CIRAIG

Centre interuniversitaire de recherche sur le cycle de vie des produits, procédés et services

FINAL REPORT

LIFE CYCLE ASSESSMENT OF THE ENVIRONMENTAL IMPACTS RESULTING FROM THE IMPLEMENTATION OF URBAN HEAT ISLAND MITIGATION MEASURES

FEBRUARY 2011

Prepared for

Institut national de santé publique du Québec
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This report was prepared by the Interuniversity Research Centre for the Life Cycle of Products, Processes and Services (CIRAIG) and funded by the Government of Quebec's Green Fund as part of Measure 21 of the 2006-2012 Quebec Action Plan on Climate Change.

Initially founded by École Polytechnique de Montréal, in collaboration with Université de Montréal and HEC Montréal, the CIRAIG was created to meet the demands of industry and governments to develop leading-edge academic expertise on sustainable development tools. The CIRAIG is the only university life cycle research centre in Canada and is also one of the largest internationally.

ACKNOWLEDGMENTS

We wish to thank Health Canada's Climate Change and Health Office for providing financial support for the translation of this report in English.

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Notice to the Reader

All the urban heat island (UHI) mitigation measures assessed in this study have been identified as being capable of reducing the ambient or surface air temperature to varying degrees (Giguère, 2009). The objective of this study is not to compare or evaluate the effectiveness of the measures, but rather to assess the other environmental impacts that result from their implementation and maintenance during a specified period. The reader will therefore not find in these pages any conclusions about the options that offer the best temperature reduction potential. However, a person or organization wishing to compare two UHI mitigation projects (involving combinations of various individual measures) will be able to use the information provided herein to determine the one that has the fewest potential environmental impacts, notably thanks to an analysis grid which makes it possible to convert the results to the scale of the planned projects.

Nor does this report constitute a technical guide for developing and implementing UHI mitigation measures. If certain technical data are presented, it is solely for purposes of modelling the potential environmental impacts. The dimensions used must therefore not be considered as guidelines to be followed and are not intended to replace specialized documentation on the subject or consultation with a professional in the field.

Finally, the UHI mitigation measures analyzed in the context of this study were chosen because they apply to the urban residential sector. Although commercial and institutional properties and buildings offer significant potential for actions of this kind, the measures modelled in this study do not reflect large-scale design criteria.

Summary

The Institut national de santé public du Québec (INSPQ) decided to draw on the expertise of the CIRAIG to conduct a life cycle assessment (LCA) of ten urban heat island mitigation (UHI) measures applicable to the residential sector. The goal was not to compare or evaluate the effectiveness of these measures, but rather to assess the other potential environmental impacts that result from their implementation and maintenance during a specified period. The options were therefore analyzed on an individual basis (implementation of a particular measure), **without taking into account their temperature reduction potential**.

This assessment was intended to:

- Make it possible to individually compare the UHI mitigation measures applicable to the residential sector with a baseline situation, which corresponds to the *status quo* (i.e. taking no action).
- Permit, if possible, a ranking of certain comparable measures according to their potential overall environmental performance.
- Facilitate the comparison of potential UHI mitigation projects (involving combinations of various individual measures).

This study was carried out in accordance with the requirements of International Standards ISO 14040 and 14044 for a LCA disclosed to the public and including a comparative assertion. It should be noted that this study was critically reviewed by a panel composed of a LCA expert and specialists in the fields involved in the study.

In all, ten options were analyzed and compared to the baseline scenario. In order to facilitate analysis of the results, they were divided into four types of applications having common functions:

Protection of the building envelope

1. **Extensive green roof:** light-weight green roof requiring little maintenance. It can be adapted to existing flat-roofed houses, but is not designed to be accessible for recreational purposes. For the purposes of this study, a green roof includes both an elastomeric bitumen membrane and a planting system.
2. **Reflective roof:** high-albedo (light-coloured) roof, which reflects the rays of the sun and thereby reduces heat absorption. For the purposes of this study, a reflective roof includes both an elastomeric bitumen membrane and the reflective components. An ethylene propylene diene monomer (EPDM) membrane was also tested in the scenario analysis.

Planting around buildings

3. **Green wall:** façade wall covered by climbing plants planted directly in the ground.
4. **Planting arrangement:** border of annuals or perennials planted directly in the ground.

