Part of the concrete ceiling, above the entrance of the building, is used as a Smart Skin. Tubes fitted into this absorb warmth and cold from outside the building, see figure 4.7. This energy is then fed into the thermal energy storage underground (Pellikaan, 2012).

Organic waste and water system

Rainwater is collected at Villa Flora in tanks with a capacity of 20m³. They are connected to a pump that supplies the water to the toilets. Villa Flora is equipped with vacuum toilet pipes and uses 1 liter of water per flush. Moreover the vacuum toilet allows transporting the black water and collecting the feces and urine in a biomass fermentation plant. By means of anaerobic fermentation, methane gas is made to power a micro-turbine during a period of 2.5 days in a bioreactor that supplies itself with electricity. Biogas exists of approximately 2/3 methane (CH_4), 1/3 CO_2, some H_2 and inert N_2 and a little sulphureted hydrogen H_2S (Kristinsson, 2012). The filtered exhaust fumes are designed to be used as fertilizer for the greenhouse plants.

4.2 Renewable Energy KPI's

4.1.1 KPI's: Operating Energy

Implementation study of renewable energy sources, and carbon cycle

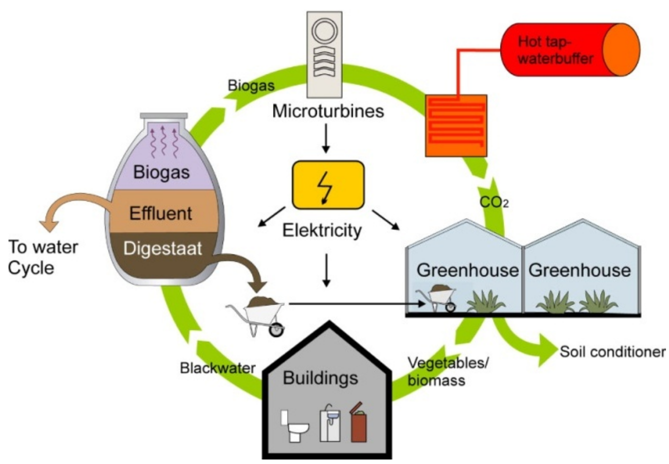

Figure 4.8 - Carbon cycle for the producing energy greenhouses. Source: Jón Kristinsson, 2012

The architect Jón Kristinsson had been involved in the studies of *energy-producing greenhouse* initiated in 2006 by four municipalities and their local market gardeners organizations. The aim of these was the use of excess heat generated by a closed greenhouse as energy for dwellings. Additionally it aimed to have closed cycles as those related to food production, drinking water purification, irrigation water generation and organic management for biogas production (Kristinsson, 2012). Figure 4.8 illustrates the carbon cycle proposed for the energy-producing greenhouse.

The design of Villa Flora incorporated the features of the former studies on *energy-producing greenhouses*. Villa Flora original design seeks the use of energy only from the sun and no use of external fuel, electricity, water or sewage. However, the original design was modified and it became necessary to include external suppliers. *Eneco* was selected as the energy supplier, which claims to be commitment in delivering electricity only from renewable sources.

EPC calculated for Villa Flora

In January 2009 (during the design phase) the EPC for Villa Flora was calculated. Its input was the data associated to the energy needed for heating, ventilation, hot water, pumps, cooling, lighting and PV panels. The total energy performance of the building was estimated as 2874517MJ while the allowed energy performance related to the functions of the building was 9649284MJ. Therefore the EPC for Villa Flora was 0,298. The EPC calculated for Villa Flora is 70.2% better than the EPC norm defined for offices as 1,1.

$$(1-(2874517MJ/9649284MJ))*100= 70.2\%$$

Renewable energy used by Villa Flora

During summer heat is harvested in the greenhouse, exported directly to the building *Innovatower*, or transported underground for storage. Heat from the greenhouse is used for the offices in spring and autumn directly by the central piping system without storage. In winter the heat stored during the other seasons is used for heating the building.

Part of the electricity needed at Villa Flora is supplied by Eneco because there are not enough PV panels to supply the building's electricity demand. For the functions of heating and cooling, the building produces more energy than it needs. It is not possible to transform efficiently the excess heat of the greenhouse (low-grade energy) into electrical energy. As a result this heat is exported to *Innovatower* that, as Villa Flora, belongs to the Green Park area.

Table 4.2 presents the expected and the real energy used by the different installations. The amounts presented under *Design phase* belongs to the expected energy performance calculated previous the construction of the building. *Operating phase* represents the real energy performance of the building during one year. The data of table 4.1 is the input for the KPI's of this subcategory. Table 4.3 presents the performance of Villa Flora associated to the Operating Energy KPI's.

Table 4.2a - Energy performance of Villa Flora

Installation/ Feature	Unit/year	Amount	
		Design Phase	Operating phase 2012
Heating Expo	kWh	735.000	311.519
Heating Office	kWh	155.000	371.200
Cooling Expo	kWh	370.000 min 930.000 max	423.288
Cooling office	kWh	110.000	164.709
Total thermal energy		1.670.000	1.270.716
Source: Biomass thermal e.	kWh	70.000	0
Source: Energy storage	kWh	1.600.000heat 1.040.000 cold	1.931.030 heat 591.300 cold

Table 4.2b - Energy performance of Villa Flora

Installation/ Feature	Unit/year	Amount	
		Design Phase	Operating phase 2012
Hot water	kWh		105.129
HVAC (Ventilation+ heat pumps)	kWh	155.000	275.824
Lighting and PC's Office (GAGE)	kWh	115.000	225.764
Lighting and PC's Expo (GAGE)	kWh	129.600	580.964
Total electrical energy		399.600	1.187.681
Source: PV pergola	kWh	105.000	133.670
Source: Eneco	kWh	165.000	1.054.011
Source: Biomass electrical e.	kWh	50.000	0

Table 4.3 - Operating Energy KPI's of Villa Flora

#	Key Performance Indicators	Formula	Unit	Ref.	Real value
1	X% of improvement on EPC	(1– EPC) * 100	%	50	70,2
	Feasibility and implementation study of renewable energy sources	Results of the feasibility and implementation study. Description of the CO2 offset strategies		The building supplies its own energy	A percentage of electricity comes from an external supplier
	CO2 offset strategies				
2	X% of renewable energy used by the building	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	100	100,00
3	X% of renewable energy used for heating	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	>100	282,84
4	X% of renewable energy used for hot water	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	100	42,38
5	X% of renewable energy used for ventilation	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	>100	16,15
6	X% of renewable energy used for cooling	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	>100	100,56
7	X% of renewable energy used for lighting	[Renewable energy sources (kWh) / energy demand (kWh)] * 100	%	25	5,52
8	X% of total renewable energy generated by the building	[Renewable energy generated by the building (kWh)/ energy demand (kWh)] *100	%	>100	103,61
9	Identification of CO2 emissions		Ton	0	213,16
10	Progress of the CO2 emissions strategies defined in design phase		%	100	0,00

4.1.2 KPI's: Embodied Energy of materials

In order to calculate the Embodied Energy (EE) and Carbon of materials, it is necessary to know the amount of them in kilograms. This category focuses on the materials employed to create and deliver energy, and the structural materials of the building. Figure 4.9 presents (using

Brand's classification) most of the materials used in the building Villa Flora. This data was collected through drawings, 3D models and documents of the building.

Appendix E contains the calculation process that was carried out for every building component. The Embodied Energy and Carbon database by the University of Bath was used to obtain the related values per material.

Example of the calculation process for the steel structure of the greenhouse and office building:

- Steel structure in the greenhouse: 271700kg

This information was based on the 3D model of the steel structure.

Considering the values of *Steel (section - average recycled content)* from the University of Bath database
EE: 21.50(MJ/kg) x 271700kg= 5841550 MJ
Embodied Carbon: 1.42 (kgCO2/kg) x 271700kg= 385814 kgCO2

- Steel structure in the office building: 16000kg

Considering the values of *Steel (pipe - average recycled content*) from the University of Bath database
EE: 19.80(MJ/kg) x 16000kg= 316800MJ
Embodied Carbon: 1.37 (kgCO2/kg) x 16000kg= 21920kgCO2

The total amount of Embodied Energy of Villa Flora, considering all the building components and materials displayed in figure 4.9, is 27.053 E^3 MJ. Likewise, the total amount of Embodied Carbon is 1.929 E^3kgCO_2. These results are compared with the 14 building case studies by Prof. Hammond and research officer Jones, creators of the University of Bath database. See figure 4.10 for comparison of the Embodied Energy and figure 4.11 for Embodied Carbon. Within the studies are three energy-efficient buildings (CS-12, CS-13, and CS-14) from USA and UK.

Case study 13 (CS-13) is the Beddington zero energy building (BedZed) designed by Bill Dunster Architects with Bioregional Development Group as the environmental consultants. Only renewable energy sources and small-scale combined heat and power (CHP) plants are used to meet the low operational energy needs of the building. BedZed has received multiple awards for architectural design, energy performance and sustainability. (Hammond & Jones, 2008). Despite of this, its Embodied Energy and Carbon results are not better than the other case studies.

The data used to calculate Villa Flora values is similar to the data used in the 14 case studies, where approximately 10 kinds of representative materials where analyzed. Based on figure 4.10 Villa Flora has the best Embodied Energy result of the group with 2378MJ/m^2. On the other hand, the result of Embodied Carbon presents Villa Flora with the highest amount of $kgCO_2$, figure 4.11. The contribution by material to both Embodied Energy and Carbon is displayed in figure 4.12.

Concrete makes the highest contribution for the total Embodied Energy. The fact that the contribution of this material is even larger for the Embodied Carbon could explain why the embodied carbon of Villa Flora is higher than the 14 case studies while the Embodied Energy is lower. Additionally the PV panels and glass have a high factor of embodied carbon.

Table 4.4 presents the results of the KPI's of this sub-category. Since Villa Flora performed better than the case studies, its results will be used as the reference values of the model.

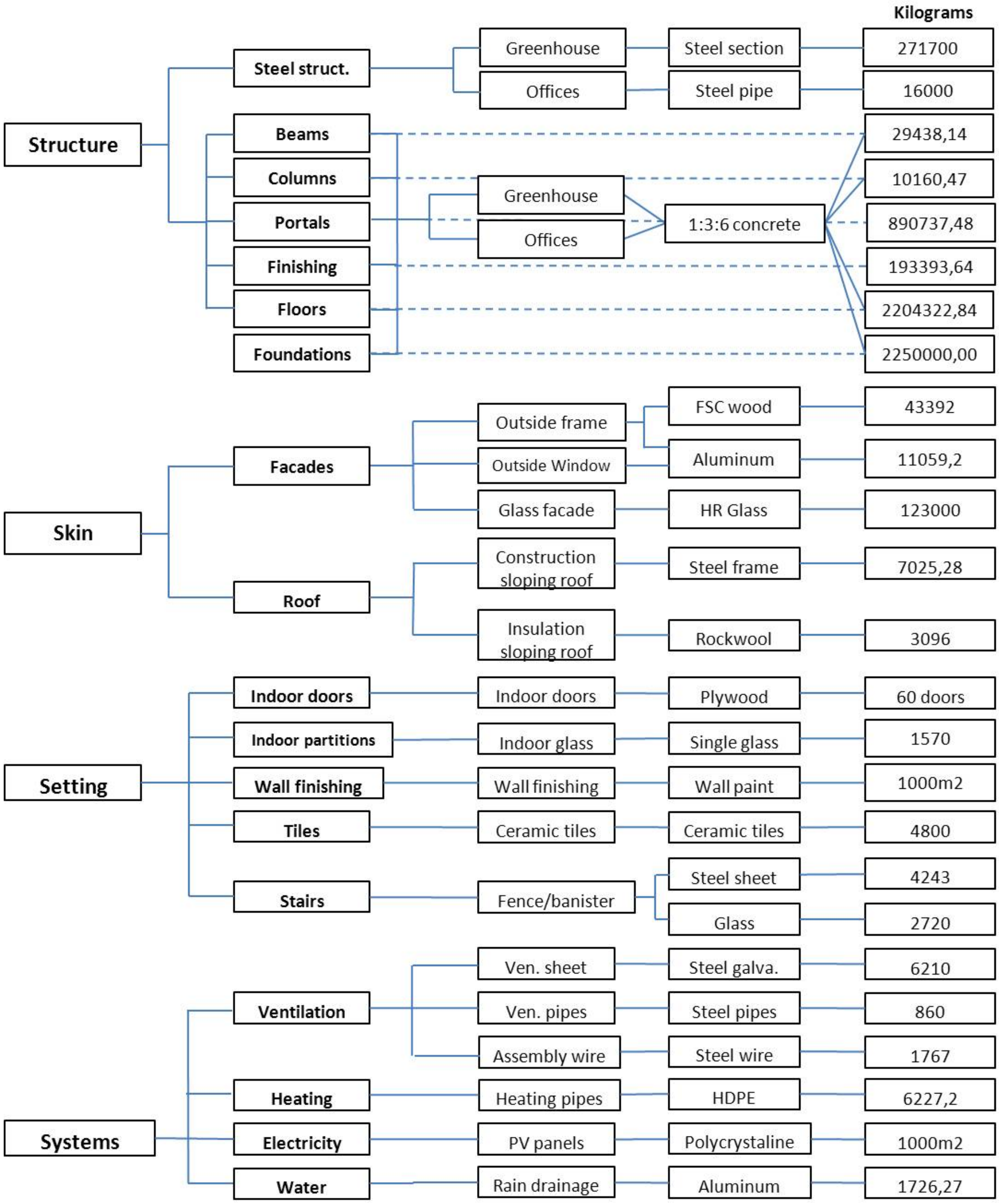

Figure 4.9 - Villa Flora materials

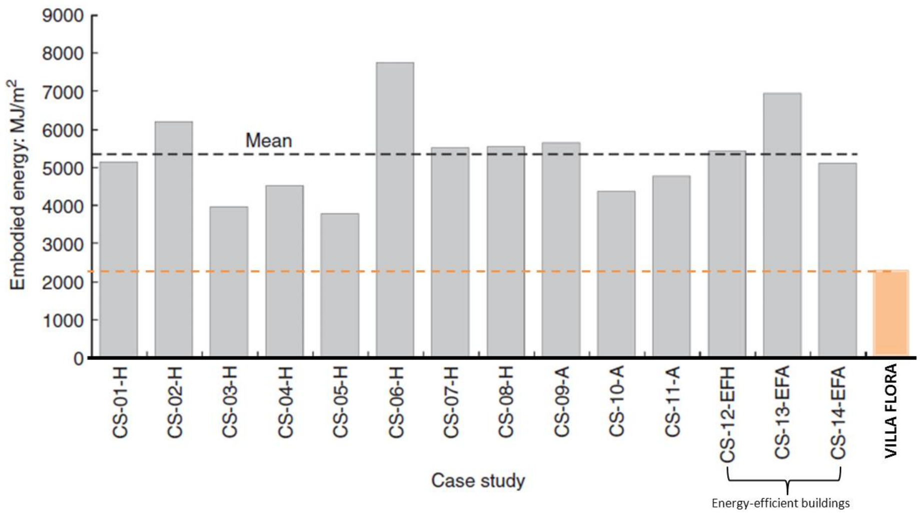

Figure 4.10 - Comparison Embodied Energy Villa Flora and 14 building case studies

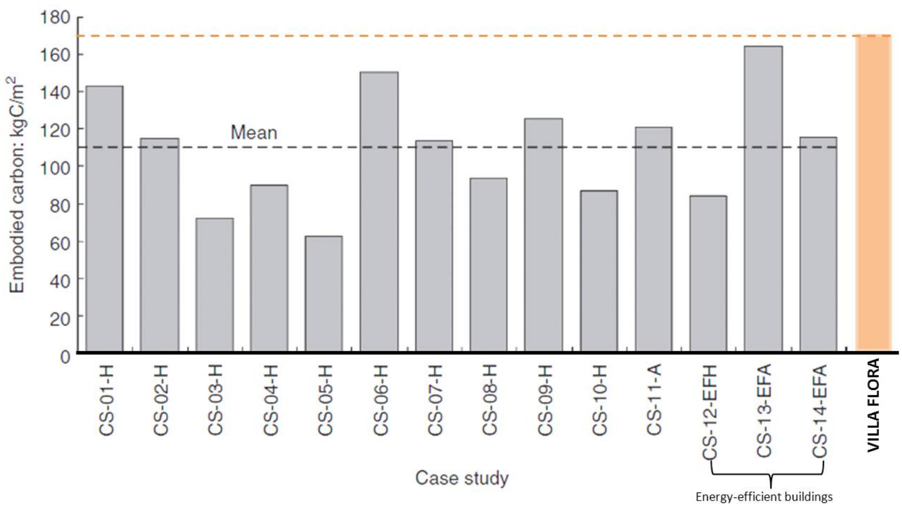

Figure 4.11 - Comparison Embodied Carbon Villa Flora and 14 case studies

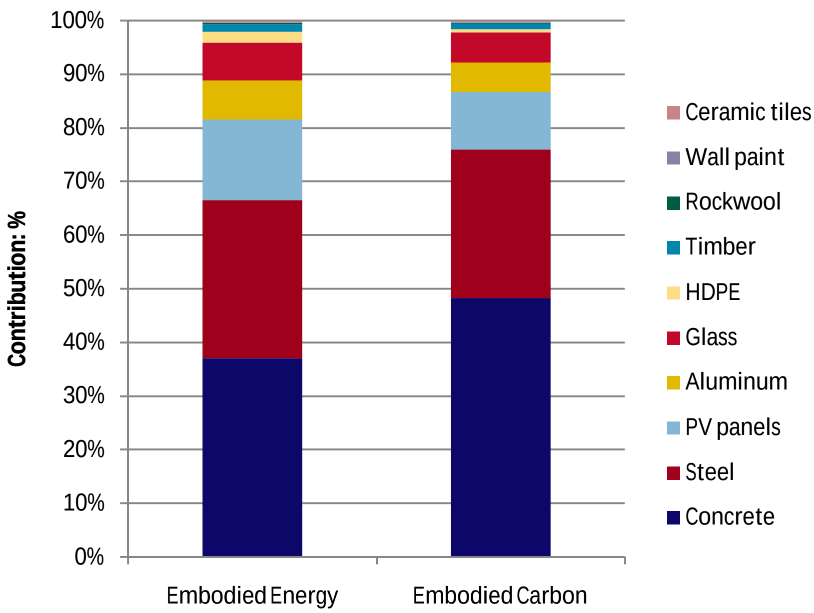

Figure 4.12 - Villa Flora material contribution to embodied energy and carbon

Table 4.4 - Embodied Energy KPI's of Villa Flora

Phase	#	Key Performance Indicators	Formula	Unit	Ref.	Value
Design Phase	1	Analysis and selection of materials according to EE and 'embodied carbon'	Result of analysis and strategy			This analysis was not carried out
	2	Strategies to offset the EE and 'embodied carbon' of materials				
	3	Projected amount of EE of the building materials	Inventory of carbon and energy database of the University of Bath	MJ/m^2	None ref. found in literature	
	4	Projected amount of 'embodied carbon' of building materials		kgC/m^2		
	5	Projected amount of EE of materials used in the renewable energy systems		MJ/m^2		
	6	Projected amount of 'embodied carbon' of materials used in the renewable energy systems		kgC/m^2		
Construction phase	7	Amount of EE of building materials	Inventory of carbon and energy database of the University of Bath	MJ/m^2		1922,46
	8	Amount of 'embodied carbon' of building materials		kgC/m^2		146,87
Operation phase	9	Amount of EE of materials used in the renewable energy systems	Inventory of carbon and energy database of the University of Bath	MJ/m^2		455,91
	10	Amount of 'embodied carbon' of materials used in the renewable energy systems		kgC/m^2		22,71

4.1.3 KPI's: Material media

Building components and materials are provided not by one but by several suppliers. In some cases these suppliers are intermediaries between others of a higher level in the production chain. More than 35 suppliers were involved in the construction process of Villa Flora. It is recommended to contact the companies involved to gather the required information for the assessment of building materials. Some requirements, based on the KPI's, could be even set for selecting the suppliers.

If designers and engineers use a specific questionnaire in their specifications demand, a database can be created with building materials, their quality and quantity for a specific building development. This can create awareness among suppliers about the requirements related to the C2C principles. Suppliers would be motivated to implement C2C in their products and materials in order to fulfill the demands of the building professionals. Appendix F presents a modified 'C2C datasheet' that could be used to collect the required information. However this datasheet was not used in the evaluation of building materials of Villa Flora. To illustrate the results of this sub-category the information gathered in the previous section (figure 4.9) was used instead.

The KPI's of this sub-category focus on the material media to generate and deliver energy. Some of the materials, listed in figure 4.9, of the energy systems are: Steel, HDPE pipe, PVC from the PV panels, and aluminum. These materials could potentially belong to the technical cycle. Therefore they are classified according to the definitions (section 3.3.5) of *Recyclable*, *Partially recyclable* and *Not recyclable*. A general classification is given without considering the detail chemical composition. It would be necessary a C2C ABC-X assessment for accurate results. The total amount of steel pipes, steel wire, HDPE and aluminum are classified as *Recyclable*.

The polycrystalline PV are considered as *Not recyclable* due to the hazard substances as dioxin, ethylene dichloride and vinyl chloride that are produced during the manufacturing of PVC. Even though lead (banned C2C metal) is often employed in the coating process of galvanized steel, it is not a banned metal of the technical nutrients list. Therefore Galvanized steel could be considered as *Recyclable* material. However it is considered here as *Partially recyclable* instead, due to its recyclability in products of lower quality. The material could be used in a re-galvanized process providing products with the same quality but it cannot be up-cycled.

An analysis about the intended pathway (biological or technical) was not carried out during the design phase. Therefore the results of the KPI's are not presented for this phase. Additionally the technical nutrients considered here have not ended their first use-scenario, so the KPI's of end-of-use scenario are not measured neither. For the KPI's of Operation phase only those related to technical nutrients are applicable. Secondary materials (heat, air, electricity and water are considered primary materials) were not identified as products of energy delivering. Likewise the material media do not provide other beneficial functions.

Table 4.5 - Material Media KPI's of Villa Flora

Phase	#	Key Performance Indicators	Formula	Unit	Ref.	Value
Design phase		Feasibility and implementation study of the energy material media for a biological or technical cycle	Results of the feasibility and implementation study			This analysis was not carried out
	1	X% of designed material used for energy delivery belongs to a biological/technical cycle	[Biological cycle material media (kg) / total material media (kg)] * 100	%	100	63
	2a	X% of intended biological/technical nutrients are degradable/recyclable	[TNs are recyclable (#) / total BNs (#)] * 100	%	Acc. building	This analysis was not carried out
	3a	X% of designed material resulting from energy delivery belongs to a biological (or technical) cycle	[Biological cycle material resulting (kg) / total material resulting(kg)] * 100	%		
	4a	Material media is designed with other beneficial functions	Explanation of the other beneficial functions			
Operation phase	**2**	X% of intended biological/technical nutrients are degradable/recyclable	[TNs are recyclable (#) / total BNs (#)] * 100	%	100	63,00
	3	X% of the material resulting from energy delivery belongs to a biological (or technical) cycle	[Biological cycle material resulting (kg) / total material resulting(kg)] * 100	%	Not defined	NA
	4	Material media provides other beneficial functions	Explanation of the other functions that material media provides			Not + functions
End-of-use scenario	**5**	X% of biological nutrients has entered in the cycle	[Biological material media in cycle (kg) / total biological material media (kg)] * 100	%	100	Have not entered this cycle yet
	6	X% of technical nutrients has entered in the cycle	[Technical material media in cycle (kg) / total technical material media (kg)] * 100	%	100	
	7	X% of biological (or technical) material resulting has entered in the cycle	[Biological material media in cycle (kg) / total biological material media (kg)] * 100	%	100	

4.1.4 KPI's: Energy Effectiveness

Figure 4.13 below illustrates the flow of energy of Villa Flora. Accordingly, the extra heat harvested during summer is exported to another building of the *Green Park*. External suppliers are needed to fill the building demand in electricity. This diagram gives information about the amount of used and exported energy. One could say that the extra heat is providing a positive impact to the environment. This 'extra' energy is not being released to the air as waste; it is used instead as a renewable source by another building.

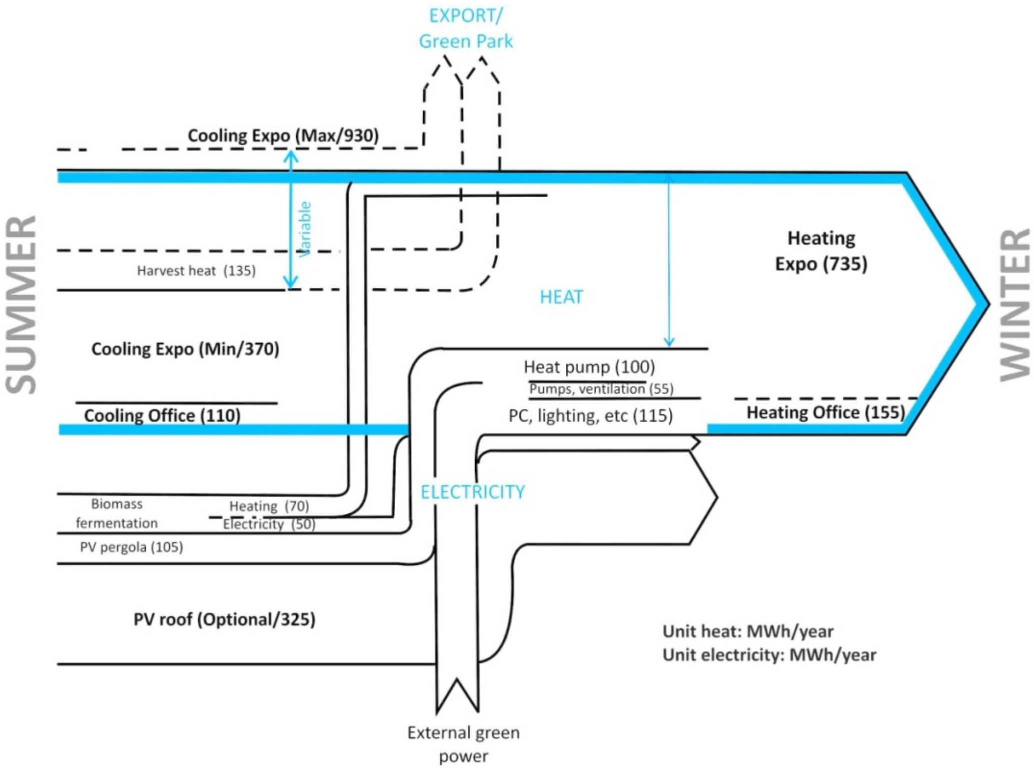

Figure 4.13 Energy flow at Villa Flora. Source: Volantis B.V.

Even though the materials used in the energy systems of Villa Flora (Steel, HDPE, and Aluminum) are not C2C certified, they are considered here as 'C2C materials' due to their classification as *Recyclable* in the previous sub-category. To compared the total amount of 'C2C materials' as energy carriers and the total amount of materials used in the energy systems, 20% of the total amount is assumed as *Not recyclable* for the PV materials.

Table 4.6 presents the results of Villa Flora within this sub-category.

Table 4.6 - *Energy effectiveness* KPI's of Villa Flora

Phase	#	Key Performance Indicators	Formula	Unit	Ref.	Value
Design/ Operation	**1**	COP of technical installations	Comparison with a standard COP of heat pumps	COP	>3-5	7 to 10
	2	X% of C2C energy used by the building	[total C2C energy (MJ) / total energy demand (MJ)] * 100	%	100	103,61
	3	X% of C2C materials as energy carriers	[C2C materials as energy carriers (kg) / total carrier materials (kg)] * 100	%	100	50,41
	4	Amount of work being waste to bring systems into a state of equilibrium	Energy balance analysis	%	0	0,00

4.3 Materials KPI's

4.3.1 KPI's: Material Inventory

During the design phase of Villa Flora, C2C certified materials and products were chosen for the interior design of the offices of Volantis. Desso carpet and Herman Miller chairs are some examples of the C2C products. However other companies are tenants of the building as well and their offices are not equipped with C2C products. *Interior design products* belong to the category *Stuff* in Brand's classification. Nevertheless these products are included here in the category *setting* The *Stuff* category has not been considered in the KPI's. It is assumed that only 30% of the products belonging to this classification are C2C certified.

None of the materials depicted in figure 4.9 belongs to the PMD or is C2C certified. Therefore the percentage of the KPI's related to materials of the structure, skin, and setting is zero. Assuming an equal division of materials belonging to these categories and *Stuff* (interior design products) the total percentage of building materials that belongs to the PMD is seven.

Table 4.7 - KPI's: *Material Inventory* of Villa Flora

Phase	#	Key Performance Indicators	Formula	Unit	Ref.	Value
Design/ Operation phase	**1**	X% of building materials belongs to the *Positive Materials database*	[Building materials of the PMD (kg) / total building materials (kg)] * 100	**%**	50	7
	2	X% of the *structure* materials belongs to the PMD	[Structure materials of the PMD (kg) / total structure materials (kg)] * 100	**%**	50	0
	3	X% of the *skin* materials belongs to the PMD	[Skin materials of the PMD (kg) / total skin materials (kg)] * 100	**%**	50	0
	4	X% of the *setting* materials belongs to the PMD	[Setting materials of the PMD (kg) / total setting materials (kg)] * 100	**%**	50	30
	5	X% of building materials is known	[Building materials known (kg) / app. total building materials (kg)] * 100	**%**	100	76.25
	6	X% of the *structure* materials is known	[Structure materials known (kg) / app. total structure materials (kg)] * 100	**%**	100	95
	7	X% of the *skin* materials is known	[Skin materials known (kg) / app. total skin materials (kg)] * 100	**%**	100	85
	8	X% of the *setting* materials is known	[Setting materials known (kg) / app. total setting materials (kg)] * 100	**%**	100	75

4.3.2 KPI's: Intended Pathway and Quality Content

Figure 4.14 presents the information that was used to calculate the KPI's of the subcategories *Intended Pathway* and *Quality Content.* Due to this analysis was not carried out during the design phase, the intended pathway and types of nutrients have been assumed. For instance, concrete components that are designed to be disassembled and re-use in a new location are considered as technical nutrients. Only the amount of concrete used in the foundations is assumed as slowly degradable nutrient. More accurate information is required in order to give a correct evaluation of the materials in these sub-categories. Due to this is only intended to illustrate the assessment process (operation phase) most of the data and percentages are assumptions and not correspond to the real performance of Villa Flora. The chemical composition of materials was not gathered. Therefore the KPI's indicators related to the C2C banned list where not answered. Likewise none of the intended technical or biological nutrients have entered the 'second cradle'. Table 4.8 and table 4.9 presents the calculated KPI's for the sub-categories *Intended Pathway* and *Quality Content* respectively.

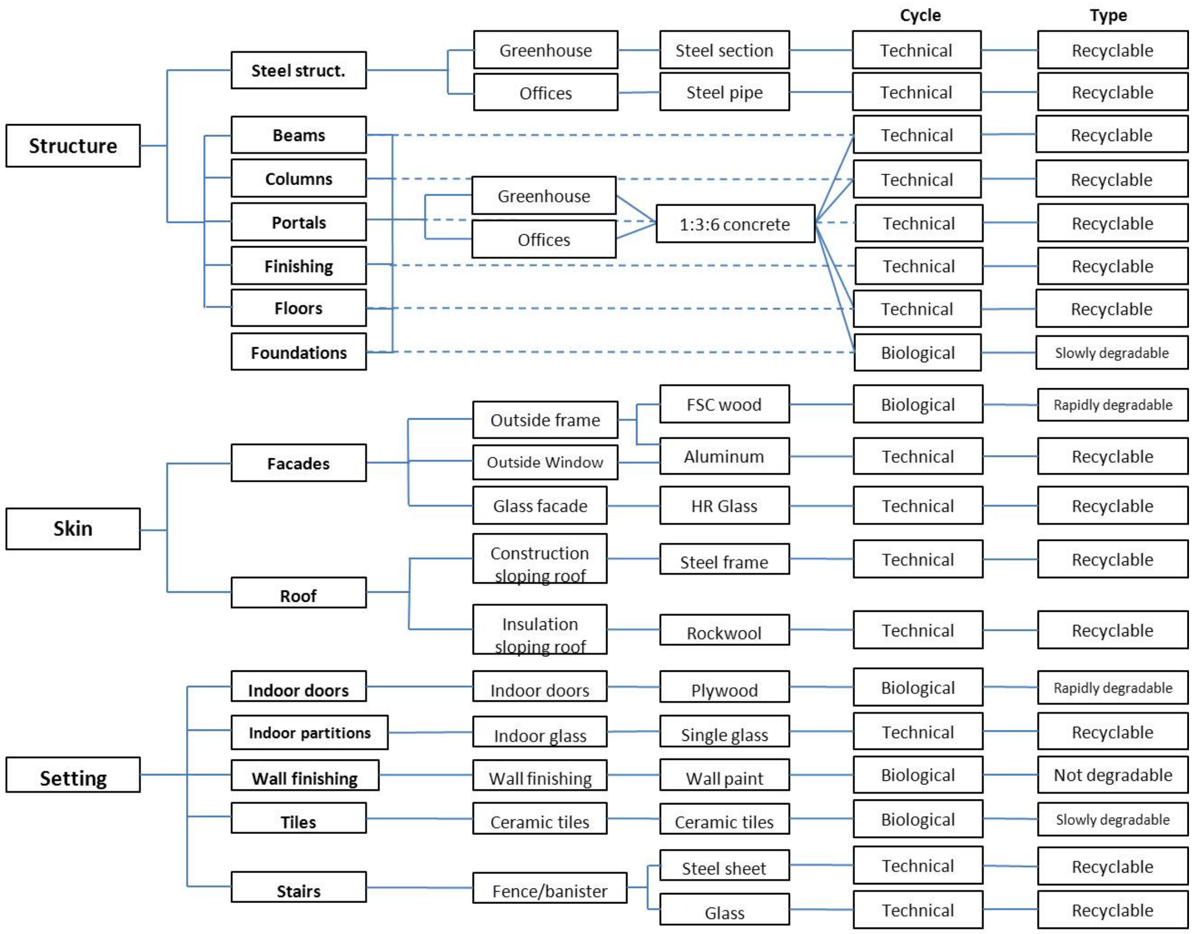

Figure 4.14 - Intended Pathway and Quality Content of Villa Flora materials

Table 4.8 - KPI's: *Intended Pathway* of Villa Flora

Phase	#	Key Performance Indicators	Formula	Unit	Ref	Value
Design Phase	1	X% of building materials belongs to either biological or technical pathway	[Building materials as TNs or BNs (kg) / total building materials (kg)] * 100	%	50	100
	2	X% of the *structure* materials belongs to either biological or technical pathway	[Structure materials as TNs or BNs (kg) / total structure materials (kg)] * 100	%	50	100
	3	X% of the *skin* materials belongs to either biological or technical pathway	[Skin materials as TNs or BNs (kg) / total structure materials (kg)] * 100	%	50	100
	4	X% of the *setting* materials belongs to either biological or technical pathway	[Setting materials as TNs or BNs (kg) / total structure materials (kg)] * 100	%	50	100
	5	X% of biological nutrients are not part of the C2C Banned list	[BNs are not part of banned list (#) / total BNs (#)] * 100	%	100	No inf.
	6	X% of technical nutrients are not part of the C2C Banned list	[TNs are not part of banned list (#) / total TNs (#)] * 100	%	100	
End of use scenario	7	X% of intended biological nutrients are following the cycle	[BNs are in the second cradle (#) / total BNs (#)] * 100	%	100	NA
	8	X% of intended technical nutrients are following the cycle	[TNs are in the second cradle (#) / total BNs (#)] * 100	%	100	

Table 4.9 - KPI's: *Quality Content* of Villa Flora

Phase	#	Key Performance Indicators	Formula	Unit	Ref.	Value
Design phase	**1**	X% of intended biological nutrients are rapidly degradable	[BNs are rapidly degradable (#) / total BNs (#)] * 100	**%**	100	2
	2	X% of intended technical nutrients are recyclable	[TNs are recyclable (#) / total BNs (#)] * 100	**%**	100	100
End of use scenario	**3**	X% of rapidly degradable biological nutrients are following the cycle	[Rapidly degradable BNs are in the second cradle (#) / total BNs (#)] * 100	**%**	100	NA
	4	X% of recyclable technical nutrients are following the cycle	[Recyclable TNs are in the second cradle (#) / total BNs (#)] * 100	**%**	100	

4.4 Villa Flora results

An evaluation scale of 0 to 3 (table 4.10) was used to assess the results of Villa Flora with the KPI's. Table 4.11 presents the *Renewable Energy* KPI's, WF, and 'green scores' per sub-category and category. The column *3rd level* represents the 'green score' per KPI's; these are obtained by multiplying the evaluation (0-3) with the WF of each KPI. The column *2nd level* is the 'green score' per subcategory, which equals to the sum of the 'green scores' of third level. Similarly, the total of *1st level* column represents the 'green score' per category, after adding the results of multiplying the 'green score' of second level with the WF of the subcategory.