5. **Tree:** planting of a tree. For the purposes of this study, it is assumed that a large tree (2 metres) is transported and planted directly in the ground. This tree is not mature enough, in terms of foliage, to provide significant shade; this UHI mitigation measure is only effective when the tree reaches maturity.

Parking area

6. **Reflective surface:** high-albedo (light-coloured) surface, which reflects the rays of the sun and thereby reduces heat absorption. For the analysis, a parking area "resurfaced" with an ultrathin layer of Portland cement reinforced with polyethylene fibre was considered.
7. **Permeable surface:** surface that allows rainwater to percolate and infiltrate into the soil. For the analysis, a parking area covered with concrete paving stones that include openings for quick drainage of the paved surface was considered.

Soil humidification (which allows runoff to be retained or captured)

8. **Rain garden:** shallow depression in the ground excavated in permeable soil with local plants or shrubs that tolerate both wet conditions and occasional periods of drought. An installation designed expressly to capture rainwater and allow the soil to absorb it slowly by infiltration. The option considered here makes it possible to drain and filter water from the roof and from the parking area.
9. **Infiltration trench:** shallow (approximately 1 m) linear trench, covered with a permeable surface that allows runoff to be collected and absorbed by the soil. The option considered here makes it possible to drain water from the roof and the parking area and requires that the soil be sufficiently permeable.
10. **Dry well:** structure of variable depth (a few metres to ten metres) designed for temporary storage of rainwater, which then seeps into the permeable layers of the soil by infiltration; used for water from the roof and from the parking area. The option chosen here is a filled well, i.e. filled with porous materials.

The main **function** of the systems studied is to "Mitigate urban heat islands through the implementation of a measure, without regard to its temperature reduction performance."

Quantification of this function is based on the implementation and continued application of this measure over a specified period. The **functional unit** chosen is defined as follows:

"The implementation, in 2010, and the continued application over a 30-year period of an individual urban heat island mitigation measure on a residential block in a large urban centre in the province of Quebec."

The boundaries included in the analysis include implementation of the measure, its operation and maintenance over 30 years, and dismantling.

Since the purpose of this study was to provide general environmental data about various UHI mitigation measures, it was carried out based on **secondary data** (i.e. generic or theoretical data derived from commercial databases or the CIRAIG database, from information provided by contractors, reports of various studies, or other published sources). In all cases, the data selected are representative of UHI mitigation measures applied in Quebec, without necessarily covering all the locally available options. The European IMPACT 2002+ method was chosen to conduct the life cycle impact assessment (LCIA) of the scenarios compared.

The interpretation of the results and the conclusions of the study are based on a complete and in-depth analysis of the inventory data and of the LCIA. This includes, specifically:

- Data quality assessment and contribution analysis;
- Consistency and completeness analysis;
- Sensitivity and scenario analyses;
- Uncertainty analyses.

Insofar as possible, the non-quantifiable functions of the options were also taken into consideration. The conclusions focussed on the practical aspects, so as to provide guidance for the implementation and maintenance of a UHI mitigation measure.

Comparison of the UHI mitigation measures to the baseline situation

In general terms, on the basis of the data and hypotheses used and the sensitivity analyses conducted, conclusions can be drawn and recommendations formulated for each type of application.

For **roofs:**

- An extensive green roof or a reflective elastomeric bitumen membrane roof are generally preferable to an asphalt and gravel roof, when maintenance is reduced (i.e. without chemical fertilization or reflective coating).
- A membrane with the longest possible lifespan should be chosen, in order to reduce the potential impacts associated with the production, transport and landfilling of the materials.
- In the case of an extensive green roof, it is preferable not to use chemical fertilizers on a regular basis, particularly if the roof water is diverted to a rainwater capture system, in order to prevent discharge of metals into water and soil.
- In the case of reflective roofs, it is preferable to opt for a membrane that can be maintained by simple washing with soap and water. The application of a reflective coating on a regular basis has significant potential impacts on the environment. If a white elastomeric bitumen membrane is installed, it is therefore better to allow it to lose its reflectivity than to apply layers of reflective product.
- White EPDM membranes have fewer potential impacts than asphalt and gravel roofs owing to their longer lifespan, ease of maintenance and the fact that they are fully recyclable at the end of their life.