Table 4.10 - Evaluation scale for the KPI's

Evaluation Scale	
0,0	Real value equally and < 0
1,0	The result is <50% the reference
1,5	The result is >50% the reference but <100%
2,0	The result is as good as the reference
3,0	The result is better than the reference

The 'green scores' of second and first level are used as an input to graphically represent the environmental performance of Villa Flora. Figure 4.15 is the result of the category Renewable Energy. In this graphic the smiley is added as qualitative recognition of the KPI number three of the sub-category *Operating Energy*. Figure 4.16 represents the result of the 'green scores' of *Materials* subcategories. Figure 4.17 illustrates the complete picture using the 'green scores' of the categories *Renewable Energy* and *Materials*. Blocks are not added to the categories that are not yet developed.

Figure 4.18 presents the results (green scores) of the categories. The total 'green score' is calculated only with the results of *Renewable Energy* and *Materials.* The WF's defined in the previous sections were not used due to the results are not available for the other categories. The correlated weighting factors in this example are 55% for Renewable Energy and 45% for Materials. Consequently 73.67% is the value to place the building in the defined 'green area' of the model (figure 4.19), although its position is considering only two categories of the model.

Table 4.11 - Evaluation scale for the KPI's

Sub-category	#	WF	Key Performance Indicators	Unit	Ref.	Value	Ev.	3rd level	2nd level	1st level
Operating Energy WF: 55%	1	1,4	X% of improvement on EPC	%	50	70,2	3	4,2		
	2	17,6	X% of renewable energy used by the building	%	100	100,00	3	52,8		
	3	6,8	X% of renewable energy used for heating	%	>100	282,84	3	20,4		
	4	6,8	X% of renewable energy used for hot water	%	100	42,38	1	6,8		
	5	6,8	X% of renewable energy used for ventilation	%	>100	16,15	1	6,8		
	6	6,8	X% of renewable energy used for cooling	%	>100	100,56	3	20,4		
	7	6,8	X% of renewable energy used for lighting	%	25	5,52	1	6,8		
	8	36,5	X% of total renewable energy generated by the building	%	>100	103,61	3	109,5		
	9	2,6	Identification of CO_2 emissions	Ton	0	213,16	3	7,8		
	10	7,9	Progress of the CO_2 emissions strategies defined in design phase	%	100	0,00	0	0	78,50	43,17
EE of materials WF:13%	7	6,4	Amount of EE of building materials	MJ/m^2	None ref. found in literature	1922,46	2	12,8		
	8	6,4	Amount of 'embodied carbon' of building materials	kgC/m^2		146,87	2	12,8		
	9	5,6	Amount of EE of materials used in the renewable energy systems	MJ/m^2		455,91	2	11,2		
	10	4,1	Amount of 'embodied carbon' of materials used in the renewable energy systems	kgC/m^2		22,71	2	8,2	66,67	8,666667
Material media WF:27%	1	20,7	X% of designed material used for energy delivery belongs to a biological/technical cycle	%	100	63	1,5	31,05		
	2	21,7	X% of intended biological/technical nutrients are degradable/recyclable	%	100	63,00	1,5	32,55		
	4	21,0	Material media provides other beneficial functions	Explanation of the other functions that material media provides		Not other beneficial functions	1	21	83,82	22,63
Energy effect. WF:5%	1	5,6	COP of technical installations	COP	>3 to 5	7 to 10	3	16,8		
	2	44,4	X% of C2C energy used by the building	%	100	103,61	2	88,8		
	3	44,4	X% of C2C materials as energy carriers	%	100	50,41	1,5	66,6		
	4	5,6	Amount of work being waste to bring systems into a state of equilibrium.	%	0	0,00	3	16,8	63,00	3,15
									Total	77,62

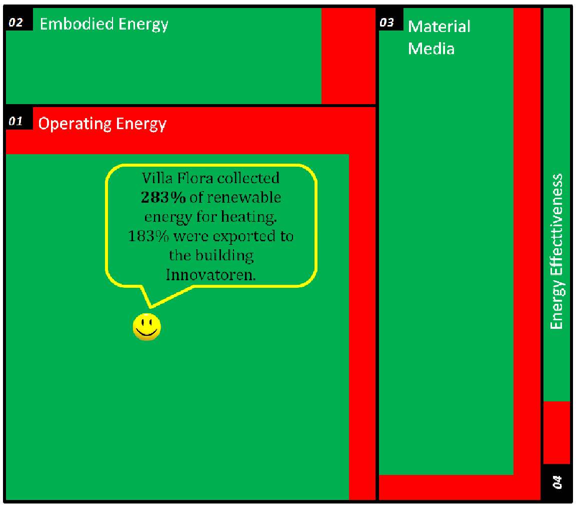

Figure 4.15 Villa Flora result on *Renewable Energy*

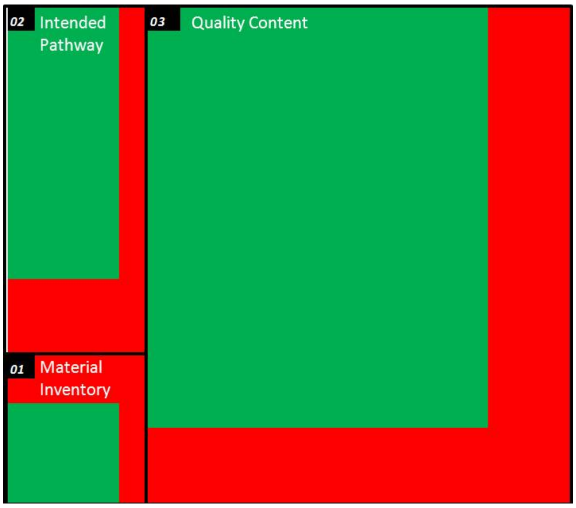

Figure 4.16 Villa Flora result on *Materials*

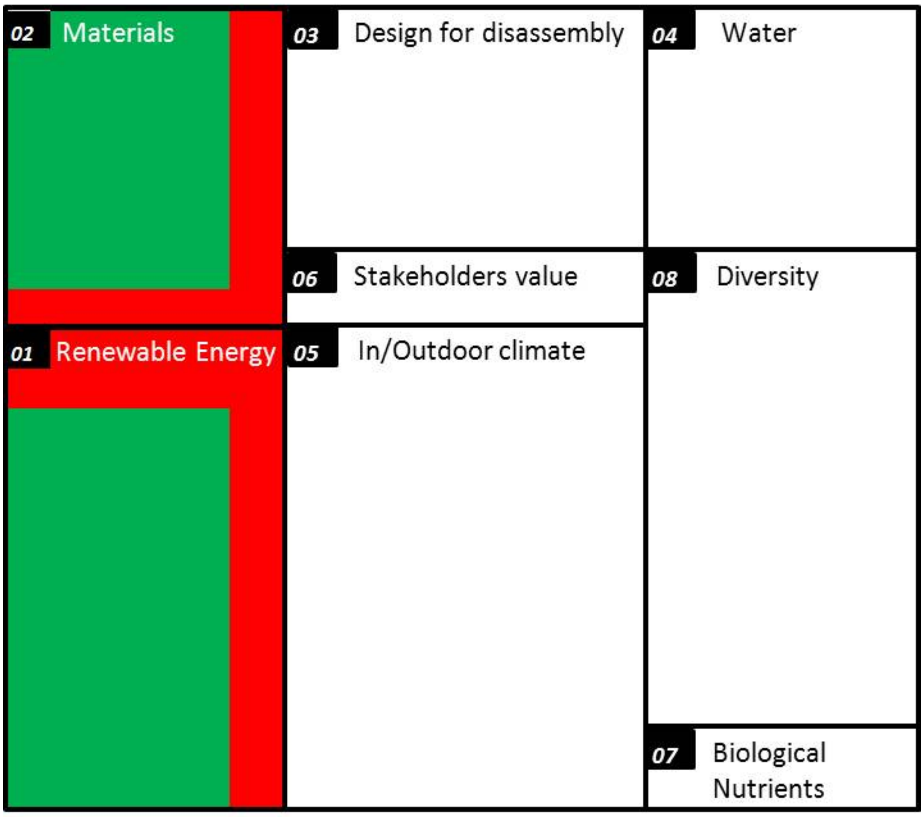

Figure 4.17 Villa Flora result on Categories

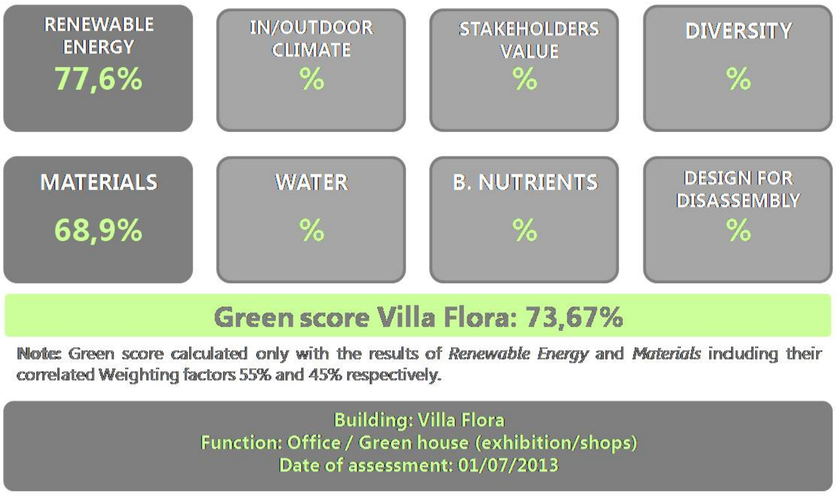

Figure 4.18 Villa Flora Green scores

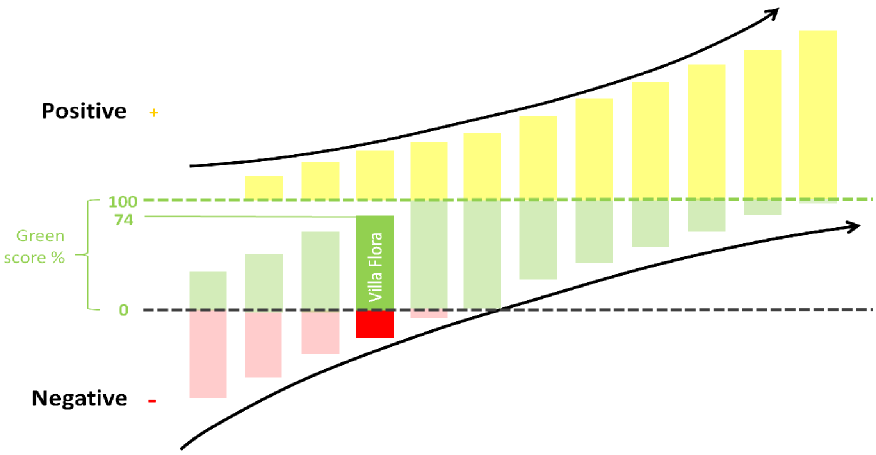

Figure 4.19 Villa Flora position in Green area

4.5 Conclusion Villa Flora

The building Villa Flora is used in this section as a case to test and complete the model. This building was presented as the *Greenest office of the Netherlands*. The model gives objective and quantitative information of its performance within two categories *Renewable Energy* and *Materials.* During the process it was necessary to define an evaluation scale (table 4.10) to obtain the 'green scores' of the different levels of the model.

The results of some KPI's were used to set the reference values of the model. The graphical results present quantitative information that helps user identifying the main aspects of the building. It was possible to measure the performance of the building according to each KPI's. Its performance was translated into 'green scores' using the weighting factors. Villa Flora has a performance of 74% within the green area. This assessment would allow comparing Villa Flora with another building and presenting objective results of its performance. Additionally figure 4.16 presents its position in relation to the goal of having a positive footprint. It is an incentive for its stakeholders to continue in the pathway and work on the positive features of the building.

CHAPTER 5
C2C Expert Panel Evaluation

This chapter summarizes the main aspects of the model that were pointed out by the C2C experts during the Panel Evaluation. This evaluation was hold separately with the members in different sessions. Additionally it includes an analysis of the recent consultative beta version of *How to plan a big beneficial footprint* by Mulhall, Braungart and Hansen (2013).

5.1 How to plan a big beneficial footprint

How to plan a big beneficial footprint (Mulhall, 2013) is the latest publication by Douglas Mulhall, Michael Braungart and Katja Hansen, related to the implementation of C2C in the built environment. The *consultative beta version* was released on May 2013, therefore not included in the literature analysis of this project. However it is necessary to analyze its content due to its relation and further development of the *C2C criteria for the built environment*. Additionally the feedbacks obtained (from the C2C experts) match the concepts described in this publication.

The main focus of the publication is on *planning, financing and goal setting*. It emphasizes on *Cradle to Cradle-inspired Elements* rather than C2C buildings as a whole. *'...there are yet no Cradle to Cradle buildings or developments. Instead there are C2C-Inspired Elements in Buildings and Developments, which are steps on the way to C2C'* (Mulhall, 2013). Cradle to Cradle-inspired Elements are preferred to generate '*quick wins*' and demonstrated the value of C2C.

The content of the publication is divided as '*a la carte'* menu using Appetizers, Main course, and Dessert. *Appetizers* presents the 'getting started' tools. It includes C2C basic information, project stage and stakeholders' identification, baseline analysis of C2C features, among others. For instance, project stage identification is an important factor of *Appetizers* because the focus of the process will differ depending on the building stage. Different advices are given according to the stage of the project, which could be on *regulatory approvals*, *building contract selection*, *site preparation*, *construction*, *operations and maintenance*, or *disassembly and reprocessing*.

Main course relates to the setting of intentions (qualitative) and goals (quantitative). The focus is on stakeholders and their aspirations for the development. After rephrasing stakeholders goals in C2C terms, five *C2C-inspired Elements* are defined in order to reach them. Each building has its own suitable *Elements* to work on. Likewise the same *Element* provides different added value, depending on the context where it is located.

Dessert suggests celebrating achievements with marketing. Some of the options provided here are: publishing the Roadmap and using it as a marketing and management tool, featuring C2C-inspired *Elements* and *Delights* and applying to the *Registry of C2C-inspired Elements in Building Developments* for an award.

The publication provides examples and options for users to use according to the needs of their developments. It aims users by identifying goals and achieving them through *C2C-inspired Elements,* see as example table 5.1 (next page).The approach is dynamic and involves different tools according to the building, location, stakeholders, among others aspects.

Table 5.1 - Example of how an element integrates C2C principles, quality dimensions & Goals. Source: (Mulhall, 2013)

C2C PRINCIPLES →→→	Everything is a Resource for Something Else. "Waste=Food" Biodiversity, Conceptual Diversity, Cultural Diversity Current Solar Income						
C2C QUALITY DIMENSION →→→	Healthy Air & Climate	Healthy Water & Nutrient Recycling	Healthy Materials	Biodiversity Enhancement	Cultural Diversity, Quality of Life, & Multifunctionality	Mobility Enchancement	Renewable Energy-Positive
C2C-INSPIRED ELEMENT ↓↓↓ **ATRIUM** Also known as; BUILDING INTEGRATED GREENHOUSE or WINTERGARDEN	**MEASURABLE TECHNICAL GOAL** Bio-filters capture & metabolise 50% of CO2 & particulates from air in the building interior rising to 70% in 3 years, and re-introduce cleaner air to meeting rooms. **FINANCIAL GOAL** Evaluate savings from using CO2 and compost to profitably grow vegetables and gain carbon credits. Savings on HVAC filter maintenance & replacement costs by using	**MEASURABLE TECHNICAL GOAL** Capture 70% of rainwater on site for reuse & discharge into ecosystems, rising to 90% over 3 years. **FINANCIAL GOAL** Quantify savings on water fees & water reprocessing costs. Quantify savings on water for urban agriculture & landscaping. **ADDED VALUE** Financial & supply security for;	**MEASURABLE TECHNICAL GOAL** Compost 50% of bionutrients used in the building, rising to 90% in 3 years. Nutrients for plants e.g. soil, fertilizer are defined for the whole cycle by year 3. **FINANCIAL GOAL** Capital savings by disassembling & reassembling old greenhouses. Evaluate savings on maintenance & renovations with easier replacement of	**MEASURABLE TECHNICAL GOAL** Declare Atrium as biodiversity zone e.g; pond as fish habitat, trees as bee habitat, landscaping as topsoil enhancement zone. Date; Year 1 of operations. **FINANCIAL GOAL** Produce profitable urban agricultural products for restaurants or occupants. Year 1 of operations. Savings on landscaping topsoil by soil manufacturing.	**MEASURABLE TECHNICAL GOAL** ***Cultural diversity.*** Integrate water reycling as art e.g. water walls, fountains Date; By completion of construction. ***Quality of Life & Multifunctionality.*** Atrium is a clean-air pre-school for children of occupants. Date; Year 1 operations. **FINANCIAL GOAL** Revenues from integrated use. Date; Year 1 of operations. Enhance lease value by offering added services to	**MEASURABLE TECHNICAL GOAL** Improve mobility between buildings in cold or hot climates by moderating temperatures and creating integrated spaces instead of divided ones. Date; By end of construction. **FINANCIAL GOAL** Business model from charging electric vehicles. Date; By beginning of construction. **SOCIAL GOAL** Use Atria to	**MEASURABLE TECHNICAL GOAL** Atrium is a functional part of the heating & cooling system, using solar energy for photosynthesis, supporting heating and cooling of the building. Date; By year 1 of operations. **FINANCIAL GOAL** Lighting costs savings from integrating more natural light. By moderating temperature extremes, uaing current solar

5.2 Critical review of the decision support model

The following review of the model (described in *Chapter 3)*, is based on the feedbacks given by Douglas Mulhall senior researcher at the Academic Chair 'Cradle to Cradle for Innovation and Quality' at Rotterdam School of Management, Tanja Scheelhaase C2C lecturer at the University of Twente, Frans Beckers manager director of EPEA Netherlands, and Bas van de Westerlo Cradle to Cradle consultant at C2C Expo Lab. The information presented in the previous section is used as well to complete the review.