In addition to these factors, it should be borne in mind that an extensive green roof is able to retain light rain and delay the arrival of water in sewers during heavy rains, which helps reduce stress on the sewer system and water treatment plants. The plants on the roof also improve air quality and reduce ambient noise, in addition to creating habitat for birds.

However, green roofs cannot be installed everywhere. The structure of older buildings is often inadequate to support the additional weight represented by the water-soaked growing medium.

For **greening measures,** it is preferable:

- Whenever possible, to keep the existing earth rather than disposing of it off-site and having new earth delivered.
- To reduce the use of chemical fertilizers insofar as possible.

In addition, greening areas that were originally paved increases the quantity of water that infiltrates into the soil, which facilitates natural aquifer recharge and reduces the problems of sewer overloading. Plants improve air quality and reduce ambient noise, in addition to creating habitat for birds and beautifying urban neighbourhoods.

However, it should be noted that when a tree is planted, its foliage does not provide significant shade. It will become an effective UHI mitigation measure only when it reaches maturity.

For **parking areas:**

- Permeable concrete paving stones have fewer potential impacts than an asphalt-paved parking area.
- Permeable concrete paving stones also have more benefits compared to reflective surfaces ("resurfacing" with Portland cement) for the *Climate change* indicator.
- Other types of permeable and reflective surfaces are available on the market. Although they were not analyzed, it appears that it is generally advantageous to replace an asphalt driveway with options that require less materials and energy.

Installing a permeable surface on areas that were originally paved increases the quantity of water that infiltrates into the soil, which facilitates natural aquifer recharge and reduces the problems of sewer overloading. However, this water may contain pollutants that can eventually contaminate soil and groundwater with oils and greases, and the potential impact associated with these substances was not assessed.

For **rain gardens,** it is preferable to:

- Keep the existing earth rather than disposing of it off-site and having new earth delivered.
- Reduce the use of chemical fertilizers insofar as possible.

In addition, as it is the case for planting arrangements, plants improve air quality, water filtration and reduce ambient noise, in addition to creating habitat for birds and beautifying urban neighbourhoods.

For constructed measures such as **dry wells and infiltration trenches:**

- The soil excavated during installation should if possible be re-used at the same site or nearby in order to reduce the impacts associated with its transport and landfilling.
- The dismantling of these structures at the end of their life contributes to nearly half of their potential impacts. In cases where the subsequent use of the site permits, leaving the gravel in place and covering it with the chosen surface would significantly improve the environmental performance of these measures by reducing the transport and landfilling of gravel and by avoiding the transport of earth to fill the hole.

Finally, for all the soil humidification measures, capturing runoff increases the quantity of water that infiltrates into the soil, which facilitates natural aquifer recharge and reduces the problems of sewer overloading. However, runoff from the parking area may contain pollutants, oils and greases, which can eventually contaminate the soil and aquifers. The rain garden substrate can filter out some of these contaminants, but the potential impact and benefit associated with these substances were not quantified.

Ranking of the measures

The wide range of functions of the assessed UHI mitigation measures make it impossible to rank all the options according to their environmental performance. In addition, given the results obtained, it is not possible to rank the measures belonging to the same type of application. Indeed, depending on the specific conditions (lifespan, type of maintenance, use of fertilizers, etc.), the results can lead to the same measures being ranked differently. A ranking of the measures without consideration of these variabilities would therefore almost certainly lead to erroneous or questionable decisions.

Comparison of UHI mitigation projects

In cases where the hypotheses used in the LCA modelling are applicable, it is possible for decision-makers to compare different UHI mitigation projects (involving combinations of various measures) that they consider equivalent in terms of heat reduction, since the results are linear.

We have proposed an analysis grid which presents the results of the damage indicators and midpoint indicators assessed for each of the measures. These results are provided in absolute values, relative to the baseline situation (whose measured impact would be zero). The options for which the indicators are less than zero indicate an environmental benefit relative to the baseline scenario.

Refer to the complete report for the details of the assumptions and modelling choices used, for the assessment results, and for the grid that can be used to compare UHI mitigation projects.

The assessment of urban heat island mitigation measures is a complex task, given the number of social, environmental and economic aspects involved. Several parameters, such as the quality of life of residents, and integration into the landscape, are elements that are not easily quantifiable, but which must nonetheless be taken into account. In this context, the LCA is not sufficient to decide which of a range of measures is the best, but it does help provide a better understanding of the impacts associated with the various options and, consequently, permits better informed decision-making.

Note: This LCA aims to inform the public and the organizations working in the field about the potential environmental impacts and benefits associated with various UHI mitigation measures throughout their life cycle. It also aims to enable the INSPQ to enhance its assessment of urban heat island mitigation measures by incorporating aspects of environmental performance based on the "life cycle" approach. The analysis was carried out from a comparative perspective relative to a baseline scenario where no UHI mitigation measures are taken. Any conclusions drawn from this study outside of its original context should be avoided.

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List of Abbreviations and Acronyms

AA	Aquatic Acidification
AE	Aquatic Eutrophication
CC	Climate Change
CIRAIG	Interuniversity Research Centre on the Life Cycle of Products, Processes and Services
CMHC	Canada Mortgage and Housing Corporation
CO_2	Carbon dioxide
DALY	Disability-adjusted life years
DDS	Dry material disposal site
EPDM	Ethylene propylene diene monomer
EQ	Ecosystem Quality
HH	Human Health
INSPQ	*Institut national de santé publique du Québec*
ISO	International Organization for Standardization
kg CO_2 eq.	Kilogram of carbon dioxide equivalent
kg PO_4 eq.	Kilogram of phosphate equivalent
kg SO_2 eq.	Kilogram of sulphur dioxide equivalent
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MJ primary	Megajoules of primary energy
MSSS	Quebec Department of Health and Social Services
NGO	Non-governmental organization
OEE	Office of Energy Efficiency
PDF*m^2*yr	Potentially disappeared fraction over a given area and a given time period
R	Resources
UHI	Urban heat island

1 BACKGROUND

In the context of the 2006-2012 Quebec Action Plan on Climate Change (2008), the Department of Health and Social Services (MSSS) has tasked the Institut national de santé public du Québec (INSPQ) to manage the implementation of mechanisms aimed at preventing and mitigating the impacts of climate change on health. In this context, the INSPQ is responsible for evaluating the applications submitted by municipalities and non-governmental organizations (NGOs) with the goal of securing funding for the proposed measures.

To complement its process of assessing the environmental performance of urban heat island mitigation measures (UHI), the INSPQ called on the expertise of the CIRAIG. Its mandate was to conduct a life cycle assessment (LCA) of ten UHI mitigation measures applicable to the residential sector. The goal was not to compare or to evaluate the effectiveness of these measures, but to assess the other potential environmental impacts which result from their implementation and maintenance during a specified period. The options were therefore analyzed on an individual basis (implementation of a particular measure), **without taking into account their temperature reduction potential**.

A preliminary version of the study was first compiled based on easily accessible public data (Martineau, 2010). Following this study, the INSPQ decided to make the results public. More detailed information concerning the LCA was therefore added in order to bring the study into compliance with the recommendations of the International Organization for Standardization.

This document constitutes the final report of the project after critical review by a panel of interested parties. It presents:

- The goal and scope of the study (Chapter 2).
- The results, their interpretation and the associated recommendations (Chapter 3).

This study was carried out in accordance with the requirements of International Standards ISO 14040 and 14044 (ISO, 2006a, b) for a LCA disclosed to the public and including a comparative assertion.

It should be noted that Appendix A presents the LCA methodology in detail, including a section defining the terms specific to the field.

A summary review of the relevant publications (LCA or other studies) dealing with the urban heat island mitigation measures was also conducted. Very little research dealing with the LCA of such measures has been published (Table 1-1) and the majority of these studies dealt with green roofs and reflective coverings in geographic contexts very different from Quebec. The documents consulted are listed in the references (Chapter 5).