5.2.1 Buildings as objects analyzed

The model attempts to guide the design and the evaluation process of buildings as a whole. Therefore its object analyzed is a *Building* while in the C2C approach it is an *Elemen*t. A C2C building does not exist yet. It is necessary a further development in materials, knowledge and parties involved to implement the C2C principles in a complete building. Although the model suggests a building classification (that could be related to *Elements*), it presents the results for the whole building. Instead, the C2C approach focuses on *Elements* to integrate its principles. *C2C-Inspired Elements* are defined as *value-added building features that measurably implement C2C at a substantive level* (Mulhall, 2013). For instance: Integrated rainwater and effluent reuse for value-added water savings.

On the contrary the *C2C-Inspired Elements* are placed in a roadmap, where measurable goals and units are defined for a specific element. The features of *C2C-Elements* cannot be compared among other *Elements*. They are only considered as individual elements matching the C2C principles, the five categories of the product certification and the triple top line.

It is not possible to compare different buildings. The following is an example given by Mulhall. A *music school* has different benefits than a *greenhouse*. The greenhouse generates renewable energy, cleans water and air, recycles nutrients, is designed for disassembly and has safe materials. The music school is in a favela and saves lives by keeping kids out of gangs but has no benefits for renewable energy, materials, climate, nutrients, water, or disassembly.

The model assesses buildings through eight categories and proposes a comparison of buildings. The values and the focus on the categories can be different for different buildings according to their own stakeholder's intentions. For instance in a dry area like the Sahara region the focus would be on the category Water, while in the Netherlands this category could have a dissimilar focus.

5.2.2 Model categories

One could say that the categories of the model are the equivalent of the *C2C Quality dimensions* presented in Table 5.1. Nevertheless the Model categories are presented as ordinary features while the *Quality dimensions* are the result of translating the Stakeholders intentions. In this way the model could limit creativity, denying the possibility to create and include new stakeholders' intentions. Furthermore some building developments will require the evaluation of their elements in some categories but not in all of them.

5.2.3 Weighting factors and 'green score' of the Model categories

To prioritize the different categories will depend on the context and the members involved in the weighting process. The model is not identifying the variety of buildings and their locations, when assessing them with the same Weighting Factors (=WF). Even when the WF could be modified for each development, there will be the question of what participants are the most suitable to decide the priority of the categories. The stakeholders and participants of a building development should decide by themselves the WF's of the categories.

Additionally, according to Mulhall (2013) '*It is seriously problematic to try comparatively scoring C2C buildings which have diverse focuses in diverse climate and geographic zones under diverse socio-economic conditions where stakeholders have differing goals".* It is better to communicate the added value of C2C-Inspired elements than giving a generic measurement.

5.2.4 Key Performance Indicators

The model suggests KPI's in order to measure the performance of building in every category. KPI's do not make any distinction between one building and another one, it was intended that the defined KPI's could be applied to different types of buildings such as offices, shops, or dwellings. The KPI's, sub-categories and categories have the same WF's in order to compare different buildings. As mentioned before, C2C focuses on *Elements* where different *Elements* involve different measurable goals that are created according to the project and intentions of stakeholders.

Previous chapter presents the KPI's for the categories *Renewable Energy* and *Materials*. One of the comments about these KPI's relates to the design of solutions according to them but not matching the C2C principles. For instance:

"A simple building such as a garage could easily built with 100% Cradle to Cradle materials (e.g. certified wood) and it could be designed like an IKEA system (e.g. shelf Billy). This building could match your KIP's of materials, water, nutrients and design for disassembly and even also generate renewable energy which could be measured. The outcome would be 99% "C2C- ness" of

this building with a very high scoring. But this scoring would be misleading. It would generate the idea that implementing such a uniform segment like garage all over the world would be a positive approach. The important aspect of Cradle to Cradle as innovation driver would get lost, different financing models and especially the adaption to the local needs would be negated. The valuation of the categories (KIP's) is very specific depending of the boundaries and conditions of the individual location and situation. Cradle to Cradle provides directly from the beginning an approach how to implement positive defined elements with the prospective of development. (You don't need to be perfect at the beginning, but you should have a plan how to get there in a defined time.) During the whole time you request innovations based on your roadmap e.g. of materials or of water treatment systems or whatever you stated as your aim for a specific element. In this way your building becomes an innovation driver" (Tanja Scheelhaase, 2013).

5.2.5 Qualitative recognition

Table 5.1 (previous section) describes the *Added value* of the *C2C-Inspired Element* per quality dimension. This information could be comparable to the qualitative recognition that the model gives to those building elements that provides a positive result. The smiley in the Mondrian graph, see section 3.5, provides quantitative information about the positive result but it is considered as a qualitative recognition due to the model does not measure the positive-ness value. Every quality dimension of table 5.1 presents an *Added value,* whereas in the model buildings could have none of this quality recognitions or smiley. Elements that have always an *Added value* are preferred among those which do not. So it is better to guide the design process considering ahead the *Added value* that an element could provide in every feature.

5.2.6 Material Inventory of the model

In section 3.3.3 the model presents a *Material Inventory* for buildings based on Brand's classification where building components and their parts are identified. This is a detailed list of the type and amounts of building materials. In the publication by Mulhall, Braungart and Hansen it is recommended not consuming time and money performing this task. Instead, it is better to identify only the resources available to add value to the building development. This depends as well on the stage of the building that this information is collected. For example: *"If site services are already installed there is not point spending time and money inventorying materials for those"* (Mulhall, 2013). The options suggested by the authors are: *Quick-Scan Site Features*, *Do Baseline Analysis (Identify what you are already doing right!)*, and *Inventory systems you might want to focus for integration*.

5.2.7 Financial Innovation

The model does not cover any aspect related to the financing of C2C-Inspired building developments. Mulhall, Braungart and Hansen present *Financial Innovation* as part of the framework in order to generate investment sources for *C2C-inspired Elements* and generate added value for stakeholders. For instance two of the steps recommended in this focus are: Identifying tools to finance *C2C-inspired Elements*, and Describing value propositions as investments instead of cost.

5.2.8 Building as Materials Banks

The concept of *Buildings as Materials Banks* is not considered by the model. Mulhall, Braungart and Hansen propose organizing buildings as materials banks to add value. This concept is based on building materials targeted as assets instead of liabilities. *"As with banks,* *many materials are deposited then removed from a building during its use"*. It aims materials that are profitably recoverable during the different scenarios of building elements.

5.2.9 Knockout criteria

The model does not describe how deal with anti-C2C buildings e.g. to torture prisoners, produce chemical weapons, or generate nuclear power. There is no such thing as a C2C torture chamber or nuclear plant, and no such thing as a C2C-Inspired Element on those types of buildings (Mulhall, 2013). The model is not specifying the type of buildings that can be and not included, for instance specifying that those buildings with ethical issues as the mentioned examples are out of the scope.

5.3 How the model could fit in the C2C approach

Previous sections presented a summary of the latest C2C publication related to the built environment and the reviews given by the C2C experts. Based on this information, it is analyzed here how the model could fit into the C2C approach.

The C2C approach aims leading the built industry into a transition from a negative environmental impact to positive one. Consequently the model is in line with this aim because it looks to bring buildings to a reference line (as a first step) after which, buildings start providing positive impacts. So the direction of the model is as well towards a positive environmental footprint.

Once the *planning*, *financing* and *goals* of the development are set, the model could be used as tool to guide the design process of *C2C-Inspired elements*. It could identify the most suitable elements of a building to work on. The KPI's can be translated as the goals to be achieved by each element. The *Intended Use* and *Defined Use* could be the foundation for the KPI's. *Intended Use* describes "what is the product or process intended to do" and is a basic part of goal-setting. *Defined Use* describes the pathway of materials in Biological or Technical metabolisms.

And the design of several C2C-Inspired elements could lead in the future to a C2C-Inspired building as a whole. The model could objectively identify and present the elements of a building that are truly C2C-inspired. The results could be used to feature the C2C-inspired *Elements* and *Delights* of a building during the marketing phase.

CHAPTER 6
Conclusion

This chapter summarizes the main features of the model and the answers to the research questions that were covered in the previous chapters. Further recommendations are provided based mainly on the C2C Expert Panel Evaluation to the model.

6.1 Thesis Goal

This research thesis proposes a model that could guide the design and evaluation process of buildings according to the C2C principles. It is intended to offer better directions to the building professionals for the implementation of C2C and to give answer to the research question:

How can the Cradle to Cradle® principles be integrated into a model to guide the design and evaluation process of buildings?

Chapter 3 describes the framework of the model. It aims designing and evaluating buildings through eight categories; only two of them (*Renewable Energy* and *Materials*) were developed in detail. While the traditional environmental assessment methods focus on reducing the negative environmental impact of buildings, C2C suggests designing systems that emulate nature and generate a beneficial impact. In practice, architects and planners follow methods and models in order to design and recognize buildings with 'sustainable' features. Directions are needed in order to translate a concept into practical examples. C2C is lacking in a comparable model that drives the design and evaluation process of buildings with positive effects.

Different opinions where found related to the measurement of the C2C features in buildings through the suggested categories and Key Performance Indicators of the model. On one hand, at the level of building designers some kind of assessment is necessary in order to make the information more clear and present the results objectively. Building professionals need tools and measurement systems in order to make objective choices during the design and operation phase of buildings. Choices based on calculations and prediction of effects. For instance the engineering and consultant company Volantis B.V. is one of those facing the challenges of implementing C2C in building design using the available C2C tools. According to the commercial director and senior consultant of the company Ing. Bas Holla, the playing field of building designers, constructors and owners need tangible and measurable systems in order to make their choices. So in addition to the holistic approach of C2C it is important to compare and assess buildings on their C2C aspects from a business and marketing point of view in a similar way that products need to be assessed through the C2C Product certification.

On the other hand it was pointed out by the C2C experts that the focus should be only on the design process avoiding the assessment of buildings. The previous chapter presents their critical review on the model. Recommendations are given in this section in order to continue with this research and link the gap between the opinion of the C2C Experts and the need of a model to design, evaluate and compare C2C-inspired buildings as objectively as possible. Architects, planners, engineers and building owners are willing to implement C2C in their developments. They are only asking for a model they could be familiar with and work with. At the end all the parties involved are unanimously working towards the same goal: *designing, constructing and using buildings with positive footprints.*

6.2 Research Answers

Throughout this thesis, an analysis of some environmental assessment methods and the C2C literature related to the built environment helped to develop the framework for the model. The C2C-Inspired building Villa Flora was used as case to test and illustrate an assessment with the model. The building helped identifying and re-defining some KPI's and aspects of the evaluation process. In this section the main conclusions are presented for each of the sub-questions of the project.

1. ***What environmental assessment models are available in the Netherlands to design and evaluate buildings in terms of 'sustainability'?***

A large number of environmental assessment methods are available to assess buildings in terms of sustainability. Chapter 2 presented five methods that are commonly used by the building professionals in the Netherlands. The analysis was carried out at two *requirement type* ***Energy Label*** and ***NEN 7120***, and *three guidance type methods* ***GPR Building***, **Eco-quantum** and **BREEAM-NL.** *Guidance type methods* evaluate buildings in a larger scale and use similar environmental parameters. *Requirement type methods* are norms or directives that usually evaluate a single aspect of the building, in this case *Energy*.

2. ***What Cradle to Cradle literature is related to the design process and evaluation of a building?***

Some C2C guidelines have been provided to the building professionals since the 1990s. Among those, published declarations such as the Hannover Principles and more recently in the Netherlands, the Almere Principles and the Floriade Venlo Principles. These are guidelines for specific regions. The Hannover principles refer better to the built environment. It suggests implicitly the analysis of the following aspects associated to the design process of a building: *materials and resource management*, *air pollution*, *noise pollution*, *ventilation systems*, *indoor air quality*, *renewable energy*, among others.

The *C2C criteria for the built environment* was the most recent publication related to the design of buildings. Those guidelines were used as baseline to develop the model. In May 2013 a consultative beta versionwas published named *How to plan a big beneficial footprint* by Mulhall, Braungart and Hansen. The content of this publication was not analyzed at the early stage of the research but at the end.

3. ***What are the differences between the available environmental assessment methods and Cradle to Cradle?***

The environmental assessment methods do not consider a positive environmental impact and future-use-scenarios as C2C does. Specific differences were outlined in Chapter 3 regarding the model categories. For instance within the category *Renewable Energy*, the environmental assessment methods measure the energy performance of buildings and seek to reduce the consumption of non-renewable energy. C2C on the other hand suggests the use of only renewable energy and the actual generation of this by the building itself.

4. ***What are the main aspects to be included in a C2C model to design and evaluate buildings?***

Section 2.2 aimed to find the meaning of Cradle to Cradle and the most important aspects to be included in the framework of the model. First of all, it was recommended to track the progress of buildings from negative to positive, or from being 'less bad' (eco-efficiency) to becoming 'good' (eco-effectiveness). The following general suggestions were given according to the C2C principles:

The first C2C principle 'Waste equals food' targets nutrients become nutrients again without the loss of quality. Therefore the model should assess materials as biological or technical nutrients and their loss of quality. The second principle 'Use current solar income' requires the measurement of this aspect objectively. It was necessary to define the required data to measure the *renewable energy* in buildings. Likewise, in relation to the third principle

'Celebrate diversity' the model should clarify the terms of conceptual diversity with innovation and how it could be objectively assessed.

5. ***How can a building be evaluated and classified in order to show its C2C features?***

The model suggests in *Chapter 3* an evaluation and classification system of buildings. This allows comparing different solutions through graphics and 'green scores'. However it was concluded in a later stage, during the C2C Expert Panel Evaluation that it is not the aim of the C2C approach classifying buildings within any kind of system.

6.3 Further research

The model was linked as close as possible to the C2C literature. Nevertheless the latest publication *How to plan a big beneficial footprint* and the C2C Expert panel evaluation, suggests implicitly a new direction to the research. Consequently, new ideas arose and research questions appeared based on the feedbacks given by the C2C Experts. Following a description of the recommendations for further development of the model:

6.3.1 Model as a design tool rather than an assessment method

Providing quantitative results and comparing different buildings was the biggest criticism by the C2C experts. Although the model is not measuring the C2C-ness of buildings it could lead to a misinterpretation of this by the users. It is out of the scope of C2C to assess and classify buildings. The developments have their own features that could not be comparable among them.

This argument had led to the recommendation of using the model as a design tool merely, avoiding any kind of evaluation through a number or score. Even though the design process of a building implies an assessment or evaluation of different solutions in order to select one, it is necessary to analyze what is the best way of presenting this kind of comparison.

6.3.2 Building as the sum of different elements

The approach of the model is to design and evaluate buildings using KPI's in each of the categories. Here, different elements of the building contribute to the performance or results within that category. Different elements contribute in different manners to the results per category. For instance, the sum of the results of the energy installations and structure materials (seen as several elements) represent the performance of buildings within the categories *Renewable Energy* and *Materials*.

The C2C experts suggest focusing only on five elements instead of a building as a whole. Taking this into account, the model could focus on these five elements and lead to the design of other C2C-Inspired elements. In the future not only five but most of the elements of a building could be C2C-Inspired and buildings as a whole could be considered as well. A suggestion is to split the building in many different elements and measure (at the very last step) the overall score of the 'parts' of the building that are C2C inspired. "*Hopefully soon there will be enough Cradle-to-Cradle Inspired Elements in buildings to qualify the total development as C2C*" (Mulhall, Braungart & Hansen).

Additionally it is recommended to consider C2C-inspired elements only, since these are the building components which are towards a positive environmental impact. There is not point on focusing on elements that have a negative impact, unless it is intended to re-design them as beneficial systems. Examples of elements are *green façade*, and *water treatment system.*

6.3.3 Categories and Weighting factors as relative aspects of buildings

The model suggests the evaluation and guidance of buildings through eight categories, see figure 3.3. It was intended to cover the *C2C principles* and *C2C guidelines for the built environment* with all of them. Nevertheless a development and its features highly depend on the context and intentions of stakeholders. The model could suggest some categories and offer the possibility to add or subtract them according to the requirements of a particular development. In the same way, it could not be assumed that every development gives the same importance or weighting factors to the categories of the model. Giving importance to the different categories will always involve subjective appreciations. It is recommended to use the Analytical Hierarchy Process to lead into a consensus between stakeholders about the features to focus. Therefore categories and their weighting factors should be seen as relative characteristics that differ from one building to another.

If Categories and Weighting factors are relative aspects of buildings, the 'green scores' and the comparison process of buildings are not valid. So it would be necessary to analyze and re-think the scoring approach of the model. Additionally C2C is measurable and one could present absolute values of the C2C features of a building, but scoring could be subjective if limited to variable Weighting factors.