Table 1-1: LCA studies on UHI mitigation measures

Authors (year)	Geographic context	Title	UHI mitigation measure assessed
GENCHI, Y. (2006)	Japan	Life Cycle Impact Assessment of Urban Heat Island in Tokyo. "LIME: Life-cycle Impact assessment Method based on Endpoint modeling"	Reflective roofs and walls
GENCHI, Y. and IHARA, T. (2009)	Japan	Environmental Impact Assessment of Urban Air Temperature Increase Based on Endpoint-Type Life Cycle Impact	Not specified
IHARA, T., KIKEGAWA, Y., OKA, K., YAMAGUCHI, K., ENDO, Y. and GENCHI, Y. (2007)	Japan	Urban Heat Island Mitigation and Life Cycle CO2 Reduction by Installation of Urban Heat Island Countermeasures	Photocatalytic and reflective coatings, green roofs and green walls
KOSAREO, L. and RIES, R. (2007)	United States (PA)	Comparative Environmental Life Cycle Assessment of Green Roofs	Green roofs
SAIZ, S., KENNEDY, C., BASS, B. and PRESSNAIL, K. (2006)	Spain	Comparative Life Cycle Assessment of Standard and Green Roofs	Green roofs

2 Goal and scope of the study

This chapter describes the goal and scope of the study, stating the methodological framework for the subsequent LCA stages.

2.1 Objectives and intended applications

The **purpose of this study** was to evaluate, on the basis of a LCA, the potential environmental impacts associated with the implementation and maintenance, during a specified period, of urban heat island mitigation measures (hereinafter referred to as “the measures”).

This assessment was intended to:

- Make it possible to individually compare the UHI mitigation measures applicable to the residential sector with a baseline situation, which corresponds to the *status quo* (i.e. taking no action).
- Permit, if possible, a ranking of certain comparable measures according to their potential overall environmental performance.
- Facilitate the comparison of potential UHI mitigation projects (involving combinations of various individual measures).

As mentioned earlier, the objective of the life cycle assessment which follows was not to evaluate the effectiveness of the measures. Thus, it was not deemed necessary that all the measures assessed have the same temperature reduction potential, since the analysis was carried out in a comparative context relative to the chosen baseline scenario. The results provide an assessment of the measures on an individual basis (planting of a tree, installation of a green roof, etc.). However, a person or organization wishing to compare two UHI mitigation projects will be able to determine the one having less potential environmental impacts, thanks to the analysis grid provided, which makes it possible to convert the results to the scale of the planned projects.

The results of this study are intended for public disclosure by the INSPQ, in order to better inform the public and the organizations working in the field about the potential environmental impacts and benefits that various UHI mitigation measures represent throughout their life cycle. The INSPQ will also be able to use this study as a complementary tool during the assessment of UHI mitigation projects.

According to ISO standards, LCA critical reviews are optional when the results are intended for internal use. However, such a review is mandatory prior to public communication (e.g. environmental product declarations according to the ISO 14020 standards or comparative assertions disclosed to the public according to the ISO 14040 standards). Moreover, it is an important step to enhance validity and credibility and improve public acceptance of the results.

A critical review of this study was carried out by an external LCA expert and a committee of stakeholders. See section 2.9 for more details on the critical review process.

2.2 General description of the assessed measures

Heat islands are a strictly urban climatic phenomenon, characterized by a substantial increase in ambient and surface temperatures relative to the adjacent natural environment. Two important factors contribute to this phenomenon, namely anthropogenic activities and the nature of the surfaces.[1]

A range of options are available in terms of measures for preventing and mitigating urban heat islands, including greening measures, changes to architecture and land use planning, stormwater management, as well as the reduction of anthropogenic heat.

Given the multiple possibilities for applying these measures, a precise definition of the options studied is provided here. These are specific choices made in collaboration with the INSPQ.

It should be noted that all the measures selected apply to the residential sector and can be implemented by individuals who wish to make modifications to their home or their private property.

2.2.1 Baseline scenario

A comparative basis was established, namely a baseline scenario in which no mitigation measures are taken. The goal here is not to quantify the environmental impacts associated with the baseline scenario, since it would be complex and of little value to model all the elements of such a situation. However, this baseline scenario must make it possible to quantify the CHANGES brought about by the assessed mitigation measures. Thus, everything that remained unchanged between the baseline situation and the options studied was not quantified. Only the parameters that are modified by the implementation of the measures were modelled and quantified. Ultimately, this approach allows to state that the implementation of measure X results in a decrease/increase in the potential environmental impacts relative to the baseline scenario. Table 2-1 summarizes the parameters of the chosen baseline scenario.