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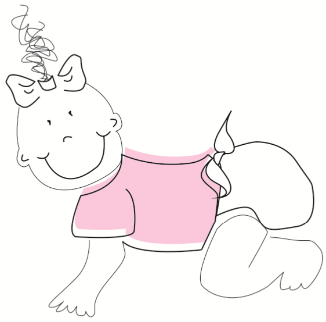
Acronyms

This section presents the meaning of the abbreviations used in this thesis. BRL 9500, IVAM, and NEN 7120 do not have an official translation in English given by their respective organizations.

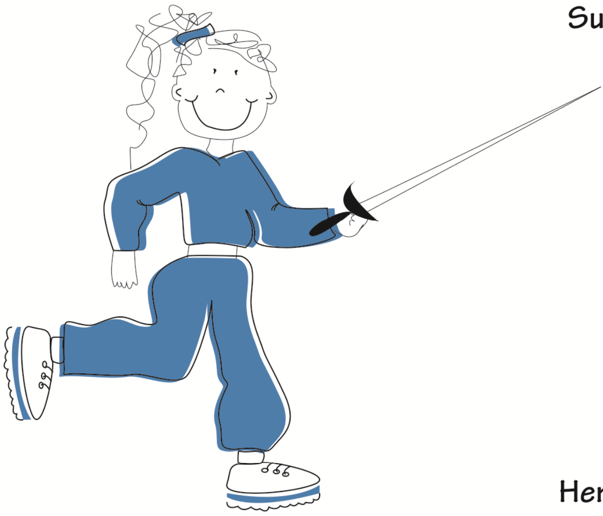
AHP:	Analytic Hierarchy Process
A/Prof:	Associate Professor
aux, to:	Auxiliary energy
BNs	Biological Nutrients
BREEAM:	Building Research Establishment Environmental Assessment Method
BRL 9500:	Energieprestatieadvisering voor gebouwen
C2C:	Cradle to Cradle. "Cradle to Cradle" and "C2C" are registered marks of McDonough Braungart Design Chemistry
C:	Cooling
DGBC:	Dutch Green Building Council
dhum:	Dehumidification
EE:	Embodied Energy
EI:	Energy Index
EPBD:	Energy Performance of Building Directive
EPC:	Energy Performance Coefficient
Ex:	Exergy
GPR:	Green Performance of Real Estate
H:	Heating
hum:	Humidification
IPCC:	Intergovernmental Panel on Climate Change
ISSO:	Dutch Buildings Services Knowledge Centre
IVAM:	Valgroep Milieukunde
KPI's:	Key Performance Indicators
L:	Lighting
LCA:	Life Cycle Assessment
MJ:	Mega Jules
NEN 7120:	Energieprestatie van gebouwen
OE:	Operating Energy
RICS:	Royal Institution of Chartered Surveyors
TNs	Technical Nutrients
V:	Ventilation
W:	Hot Water

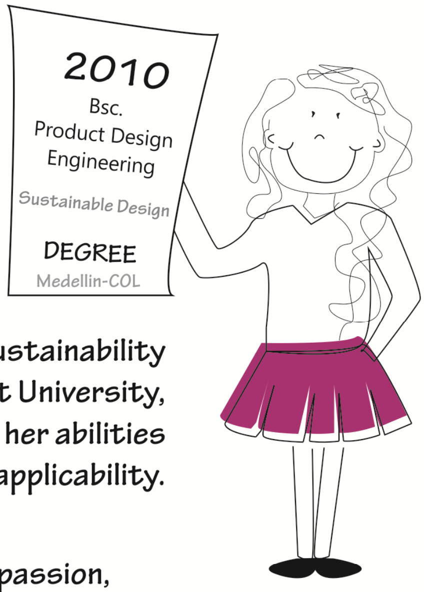
About the Author...



Andrea was one year old
when the definition of SUSTAINABLE
DEVELOPMENT was released to the world...

Surrounded by love of her Colombian family,
the little girl became active
in sports and studies!





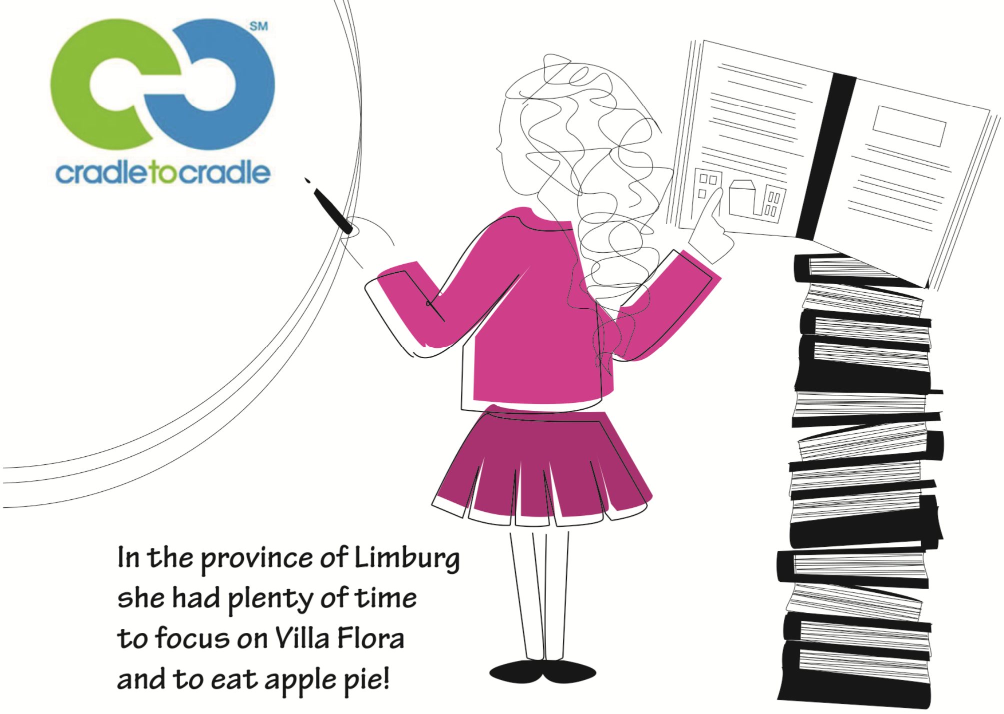
Her love for sustainability
was born at Eafit University,
where she developed her abilities
and design applicability.

Highly motivated by her passion,
Andrea applied to a Dutch University
and after getting the admission
she packed and went immediately!

At the University of Twente
she followed two Master tracks
and learnt about products
that are 'good' and not 'less bad'.

... she became active as a member of the
Latin American Student Association
and Ariëns Katholieke Studenten.

Andrea went to Venlo!
to do a research at the C2C Expo Lab
and started two months later
with her thesis at Volantis totaal.



In the province of Limburg
she had plenty of time
to focus on Villa Flora
and to eat apple pie!

On 27th August
a new life is going to start,
hopefully with her diploma
to Colombia she will depart!

Appendix

Appendix A: Inventory of Embodied Energy and Carbon Database

Source: University of Bath

Material	Energy MJ/kg	Carbon kg CO^2/kg	Density kg /m^3
Aggregate	0.083	0.0048	2240
Concrete (1:1.5:3 e.g. in-situ floor slabs, structure)	1.11	0.159	2400
Concrete (e.g. in-situ floor slabs) with 25% PFA RC40	0.97	0.132	
Concrete (e.g. in-situ floor slabs) with 50% GGBS RC40	0.88	0.101	
Bricks (common)	3.0	0.24	1700
Concrete block (Medium density 10 N/mm2)	0.67	0.073	1450
Aerated block	3.50	0.30	750
Rammed earth (no cement content)	0.45	0.023	1460
Limestone block	0.85		2180
Marble	2.00	0.116	2500
Cement mortar (1:3)	1.33	0.208	
Steel (general - average recycled content)	20.10	1.37	7800
Steel (section - average recycled content)	21.50	1.42	7800
Steel (pipe - average recycled content)	19.80	1.37	7800
Stainless steel	56.70	6.15	7850
Timber (general - excludes sequestration)	8.50	0.46	480 - 720
Glue laminated timber	12.00	0.87	
Sawn hardwood	10.40	0.86	700 - 800
Cellular glass insulation	27.00		
Cellulose insulation (loose fill)	0.94 – 3.3		43
Cork insulation	26.00*		160
Glass fiber insulation (glass wool)	28.00	1.35	12
Flax insulation	39.50	1.70	30*
Rockwool (slab)	16.80	1.05	24
Expanded Polystyrene insulation	88.60	2.55	15 – 30*
Polyurethane insulation (rigid foam)	101.50	3.48	30
Woodwool board insulation	20.00	0.98	
Wool (recycled) insulation	20.90		25*
Straw bale	0.91		100– 110*
Mineral fiber roofing tile	37	2.70	1850*
Slate (UK – imported)	0.1 – 1.0	0.006-.058	1600
Clay tile	6.50	0.45	1900
Aluminum (general & incl 33% recycled)	155	8.24	2700
Bitumen (general)	51	0.38 - 0.43	
Hardboard	16.00	1.05	600- 1000
MDF	11.00	0.72	680– 760*
OSB	15.00	0.96	640*
Plywood	15.00	1.07	540 - 700
Plasterboard	6.75	0.38	800
Gypsum plaster	1.80	0.12	1120
Glass	15.00	0.85	2500

Material	Energy MJ/kg	Carbon kg CO^2/kg	Density kg /m^3
PVC (general)	77.20	28.1	1380
PVC pipe	67.50	24.40	1400*
Linoleum	25.00	1.21	1200
Vinyl flooring	65.64	2.92	1200
Terrazzo tiles	1.40	0.12	1750*
Ceramic tiles	12.00	0.74	2000
Carpet tiles, nylon (Polyamide), pile weight 770 g/m2	279 MJ/m2	13.7 / m2	4.6 kg/m2
Wool carpet	106.00	5.53	
Wallpaper	36.40	1.93	
Wood stain / varnish	50.00	5.35	
Vitrified clay pipe (DN 500)	7.90	0.52	
Iron (general)	25	1.91	7870
Copper (average incl. 37% recycled)	42	2.60	8600
Lead (incl 61% recycled)	25.21	1.57	11340
Ceramic sanitary ware	29.00	1.51	

Windows

1200 x 1200 2x glazed, air or argon filled	MJ per window	kg CO^2
Aluminum frame	5470	279
PVC frame	2150-2470	110-126
Aluminum clad timber frame	950 - 1460	48 - 75
Timber frame	230 - 490	12 - 25
Krypton filled add:	510	26
Xeon filled add:	4500	229

Paint

Material	Energy MJ/m^2	Carbon kg CO^2/m^2
Water-borne paint	59.0	2.12
Solvent-borne paint	97.0	3.13

Photovoltaic (PV) cells

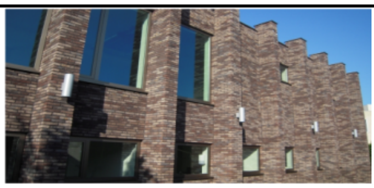
Material	Energy MJ/m^2	Carbon kg CO^2/m^2
Monocrystalline (average)	4750	242
Polycrystalline (average)	4070	208
Thin film (average)	1305	67

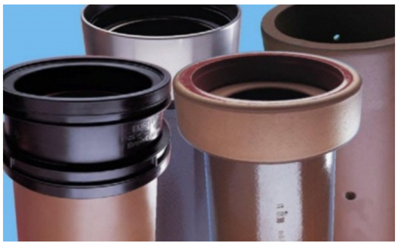
Appendix B: Positive Materials Database

The following information and images were obtained from the website of the C2C centre. It is displayed here only as an example of the data that could be integrated into the model, where users now the benefits of the C2C materials.

Source: C2C centre, C2C Expo Lab, Venlo
www.c2c-centre.com

Building Materials

	Material	Positive Feature	Pathway	C2C certification
STRUCTURE	 Galvanized Steel, type S235	After use this product can be returned to the supplier for re-use purposes. The remaining zinc will be removed with a low concentration of hydrochloric acid	Technical	Basic
SKIN	 Handmade Bricks	It is made of local clay and degrades naturally or can be constantly recycled in the industrial process.	Technical Biological	Basic
	 RHEINZINK Roof and Facade	RHEINZINK roof and façade systems are 100% recyclable, non toxic and have long lifetimes, and don't need maintenance. Due to their high residual value, RHEINZINK is mostly collected for recycling. A 30 year guarantee is given on all products	Technical	Silver
SETTING	 Mosa Unglazed Wall Tiles	Unglued tiles are 100% re-used for making new tiles. If they are glued the tiles can be used for foundations in road works. The products are designed for the technological cycle, but totally safe for the biological cycle. Mosa is developing new systems to avoid gluing tiles.	Technical	Silver

	Material	Positive Feature	Pathway	C2C certification
SYSTEMS	 Vitrified Clay Pipes & Fittings for Sewers	The product is made out of natural materials without additives and suited for the biological cycle. The product is 100% recyclable to chamotte clay, one of the ingredients for vitrified clay pipes & fittings.	Technical	Silver
	 Roof drainage system	RHEINZINK roof drainage systems are 100% recyclable, non toxic and have long lifetimes, and don't need maintenance. Due to their high residual value, RHEINZINK drainage systems are mostly collected for recycling. A 30 year guarantee is given on all products.	Technical	Silver
	 SlimFix DecoBio	Insulation system to save valuable energy. Its field of application is at the inside of pitched roofs (attics). The insulation material is BioFoam. BioFoam is a polyactic acid (PLA) that has the same characteristics as EPS insulation. BioFoam is made out of plants. BioFoam can be completely biodegraded, composted or used for feedstock for recycling	Technical	No information

Appendix C: C2C banned list of chemicals

Source: Cradle Certified[CM] Products Program, Version 3.

Banned List of Chemicals for Technical Nutrients

SUBSTANCE	CAS #	COMMENTS
Metals		
Arsenic	7440-38-2	
Cadmium	7440-43-9	Banned only for products with no guaranteed nutrient management
Chromium VI	18540-29-9	
Mercury	7439-97-6	
Flame Retardants		
Hexabromocyclododecane	3194-55-6; 25637-99-4	
Penta-BDE	32534-81-9	
Octa-BDE	32536-52-0	
Deca-BDE	1163-19-5	
Polybrominated Diphenyl Ethers (PBDEs)	Several	
Tetrabromobisphenol A	79-94-7	
Tris (1,3-dichloro-2-propyl) phosphate	13674-87-8	
Phthalates		
Bis (2-ethylhexyl) phathalate	117-81-7	
Butyl benzyl phthalate	85-68-7	
Dibutyl phthalate	84-74-2	
Halogenated Polymers		
Polyvinyl chloride (PVC)	9002-86-2	
Polyvinylidenechloride (PVDC)	9002-85-1	
Chlorinated polyvinyl chloride (CPVC)	68648-82-8	
Polychloroprene	9010-98-4	
Chlorinated Hydrocarbons		
1,2-Dichlorobenzene	95-50-1	
1,3-Dichlorobenzene	541-73-1	
1,4-Dichlorobenzene	106-46-7	
1,2,4-Trichlorobenzene	120-82-1	
1,2,4,5-Tetrachlorobenzene	95-94-3	
Pentachlorobenzene	608-93-5	
Hexachlorobenzene	117-74-1	
PCB and Ugilec	Several	
Short-chain chlorinated paraffins	Several	

SUBSTANCE	CAS #	COMMENTS
Others		
Pentachlorophenol	87-86-5	
Nonylphenol	104-40-5, 84852-15-3	
Octylphenol	27193-28-8	
Nonylphenol ethoxylates	Several	
Octylphenol ethoxylates	Several	
Tributyltin	688-73-3	
Trioctyltin	869-59-0	
Triphenyltin	892-20-6	
Perfluorooctane sulfonic acid	1763-23-1	
Perfluorooctanoic acid	335-67-1	

Banned List of Chemicals for Biological Nutrients

SUBSTANCE	CAS #	COMMENTS
Metals		
Arsenic	7440-38-2	Restricted to maximum background concentration in soils
Cadmium	7440-43-9	
Chromium VI	18540-29-9	
Mercury	7439-97-6	
***Lead**	7439-92-1	
Flame Retardants		
Hexabromocyclododecane	3194-55-6; 25637-99-4	
Penta-BDE	32534-81-9	
Octa-BDE	32536-52-0	
Deca-BDE	1163-19-5	
Polybrominated Diphenyl Ethers (PBDEs)	Several	
Tetrabromobisphenol A	79-94-7	
Tris (1,3-dichloro-2-propyl) phosphate	13674-87-8	
Phthalates		
Bis (2-ethylhexyl) phathalate	117-81-7	
Butyl benzyl phthalate	85-68-7	
Dibutyl phthalate	84-74-2	
Halogenated Polymers		
Polyvinyl chloride (PVC)	9002-86-2	
Polyvinylidenechloride (PVDC)	9002-85-1	
Chlorinated polyvinyl chloride (CPVC)	68648-82-8	
Polychloroprene	9010-98-4	
***Polytetrafluoroethylene (PTFE)**	9002-84-0	

*Note these chemicals are on the Banned list for Biological Nutrients only

SUBSTANCE	CAS #	COMMENTS
Chlorinated Hydrocarbons		
1,2-Dichlorobenzene	95-50-1	
1,3-Dichlorobenzene	541-73-1	
1,4-Dichlorobenzene	106-46-7	
1,2,4-Trichlorobenzene	120-82-1	
1,2,4,5-Tetrachlorobenzene	95-94-3	
Pentachlorobenzene	608-93-5	
Hexachlorobenzene	117-74-1	
PCB and Ugilec	Several	
Short-chain chlorinated paraffins	Several	
Others		
Pentachlorophenol	87-86-5	
Nonylphenol	104-40-5, 84852-15-3	
Octylphenol	27193-28-8	
Nonylphenol ethoxylates	Several	
Octylphenol ethoxylates	Several	
Tributyltin	688-73-3	
Trioctyltin	869-59-0	
Triphenyltin	892-20-6	
Perfluorooctane sulfonic acid	1763-23-1	
Perfluorooctanoic acid	335-67-1	
*Polycyclic Aromatic Hydrocarbons		
PAH group (as defined in TRI)	Not applicable	
Benzon(a)pyrene	50-32-8	
5-Methylchrysene	3697-24-3	
Acenaphthene	83-32-9	
Anthracene	120-12-7	
Benz(a)anthracene	56-55-3	
Benz(j)aceanthrylene	202-33-5	
Benz(j)aceanthrylene	202-33-5	
Benzo(b)fluoranthene	205-99-2	
Benzo(c)phenanthrene	195-19-7	
Benzo(g,h,l)perylene	191-24-2	
Benzo(j)fluoranthene	205-82-3	
Benzo(k)fluoranthrene	207-08-9	
Chrysene	218-01-9	
Cyclopentac(c,d)pyrene	27208-37-3	
Dibenzo(a,h)anthracene	53-70-3	
Dibenzo(a,h)pyrene	189-64-0	
Dibenzo(a,i)pyrene	189-55-9	
Dibenzo(a,l)pyrene	191-30-0	
Fluoranthene	206-44-0	
Fluorene	86-73-7	
Indeno(1,2,3,c,d)pyrene	193-39-5	
Naphthalene	91-20-3	
Phenanthrene	85-01-8	
Pyrene	129-00-0	

Appendix D: Weighting factors using the Analytical Hierarchy Process (AHP)

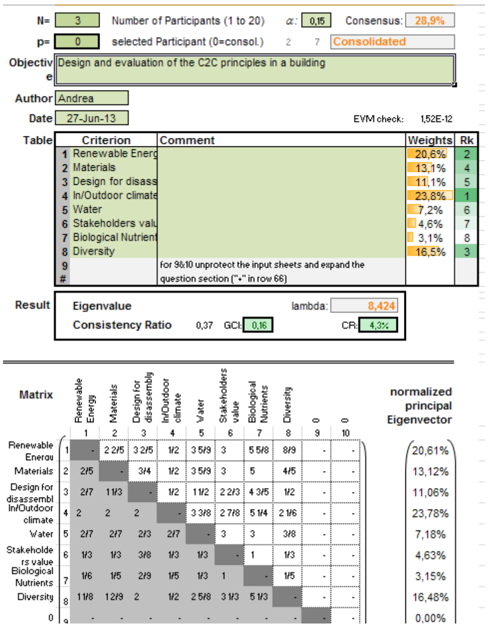
The *BPMSG AHP Excel Template* by Klaus D. Goepel (2013) is used to calculate the *Weighting factors* of the categories, sub-categories and KPI's of the model with the method Analytical Hierarchy Process. These values only represent the opinion of the members involved.

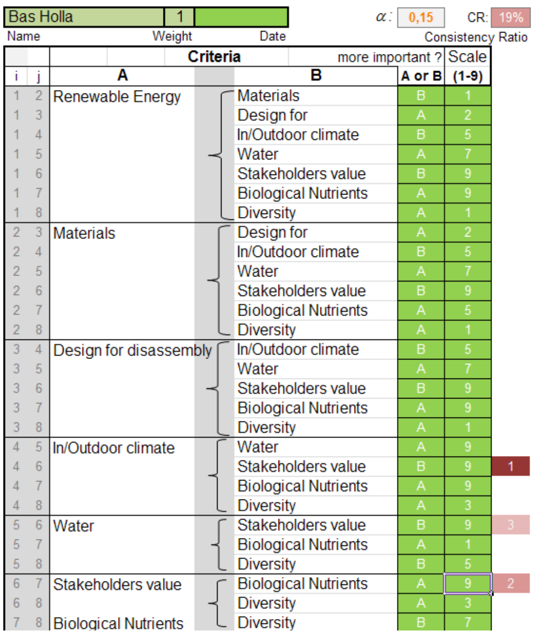
1st level: Model categories

Bas Holla, Koen Gommans and Andrea Herrera were the members involved to prioritize the categories of the model. The members selected the most important category of each pair (A or B) and indicated how much more important it was on a scale of 1-9, see table below.

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8 can be used to express intermediate values		

Following the global results and the evaluation per member:





Global results Model categories **Evaluation of the Model categories by Bas Holla**

Koen Gommans	1		α: 0,15	CR: 15%
Name	Weight	Date		Consistency Ratio

i	j	A	B	A or B	Scale (1-9)
1	2	Renewable Energy	Materials	A	3
1	3		Design for	A	3
1	4		In/Outdoor climate	B	7
1	5		Water	A	3
1	6		Stakeholders value	A	5
1	7		Biological Nutrients	A	5
1	8		Diversity	B	4
2	3	Materials	Design for	B	3
2	4		In/Outdoor climate	B	7
2	5		Water	A	3
2	6		Stakeholders value	A	5
2	7		Biological Nutrients	A	5
2	8		Diversity	B	5
3	4	Design for disassembly	In/Outdoor climate	B	7
3	5		Water	A	3
3	6		Stakeholders value	A	5
3	7		Biological Nutrients	A	5
3	8		Diversity	B	5
4	5	In/Outdoor climate	Water	A	7
4	6		Stakeholders value	A	6
4	7		Biological Nutrients	A	7
4	8		Diversity	A	4
5	6	Water	Stakeholders value	A	5
5	7		Biological Nutrients	A	5
5	8		Diversity	B	5
6	7	Stakeholders value	Biological Nutrients	B	3
6	8		Diversity	B	5
7	8	Biological Nutrients	Diversity	B	5

Evaluation of the Model categories by Koen

Andrea Herrera	1		α: 0,15	CR: 8%
Name	Weight	Date		Consistency Ratio

i	j	A	B	A or B	Scale (1-9)
1	2	Renewable Energy	Materials	A	3
1	3		Design for	A	5
1	4		In/Outdoor climate	A	3
1	5		Water	A	3
1	6		Stakeholders value	A	9
1	7		Biological Nutrients	A	5
1	8		Diversity	A	3
2	3	Materials	Design for	A	1
2	4		In/Outdoor climate	A	3
2	5		Water	A	3
2	6		Stakeholders value	A	9
2	7		Biological Nutrients	A	5
2	8		Diversity	A	3
3	4	Design for disassembly	In/Outdoor climate	A	3
3	5		Water	B	3
3	6		Stakeholders value	A	7
3	7		Biological Nutrients	A	3
3	8		Diversity	A	1
4	5	In/Outdoor climate	Water	A	1
4	6		Stakeholders value	A	7
4	7		Biological Nutrients	A	3
4	8		Diversity	A	1
5	6	Water	Stakeholders value	A	9
5	7		Biological Nutrients	A	3
5	8		Diversity	A	1
6	7	Stakeholders value	Biological Nutrients	A	1
6	8		Diversity	B	7
7	8	Biological Nutrients	Diversity	B	5

Evaluation of the Model categories by Andrea

2nd level: Renewable Energy Sub-categories

Andrea Herrera made the evaluation for the sub-categories and KPI's of the categories Renewable Energy and Materials.

n=	4	Number of criteria (3 to 10)	Scale: 1	Linear
N=	1	Number of Participants (1 to 20)	α: 0,15	Consensus: n/a
p=	0	selected Participant (0=consol.)	2 7	Consolidated
Objective	Design and evaluation of Renewable Energy in a building			
Author	Andrea			
Date	27-Jun-13			EVM check: 4,63E-08

Table	Criterion	Comment	Weights	Rk
1	Operating Energy		55,1%	1
2	Embodied Energy		13,1%	3
3	Material media		27,4%	2
4	Energy Effectiver		4,4%	4
5				
6				
7				
8				
9		for 9&10 unprotect the input sheets and expand the		
#		question section ("+" in row 66)		

Result				
Eigenvalue			lambda:	4,240
Consistency Ratio	0,37	GCI: 0,31	CR:	8,8%

Matrix		Operating Energy 1	Embodied Energy of 2	Material media 3	Energy Effectiveness 4	0 5	0 6	0 7	0 8	0 9	0 10	normalized principal Eigenvector
Operating Energy	1	-	5	3	7	-	-	-	-	-	-	55,11%
Embodied Energy of	2	1/5	-	1/3	5	-	-	-	-	-	-	13,07%
Material media	3	1/3	3	-	7	-	-	-	-	-	-	27,37%
Energy Effectivene	4	1/7	1/5	1/7	-	-	-	-	-	-	-	4,44%
0	5	-	-	-	-	-	-	-	-	-	-	0,00%
0	6	-	-	-	-	-	-	-	-	-	-	0,00%
0	7	-	-	-	-	-	-	-	-	-	-	0,00%
0	8	-	-	-	-	-	-	-	-	-	-	0,00%

Pair wise comparison matrix for the sub-categories

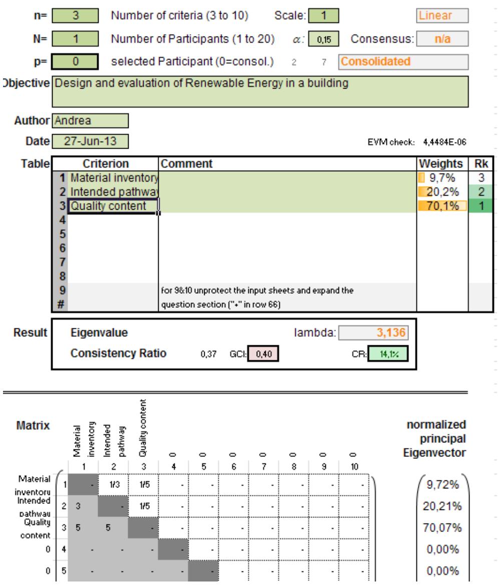
n	Criteria	Comment	RGMM
1	Operating Energy		55%
2	Embodied Energy of materi		13%
3	Material media		28%
4	Energy Effectiveness		4%
5			
6			
7			
8			
9		for 9&10 unprotect the input sheets and expand the	
10		question section ("+" in row 66)	

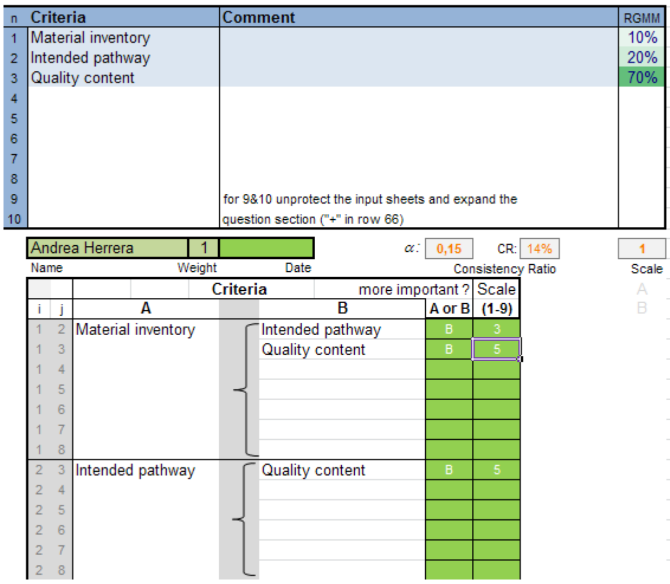
Andrea Herrera	1		α: 0,15	CR: 8%	1
Name	Weight	Date		Consistency Ratio	Scale

i	j	A	B	A or B	Scale (1-9)
1	2	Operating Energy	Embodied Energy of	A	5
1	3		Material media	A	3
1	4		Energy Effectiveness	A	7
1	5				
1	6				
1	7				
1	8				
2	3	Embodied Energy of mater	Material media	B	3
2	4		Energy Effectiveness	A	5
2	5				
2	6				
2	7				
2	8				
3	4	Material media	Energy Effectiveness	A	7
3	5				
3	6				

Evaluation of the sub-categories by Andrea

2nd level: Materials Sub-categories

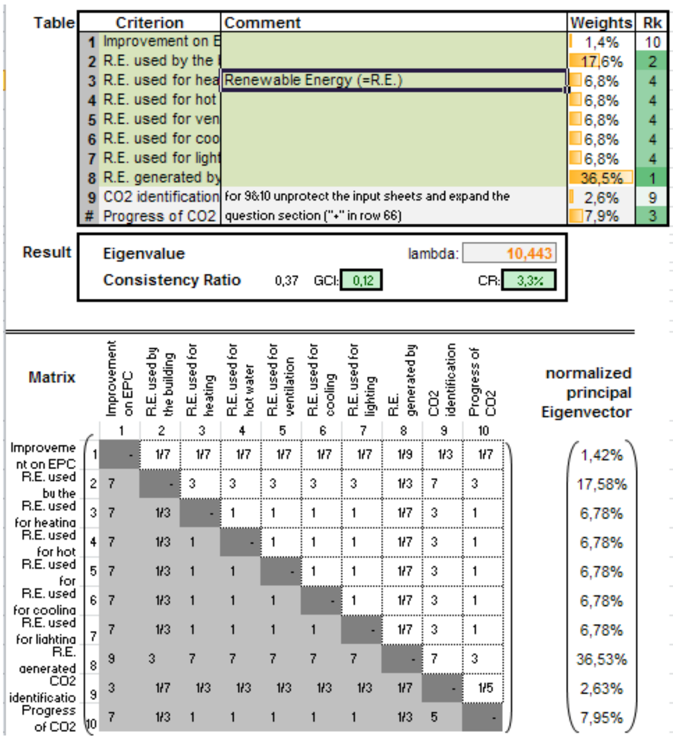


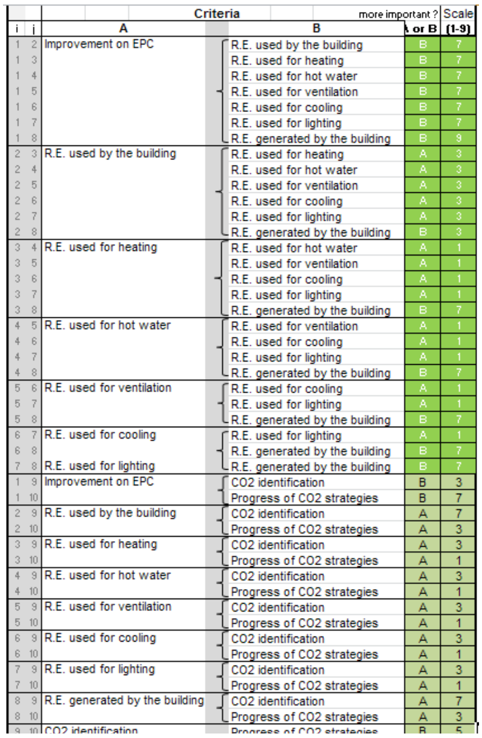


Pair wise comparison matrix for the sub-categories

Evaluation of the sub-categories by Andrea

3rd level: Renewable Energy/ Operation Energy KPI’s





Pair wise comparison matrix for the OP KPI’s

Evaluation of the KPI’s by Andrea

3rd level: Renewable Energy/ Embodied Energy of Materials KPI's

The member gave more importance for the KPI's of the design phase. In this phase materials are chosen and offset strategies can be defined. Additionally a preference was given to the EE of the material media over the building materials. According to Mulhall and Braungart the EE of material used to create and deliver the renewable energy is an important aspect of the 'C2C energy'. Although none inconsistencies were presented in the input data (Evaluation of the KPI's) the pair wise comparison presents a high consistency ratio of 20.8%. This is due to four KPI's are ranking in the same level. These four KPI's are lasted to the different energy system and it is intended not to give priority among them.

Table

	Criterion	Comment	Weights	Rk
1	Materials selectio	EE and Embodied Carbon	33,6%	1
2	Offset strategies	EE and Embodied Carbon	25,1%	2
3	Projected amoun		4,7%	6
4	Projected amoun	Embodied carbon (EC)	4,7%	6
5	Projected amoun	Material used in the Energy systems	4,7%	6
6	Projected amoun	Embodied carbon in materials of energy systems	4,7%	6
7	Amount of EE of		6,4%	3
8	Amount of EC of		6,4%	4
9	Amount of EE of	Material used in the Energy systems	5,6%	5
#	Amount of EC of	Material used in the Energy systems	4,1%	10

Result

Eigenvalue			lambda:	12,770
Consistency Ratio	0,37	GCI: 0,69	CR:	20,8%

Matrix

		Materials selection 1	Offset strategies of EE 2	Projected amount of EE 3	Projected amount of EC 4	Projected amount of EE 5	Projected amount of EC 6	Amount of EE of building 7	Amount of EC of building 8	Amount of EE of material 9	Amount of EC of material 10	normalized principal Eigenvector
Materials selection	1	-	5	7	7	7	7	7	7	5	5	33,59%
Offset strategies of	2	1/5	-	7	7	7	7	7	7	7	7	25,12%
Projected amount of	3	1/7	1/7	-	1	1	1	1/3	1/3	3	3	4,73%
Projected amount of	4	1/7	1/7	1	-	1	1	1/3	1/3	3	3	4,73%
Projected amount of	5	1/7	1/7	1	1	-	1	1/3	1/3	3	3	4,73%
Projected amount of	6	1/7	1/7	1	1	1	-	1/3	1/3	3	3	4,73%
Amount of EE of	7	1/7	1/7	3	3	3	3	-	1	1/3	1/2	6,40%
Amount of EC of	8	1/7	1/7	3	3	3	3	1	-	1/4	1/2	6,37%
Amount of EE of	9	1/5	1/7	1/3	1/3	1/3	1/3	3	4	-	1	5,55%
Amount of EC of	10	1/5	1/7	1/3	1/3	1/3	1/3	2	2	1	-	4,05%

Andrea Herrera | Name | 1 Weight | Date | α: 0,15 | CR: 15% Consistency Ratio

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Materials selection according to EE	Offset strategies of EE	A	5
1	3		Projected amount of EE	A	7
1	4		Projected amount of EC	A	7
1	5		Projected amount of EE of Material media	A	7
1	6		Projected amount of EC of Material	A	7
1	7		Amount of EE of building materials	A	7
1	8		Amount of EC of building materials	A	7
2	3	Offset strategies of EE	Projected amount of EE	A	7
2	4		Projected amount of EC	A	7
2	5		Projected amount of EE of Material media	A	7
2	6		Projected amount of EC of Material	A	7
2	7		Amount of EE of building materials	A	7
2	8		Amount of EC of building materials	A	7
3	4	Projected amount of EE	Projected amount of EC	A	1
3	5		Projected amount of EE of Material media	A	1
3	6		Projected amount of EC of Material	A	1
3	7		Amount of EE of building materials	B	3
3	8		Amount of EC of building materials	B	3
4	5	Projected amount of EC	Projected amount of EE of Material media	A	1
4	6		Projected amount of EC of Material	A	1
4	7		Amount of EE of building materials	B	3
4	8		Amount of EC of building materials	B	3
5	6	Projected amount of EE of Material media	Projected amount of EC of Material	A	1
5	7		Amount of EE of building materials	B	3
5	8		Amount of EC of building materials	B	3
6	7	Projected amount of EC of Material media	Amount of EE of building materials	B	3
6	8		Amount of EC of building materials	B	3
7	8	Amount of EE of building materials	Amount of EC of building materials	A	1
1	9	Materials selection according to EE	Amount of EE of material media	A	5
1	10		Amount of EC of material media	A	5
2	9	Offset strategies of EE	Amount of EE of material media	A	7
2	10		Amount of EC of material media	A	7
3	9	Projected amount of EE	Amount of EE of material media	A	3
3	10		Amount of EC of material media	A	3
4	9	Projected amount of EC	Amount of EE of material media	A	3
4	10		Amount of EC of material media	A	3
5	9	Projected amount of EE of Material media	Amount of EE of material media	A	3
5	10		Amount of EC of material media	A	3
6	9	Projected amount of EC of Material media	Amount of EE of material media	A	3
6	10		Amount of EC of material media	A	3
7	9	Amount of EE of building materials	Amount of EE of material media	B	3
7	10		Amount of EC of material media	B	2
8	9	Amount of EC of building materials	Amount of EE of material media	B	4
8	10		Amount of EC of material media	B	2
9	10	Amount of EE of material media	Amount of EC of material media	A	1

Pair wise comparison matrix for the EE KPI's **Evaluation of the KPI's by Andrea Herrera**

3rd level: Renewable Energy/ Material Media KPI's

Preference was given to the material media than to the material resulting from the energy systems. Additionally material media with beneficial functions was considered more important than biological and technical nutrients entering the cycle at the end of their use.

Table

	Criterion	Comment	Weights	Rk
1	Material media in	Material media as material used in the Energy syster	20,7%	3
2	Material media de		21,7%	1
3	Material output is	Material output as resulting from energy systems	4,0%	7
4	Material media + b	Material media with other beneficial functions	21,0%	2
5	Biological nutrient	Material used in the Energy systems	12,9%	4
6	Technical nutrients	Embodied carbon in materials of energy systems	12,9%	4
7	Material output en	Either Biological or technical cycle	6,9%	6
8				
9				
10				

Result

Eigenvalue			lambda:	7,926
Consistency Ratio	0,37	GCI: 0,41	CR:	11,5%

Matrix

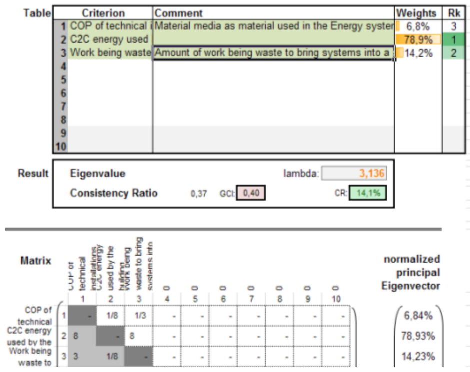
		Material media in biological or technical cycle 1	Material media degradable or recyclable 2	Material output is biological or technical 3	Material media + beneficial functions 4	Biological nutrients entering the 5	Technical nutrients entering the 6	Material output entering the cycle 7	0 8	0 9	0 10	normalized principal Eigenvector
Material media in	1	-	1	3	3	1	1	3	-	-	-	20,68%
Material media	2	1	-	5	3	1	1	3	-	-	-	21,68%
Material output is	3	1/3	1/5	-	1/5	1/5	1/5	1	-	-	-	3,97%
Material media +	4	1/3	1/3	5	-	3	3	5	-	-	-	21,04%
Biological nutrients	5	1	1	5	1/3	-	1	1	-	-	-	12,85%
Technical nutrients	6	1	1	5	1/3	1	-	1	-	-	-	12,85%
Material output	7	1/3	1/3	1	1/5	1	1	-	-	-	-	6,93%

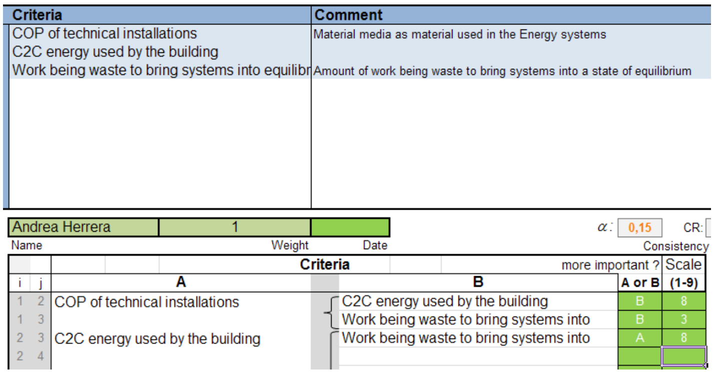
Andrea Herrera | Name | 1 Weight | Date | α: 0,15 | CR: 13% Consistency Ratio

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Material media in biological or technical cycle	Material media degradable or recyclable	A	1
1	3		Material output is biological or technical	A	3
1	4		Material media + beneficial functions	A	3
1	5		Biological nutrients entering the cycle	A	1
1	6		Technical nutrients entering the cycle	A	1
1	7		Material output entering the cycle	A	3
1	8				
2	3	Material media degradable or recyclable	Material output is biological or technical	A	5
2	4		Material media + beneficial functions	A	3
2	5		Biological nutrients entering the cycle	A	1
2	6		Technical nutrients entering the cycle	A	1
2	7		Material output entering the cycle	A	3
2	8				
3	4	Material output is biological or technical nutrie	Material media + beneficial functions	B	5
3	5		Biological nutrients entering the cycle	B	5
3	6		Technical nutrients entering the cycle	B	5
3	7		Material output entering the cycle	B	1
3	8				
4	5	Material media + beneficial functions	Biological nutrients entering the cycle	A	3
4	6		Technical nutrients entering the cycle	A	3
4	7		Material output entering the cycle	A	5
4	8				
5	6	Biological nutrients entering the cycle	Technical nutrients entering the cycle	A	1
5	7		Material output entering the cycle	B	1
5	8				
6	7	Technical nutrients entering the cycle	Material output entering the cycle	B	1
6	8				

Pair wise comparison matrix for the MM KPI's **Evaluation of the KPI's by Andrea Herrera**

3rd level: Renewable Energy/ Energy Effectiveness KPI's

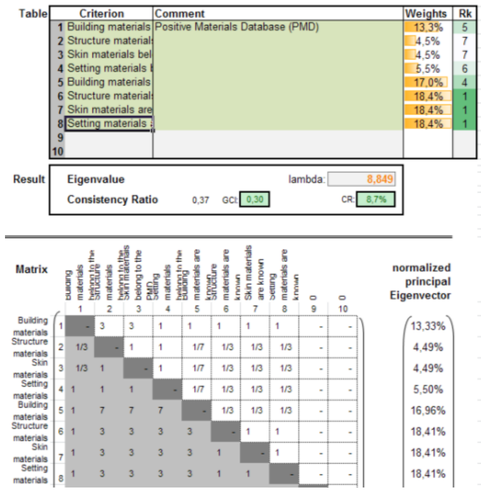


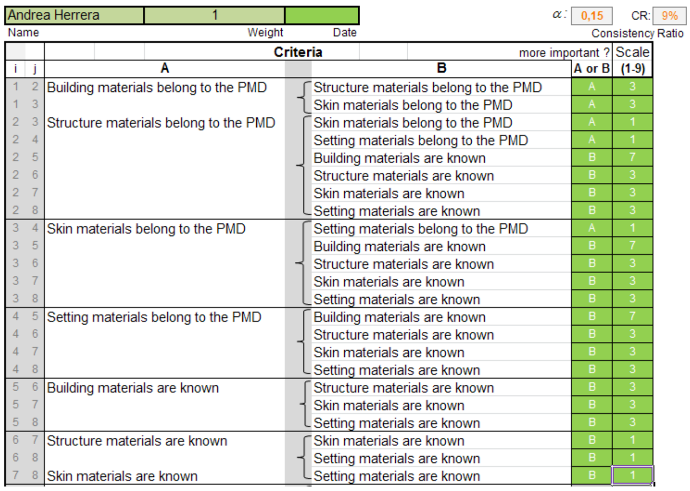


Pair wise comparison matrix for the E. Effectiveness KPI's Evaluation of the KPI's by Andrea Herrera

3rd level: Materials/ Material Inventory KPI's

With the current offer of C2C materials is not possible to cover the material demand of a complete building. Therefore preference is given to the known materials. It is intended that the building professionals identify and know what kind of materials they are using in their developments. The KPI's and WF are the same for both *Design phase* and *Operation phase*. *Building materials* are the sum of *structure*, *skin*, and *setting*. Building materials is slightly assessed better due to it involves all the parts.

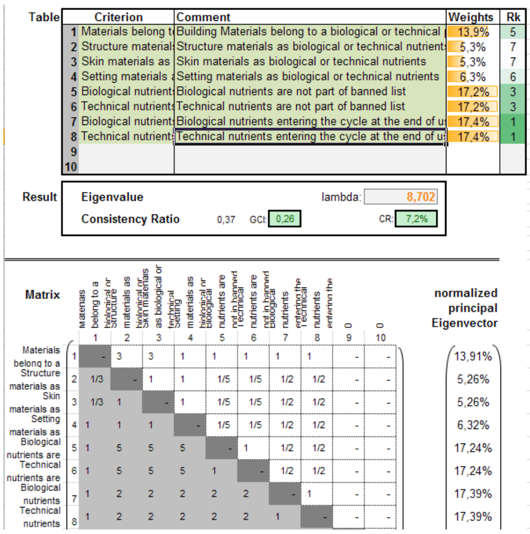


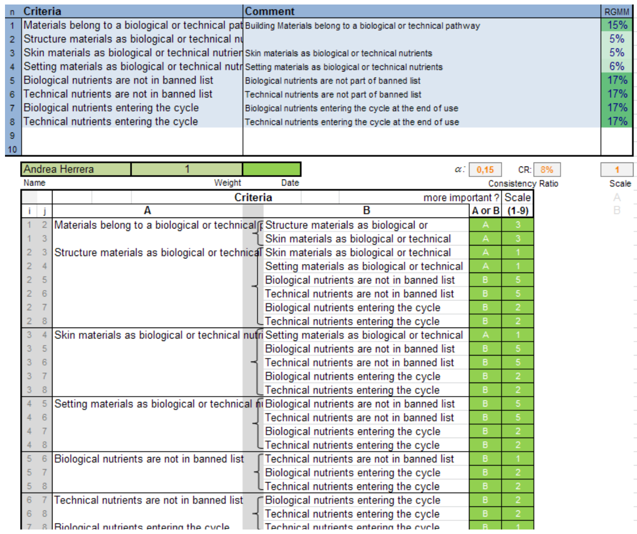


Pair wise comparison matrix for the Material Inventory KPI's Evaluation of the KPI's by Andrea Herrera

3rd level: Materials/ Intended Pathway KPI's

Preference given to materials that are defined as biological and technical nutrients and they are not in the C2C banned list. More importance (slightly) for nutrients that have entering the cycle or next cradle, since it is in that phase where they are used as nutrients.

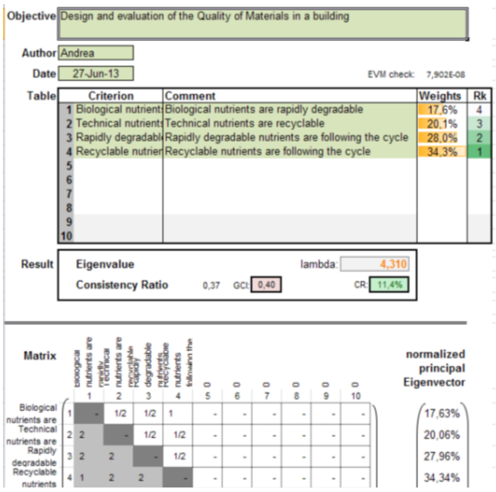


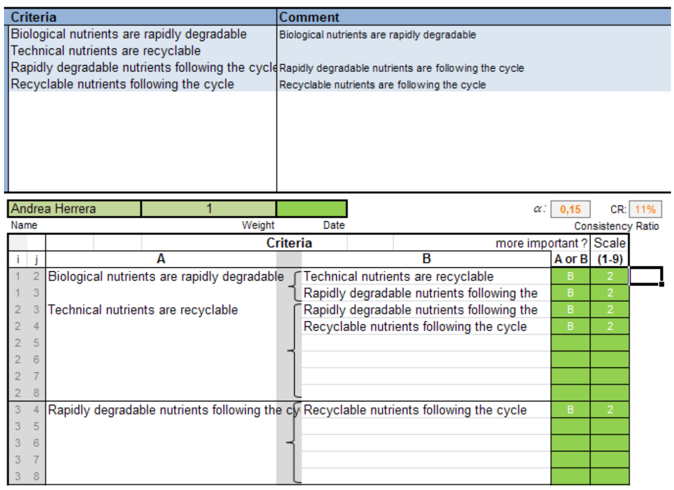


Pair wise comparison matrix for the Intended Pathway KPI's   Evaluation of the KPI's by Andrea

3rd level: Materials/ Quality Content KPI's

The technical nutrients presents better importance due to the building professionals are more aware and already working on systems that keeps material in a technical cycle.





Pair wise comparison matrix for the Quality Content KPI's   Evaluation of the KPI's by Andrea

Appendix E: Material Inventory, EE and Carbon of Villa Flora

The dimensions of the different building components of Villa Flora were obtained based on drawings, 3D models and documents. The factors used to calculate the EE and embodied Carbon of materials are the values suggested by the Embodied energy and Carbon database of the University of Bath.

A. STRUCTURE

1. Steel structure and reinforcement

Steel structure in the greenhouse: 271700kg
This information was based on the 3D model of the steel structure.

Considering the values of *Steel (section - average recycled content)* from the University of Bath database,

EE: 21.50(MJ/kg) x 271700kg= 5841550 MJ
Embodied Carbon: 1.42 (kgCO_2/kg) x 271700kg= 385814 kgCO_2

Steel structure in the office building: 16000kg

Considering the values of *Steel (pipe - average recycled content)* from the University of Bath database

EE: 19.80(MJ/kg) x 16000kg= 316800MJ
Embodied Carbon: 1.37 (kgCO_2/kg) x 16000kg= 21920kgCO_2

2. Beams, Columns, Portals, Finishing, and floors

Table 4.3. Concrete elements at Villa Flora. Source: Holcon B.V.

Element	Quantity (Parts)		Volume (m^3)		Weight (tons)	
	Expo	Office	Expo	Office	Expo	Office
Portals	36	21	118.00	274.43	295.00	686.07
Finishing	36	85	56.56	28.71	141.40	71.78
Floors	64	176	311.94	660.00	779.85	1650.00
Beams		6		12.98		32.45
Columns		4		4.48		11.20
Total	136	292	486.50	980.60	1216.25	2451.50

Confidential information was provided by the supplier in order to identify the best option of the material from the University of Bath database. None of the options provided by this database match with the characteristics of the material. However the option with ratio 1:3:6 cement: sand: aggregate is the most similar with the real ratio of the concrete used at Villa Flora of 1:3:5.

Therefore, from the University of Bath database *Concrete-Nominal proportions method-1:3:6* the factors for embodied energy and carbon are: 0.77(MJ/kg) and 0.096(kgCO_2/kg).

Due to steel bars were used as reinforcement in the concrete, coefficients of 0.26(MJ/kg) and 0.018(kgCO_2/kg) are added for each *25kg steel per m^3 concrete* according to the

University of Bath database. The following *reinforcement in concrete* data (standard values) are used to calculate the coefficients that should be added. Foundation: *100kg/m³*, Columns: *200kg/m³*, Floors: *90 kg/m³*, and Beams *125kg/m³*

Foundations concrete: 2250000kg.
This amount of concrete was used in the foundations of the building.

EE: (0.77(MJ/kg) + 0.26(MJ/kg) x 100/25) x 2250000kg= 4072500MJ
Embodied Carbon: (0.096 ($kgCO_2$/kg) + 0.018 ($kgCO_2$/kg) x 100/25) x 2250000kg
= 378000 $kgCO_2$

Columns: 11.20 tons= 10160.47kg

EE: (0.77(MJ/kg) + 0.26(MJ/kg) x 200/25) x 10160.47kg= 28957.34MJ
Embodied Carbon: (0.096 ($kgCO_2$/kg) + 0.018 ($kgCO_2$/kg) x 200/25) x 10160.47kg
= 2438.51 $kgCO_2$

Floors: 779.85tons + 1650.00tons= 2429.85 tons = 2204322.84kg

EE: (0.77(MJ/kg) + 0.26(MJ/kg) x 90/25) x2204322.84kg= 3760574.76MJ
Embodied Carbon: (0.096 ($kgCO_2$/kg) + 0.018 ($kgCO_2$/kg) x 90/25) x 2204322.84kg
= 354455.11 $kgCO_2$

Beams: 32.45 tons = 29438.14kg

EE: (0.77(MJ/kg) + 0.26(MJ/kg) x 125/25) x 29438.14kg= 60936.94MJ
Embodied Carbon: (0.096 ($kgCO_2$/kg) +0.018 ($kgCO_2$/kg) x 125/25) x 29438.14kg
= 5475.49 $kgCO_2$

Portals: 295.00tons + 686.87tons = 981.87tons = 890737.48kg
950 kg of steel were used as reinforcement per portal. Villa Flora has 57 portals in total (office + greenhouse). Consequently 138kg of steel were used per m³ in the portals.

EE: (0.77(MJ/kg) + 0.26(MJ/kg) x 138/25) x 890737kg= 1954989.57 MJ
Embodied Carbon: (0.096 ($kgCO_2$/kg) +0.018 ($kgCO_2$/kg) x 138/25) x 890737kg
= 174014.38 $kgCO_2$

Finishing: 141.40 tons + 71.78 tons = 213.18 tons = 193393.64kg

EE: 0.77(MJ/kg) x 193393.64kg= 148913.10 MJ
Embodied Carbon: 0.096 ($kgCO_2$/kg) x 193393.64kg= 18565.79$kgCO_2$

B. SKIN

1. Facades

Glass façade
For the office part *Scheuten* supplied 2.400m² of insulating glass with sun proof and neutral coating. An amount of 9.900m² of insulating glass in two different compositions was supplied for the greenhouse (Scheuten, 2013).

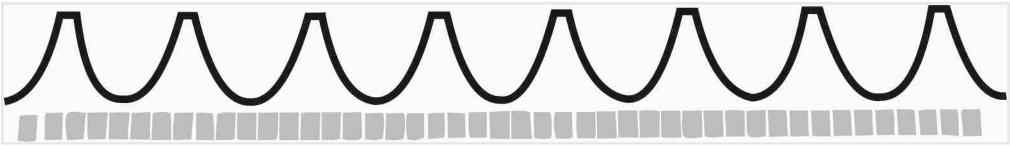
Greenhouse: 9900m² x 0.004m x 2500kg/m³= 99000kg
Office: 2400m² x 0.004m x 2500kg/m³= 24000kg

Total Glass: 99000kg + 24000kg= 123000kg

Considering the values of *Glass* from the University of Bath database

EE: 15.00(MJ/kg) x 123000kg= 1845000MJ
Embodied Carbon: 0.85 ($kgCO_2$/kg) x 123000kg= 104550$kgCO_2$

2. Roof



18.1m (length) x 12.4 (surface parabola) = 224.44m^2 x 8 (parabolas) = 1795.52m^2

Construction sloping roof: Steel
1795.52m^2 x 0.005m (assumed thickness) x 7800kg/m^3= 70025.28kg

Considering the values of *Steel>general - average recycled content* from the University of Bath database
EE: 20.10(MJ/kg) x 70025.28kg= 1407508.13MJ
Embodied Carbon: 1.37 ($kgCO_2$/kg) x 70025.28kg= 95934.64$kgCO_2$

Insulation sloping roof: Rockwool (stone wool)
860m^2 x 0.15m x 24kg/m^3= 3096kg

Considering the values of *Insulation> Rockwool (stone wool)* from the University of Bath database
EE: 16.80(MJ/kg) x 3096kg= 52012.8 MJ
Embodied Carbon: 1.05 ($kgCO_2$/kg) x 3096kg= 3250.8 $kgCO_2$

3. Setting

Indoor doors: 60 doors

Considering *Single fixed- type FG* the embodied energy per door is 483.8MJ (from database based on the University of Bath).
EE: 483.8(MJ/door) x 60doors= 29028MJ
Embodied Carbon: No factor ($kgCO_2$/door) available

Tiles: Ceramic tiles
600m^2 x 0.004m x 2000kg/m^3 = 4800kg

Considering the values of *Ceramic> tile* from the University of Bath database
EE: 12.00(MJ/kg) x 4800kg= 57600MJ
Embodied Carbon: 0.74 ($kgCO_2$/kg) x 4800kg= 3552$kgCO_2$

Stairs Fence/banister: Steel sheet
170m x 0.8m x 0.004m x 7800kg/m^3 = 4243kg

Considering the values of *Steel>general - average recycled content* from the University of Bath database

EE: 20.10 (MJ/kg) x 4243kg= 85284.3MJ
Embodied Carbon: 1.37 (kgCO_2/kg) x 4243kg= 5812.91kgCO_2

Stairs Fence/banister: Glass
170m x 0.8m x 0.008m x 2500kg/m^3 = 2720kg

Considering the values of *Glass> general* from the University of Bath database
EE: 15(MJ/kg) x 2720kg= 40800MJ
Embodied Carbon: 0.85 (kgCO_2/kg) x 2720kg= 2312kgCO_2

4. Systems

Ventilation system: Steel galvanized sheet

Element	Dimension	Mass [kg]
Sheet galvanized steel	1000x500x2mm	2300 kg
	900x500x2mm	2070 kg
	750x500x2mm	1840 kg
Total		6210 kg
Assembly	25% of total	1552 kg

Considering *Steel- Sheet -Galvanized –Virgin* from the University of Bath database
EE: 39(MJ/kg) x 6210kg= 242190 MJ
Embodied Carbon: 2.82 (kgCO_2/kg) x 6210kg= 17512.2kgCO_2

Ventilation system: Steel pipes

Element	Dimension	Mass [kg]
Ground floor	Ø200 x 110m	187
	Ø100 x 25m	17.5
	Ø200 x 65m	110.5
1st floor	Ø100 x 30m	21
	Ø160 x 15m	19.5
	Ø200 x 60m	102
	Ø280 x 23m	62.1
2nd floor	Ø160 x 12m	15.6
	Ø200 x 32m	54.4
	Ø280 x 60m	162
	Ø100 x 30m	21
3rd floor	Ø160 x 12m	15.6
	Ø200 x 32m	54.4
	Ø280 x 60m	162
	Ø100 x 30m	21
4th floor	Ø160 x 12m	15.6
	Ø200 x 45m	76.5
	Ø280 x 60m	162
	Ø100 x 30m	21
Total		860 kg
Assembly	25% of total	215 kg

Considering *Steel- pipe - average recycled content* from the University of Bath database

EE: 19.8(MJ/kg) x 860kg= 17028 MJ
Embodied Carbon: 1.37 ($kgCO_2$/kg) x 860kg= 1178.2$kgCO_2$

Ventilation system: Assembly steel wire
1552kg + 215kg = 1767kg

Considering *Wire-Virgin* from the University of Bath database
EE: 36(MJ/kg) x 1767kg= 63612 MJ
Embodied Carbon: 2.83 ($kgCO_2$/kg) x 1767kg= 5000.61$kgCO_2$

Heating system: HDPE pipes

Conforming to DIN 8074, 8075, SFS 2336, 2337, ISO 161

	Pressure Class									
Size	PN 2.5		PN 4		PN 6		PN 10			PN 16
Desig. d (mm)	S (mm)	Weight (Kg/m)	S (mm)	Weight (Kg/m)	S (mm)	Weight (Kg/m)	S (mm)	Weight (Kg/m)	S (mm)	Weight (Kg/m)
16	-	-	-	-	-	-	1.8	0.084	2.3	0.103
20	-	-	-	-	1.8	0.108	1.9	0.113	2.8	0.154

Note:
1. d = outside diameter of pipe
s = wall thickness of pipe
PN = Nominal pressure rating, in bar at 20ºC

The HDPE pipe used at Villa Flora is: 16mm (d) x 1.8 mm (S). According to the previous table the weight is 0.084 kg/m

A square meter of floor has 6.7m pipe resulting in 0.56 kg/m^2. Taking the area of Villa Flora 11120m^2 (Bruto-Vloeroppervlakte), the weight of the HDPE used in the heating system is 6227.2kg.

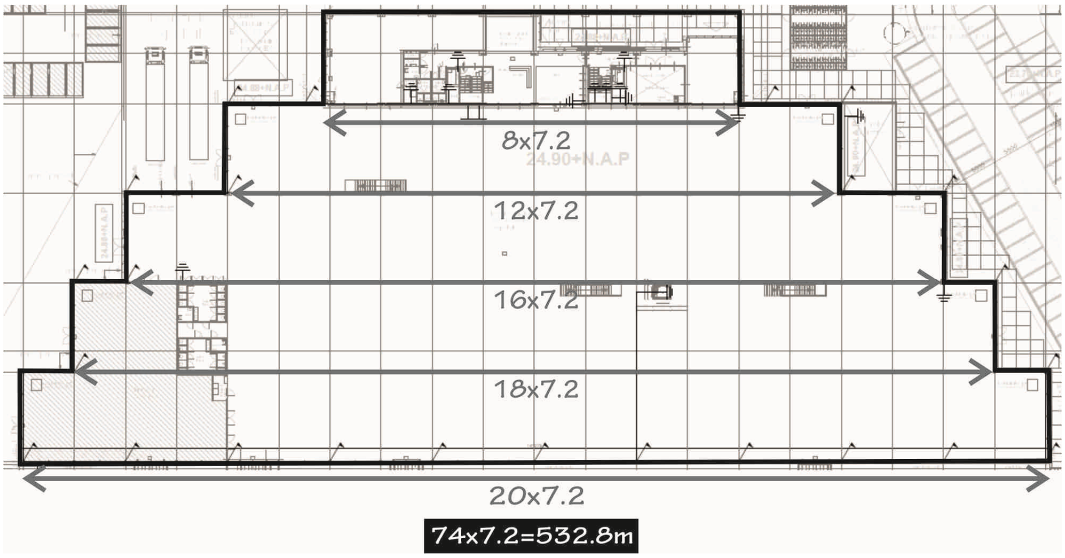
Considering the factors for *Plastics-HDPE-pipe* from the University of Bath database (data including 55.1MJ/kg of feedstock energy):
EE: 84.4(MJ/kg) x 6227.2kg= 525575.88 MJ
Embodied Carbon: 2.00 ($kgCO_2$/kg) x 6227.2kg= 12454.4$kgCO_2$

Electricity: Polycrystalline PV panels

Villa Flora is equipped with 1000m^2 of polycrystalline PV panels. The EE and carbon database suggest a range of values for this kind of product. 4070 MJ/m^2 and 208 $kgCO_2$/m^2 are selected for the calculation.
EE: 4070(MJ/m^2) x 1000m^2= 4070000 MJ
Embodied Carbon: 208 ($kgCO_2$/m^2) x 1000m^2= 208000$kgCO_2$

Water system: Rain drainage- Aluminum

From drawing it is considering 532.8m of rain drainage. To calculate the weight the following dimensions are assumed: 532.8m x 0.40m x 0.003m = 0.6394m^3
Consequently 0.6394m^3 x 2700kg/m^3= 1726.27kg



Considering the factors for *Aluminum- General* from the University of Bath database (Including 13.8MJ/kg of feedstock energy and worldwide recycled content of 33%)
EE: 155(MJ/kg) x 1726.27kg= 267571.85 MJ
Embodied Carbon: 8.24 (kgCO_2/kg) x 1726.27kg= 14224.46kgCO_2

Appendix F: Modified ‘C2C suppliers datasheet’

This is a C2C modified datasheet. It was intended to use it for the data collection of the materials of Villa Flora. Due to the limitation of time this datasheet was not implemented during the project and the information was collected with the available documents at Volantis B.V. It is recommended making the datasheet or a questionnaire easier to fill and understand by the suppliers.

Contact Information

Product Trade Name: ______________ **Contact Name & Title:** ______________

Product Type: ______________ **Phone & Email:** ______________

Company Name: ______________ **Company Address:** ______________

Is your product Cradle to Cradle® certified? **C2C level and cycle:** ______________

Where is your product manufactured? ______________

Product Formulation (only for non C2C products)

Please provide the following data for all different materials in the product.

#	**Material Ingredient** (Include trade name or part number)	**CAS #** (Chemical Abstract Service)	**Weight (kg) or (% of product's weight)**	**Function** (Within Product)	**Recycled Content** (Post-Industrial & Consumer	**Supplier Name & Contact Info** (If Different from Product Manufacturer)	**COMMENTS:**
Ex:	*C.I. Pigment Blue 15*	*147-14-8*	*0,5% of (3,5kg)*	*colorant*	*0%*	*Acme Products, John Doe, (555)555-1234, jd@acme.net*	*This is one of 10 possible color choices*
1)							
2)							
3)							
4)							
5)							
6)							
7)							
8)							
9)							
10)							
11)							
12)							

Product Formulation Biological/ Technical cycle (only for non C2C products)

Does your product contain recycled or renewable content?

Is your product disassemblable, recyclable and/or compostable? Explain

If Yes, Does your product contain any of the following chemicals?
Please mark with a **X** if containing.

Type	Substance	CAS #	X	Type	Substance	CAS #	X
Metals	Arsenic	7440-38-2		Chlorinated Hydrocarbons	1,2-Dichlorobenzene	95-50-1	
	Cadmium	7440-43-9			1,3-Dichlorobenzene	541-73-1	
	Chromium VI	18540-29-9			1,4-Dichlorobenzene	106-46-7	
	Lead	7440-43-9					
	Mercury	7439-97-6			1,2,4-Trichlorobenzene	120-82-1	
Flame Retardants	Hexabromocyclododecane	3194-55-6; 25637-99-4			1,2,4,5-Tetrachlorobenzene	95-94-3	
	Penta-BDE	32534-81-9			Pentachlorobenzene	608-93-5	
	Octa-BDE	32536-52-0			Hexachlorobenzene	118-74-1	
	Deca-BDE	1163-19-5			PCB and Ugilec	Several	
	Polybrominated Diphenyl Ethers (PBDEs)	Several			Short-chain chlorinated paraffins	Several	
	Tetrabromobisphenol A	79-94-7		Others	Pentachlorophenol	87-86-5	
	Tris(1,3-dichloro-2-propyl)phosphate	13674-87-8			Nonylphenol	104-40-5, 84852-15-3	
Phthalates	Bis(2-ethylhexyl) phthalate	117-81-7			Octylphenol	27193-28-8	
	Butyl benzyl phthalate	85-68-7			Nonylphenol ethoxylates	Several	
	Dibutyl phthalate	84-74-2			Octylphenol ethoxylates	Several	
Halogenated Polymers	Polyvinyl chloride (PVC)	9002-86-2			Tributyltin	688-73-3	
	Polyvinylidenechloride (PVDC)	9002-85-1			Trioctyltin	869-59-0	
	Chlorinated polyvinyl chloride (CPVC)	68648-82-8			Triphenyltin	892-20-6	
	Polychloroprene	9010-98-4			Perfluorooctane sulfonic acid	1763-23-1	
	Polytetrafluoroethylene (PTFE)	9002-84-0			Perfluorooctanoic acid	335-67-1	

Do you have strategies to close the loop on your product at the end of its useful life and prevent it for ending up in a landfill? Explain.

Product Formulation Biological/ Technical cycle (only for non C2C products)

If Yes, Does your product contain any of the following chemicals?
Please mark with a **X** if containing.

Type	Substance	CAS #	X
Polycyclic Aromatic	PAH group (as defined in TRI)		
	Benzo(a)pyrene	50-32-8	
	5-Methylchrysene	3697-24-3	
	Acenaphthene	83-32-9	
	Anthracene	120-12-7	
	Benz(a)anthracene	56-55-3	
	Benz(j)aceanthrylene	202-33-5	
	Benzo(b)fluoranthene	205-99-2	
	Benzo(c)phenanthrene	195-19-7	
	Benzo(g,h,I)perylene	191-24-2	
	Benzo(j)fluoranthene	205-82-3	
	Benzo(k)fluoranthene	207-08-9	
	Chrysene	218-01-9	
	Cyclopenta(c,d)pyrene	27208-37-3	
	Dibenzo(a,h)anthracene	53-70-3	
	Dibenzo(a,h)pyrene	189-64-0	
	Dibenzo(a,i)pyrene	189-55-9	
	Dibenzo(a,l)pyrene	191-30-0	
	Fluoranthene	206-44-0	
	Fluorene	86-73-7	
	Indeno(1,2,3,c,d)pyrene	193-39-5	
	Naphthalene	91-20-3	
	Phenanthrene	85-01-8	
	Pyrene	129-00-0	

Product Formulation Biological cycle (only for non C2C products)

Is your product compostable? Explain

If Yes, Does your product contain any of the following chemicals?
Please mark with a **X** if containing.

Type	Substance	CAS #	X	Type	Substance	CAS #	X
Metals	Arsenic	7440-38-2		Chlorinated Hydrocarbons	1,2-Dichlorobenzene	95-50-1	
	Cadmium	7440-43-9			1,3-Dichlorobenzene	541-73-1	
	Chromium VI	18540-29-9			1,4-Dichlorobenzene	106-46-7	
	Lead	7439-92-1					
	Mercury	7439-97-6			1,2,4-Trichlorobenzene	120-82-1	
Flame Retardants	Hexabromocyclododecane	3194-55-6; 25637-99-4			1,2,4,5-Tetrachlorobenzene	95-94-3	
	Penta-BDE	32534-81-9			Pentachlorobenzene	608-93-5	
	Octa-BDE	32536-52-0			Hexachlorobenzene	118-74-1	
	Deca-BDE	1163-19-5			PCB and Ugilec	Several	
	Polybrominated Diphenyl Ethers (PBDEs)	Several			Short-chain chlorinated paraffins	Several	
	Tetrabromobisphenol A	79-94-7		Others	Pentachlorophenol	87-86-5	
	Tris(1,3-dichloro-2-propyl)phosphate	13674-87-8			Nonylphenol	104-40-5, 84852-15-3	
Phthalates	Bis(2-ethylhexyl) phthalate	117-81-7			Octylphenol	27193-28-8	
	Butyl benzyl phthalate	85-68-7			Nonylphenol ethoxylates	Several	
	Dibutyl phthalate	84-74-2			Octylphenol ethoxylates	Several	
Halogenated Polymers	Polyvinyl chloride (PVC)	9002-86-2			Tributyltin	688-73-3	
	Polyvinylidenechloride (PVDC)	9002-85-1			Trioctyltin	869-59-0	
	Chlorinated polyvinyl chloride (CPVC)	68648-82-8			Triphenyltin	892-20-6	
	Polychloroprene	9010-98-4			Perfluorooctane sulfonic acid	1763-23-1	
					Perfluorooctanoic acid	335-67-1	
	Polytetrafluoroethylene (PTFE)	9002-84-0					

Do you have strategies to close the loop on your product at the end of its useful life and prevent it for ending up in a landfill? Explain.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