Table 2-1: Parameters of the baseline scenario

Parameters
• A residential block typical of central Montreal island neighbourhoods (but which can also be representative of any large urban centre in Quebec), where no mitigation measures are implemented.
• Townhouses or semi-detached houses.
• Flat, multilayer asphalt and gravel roofs. Assumed lifespan of 15 years. N.B. Although elastomer membranes are also considered multilayer membranes, they are not part of the baseline scenario.
• Brick walls, façade 7.62 m (25 ft) wide, with a total height of approximately 8 m (two storeys).
• Backyards and building periphery including an asphalt-paved parking space (assumed 20-year lifespan), with little vegetation.
• All the precipitation falling on the roof and on the property around the building ends up in the municipal sewer and must be treated in a water treatment plant.

[1] Definition taken from an article entitled "Vert urbain" published in the magazine *Découvrir* (Robichaud and Saint-Onge, Vol. 30, No. 4, October 2009), p. 34.

2.2.2 UHI mitigation measures assessed

In all, ten options were analyzed and compared to the baseline scenario. In order to facilitate the analysis of the results, they were divided into four types of applications that have common functions:

Protection of the building envelope

1. **Extensive green roof:** light-weight green roof requiring little maintenance. It can be adapted to existing flat-roofed houses, but is not designed to be accessible for recreational purposes. For the purposes of this study, a green roof includes both an elastomeric bitumen membrane and a planting system.
2. **Reflective roof:** high-albedo (light-coloured) roof, which reflects the rays of the sun and thereby reduces heat absorption. For the purposes of the study, the reflective roof includes both an elastomeric bitumen membrane and the reflective components. Another type of membrane was also tested in the scenario analysis.

Planting around buildings

3. **Green wall:** façade wall covered by climbing plants planted directly in the ground.
4. **Planting arrangement:** border of annuals or perennials planted directly in the ground.
5. **Tree:** planting of a tree. For the purposes of the study, it is assumed that a large tree (2 metres) is transported and planted directly in the ground. This tree is not mature enough, in terms of foliage, to provide significant shade; this UHI mitigation measure is only effective when the tree reaches maturity.

Parking area

6. **Reflective surface:** high-albedo (light-coloured) surface, which reflects the rays of the sun and thereby reduces heat absorption.
7. **Permeable surface:** surface that allows rainwater to percolate and infiltrate into the soil.

Soil humidification (which allows runoff to be retained or captured)

8. **Rain garden:** shallow depression in the ground excavated in permeable soil with local plants or shrubs that tolerate both wet conditions and occasional periods of drought. An installation designed expressly to capture rainwater and allow the soil to absorb it slowly by infiltration. The option considered here makes it possible to drain and filter water from the roof and the parking area.
9. **Infiltration trench:** shallow linear trench (approximately 1 m), covered by a permeable surface that allows runoff to be collected and absorbed by the soil. The option considered here makes it possible to drain water from the roof and the parking area and requires that the soil be sufficiently permeable.
10. **Dry well:** structure of variable depth (a few metres to ten metres) designed for the temporary storage of rainwater, which then seeps into the permeable layers of the soil by infiltration; used for water from the roof and the parking area. The option chosen here is a filled well, i.e. filled with porous materials.

This division was chosen in order to facilitate comparisons of the measures assessed, despite their functional differences. Indeed, a private individual will generally make the decision to implement a UHI mitigation measure when the time comes to replace his roof or to pave or repave his private driveway or when he decides to landscape his property. Thus, although from a strict LCA standpoint, it is not possible to compare options that have different secondary functions, from a practical standpoint, certain measures are entirely equivalent and have therefore been compared for the benefit of the readers (Chapter 3).

2.2.3 Mitigation measures excluded

Certain UHI mitigation measures surveyed by Giguère (2009) were excluded from the analysis, since they were not applicable to existing residential buildings or were not easily quantifiable in a generic way:

- Reflective walls (high-albedo (light-coloured) walls, which reflect the rays of the sun and thereby reduce heat absorption);
- Measures involving lowering of the inside temperature (misters, ventilation, insulation/air-tightness/thermal mass, etc.);
- Measures to reduce anthropogenic heat (energy efficiency, active transport, etc.);
- Rainwater retention structures of large dimensions or not easily installed by individuals in an urban residential context (e.g. swales, filter strips, treatment wetland);
- Albedo of paints for vehicles and watering of pavement with recycled water;
- Intensive green roofs;
- Simple measures such as replacing the asphalt in the backyard with grass or using a crushed gravel surface, because their benefit depends entirely on the specific context of the site (not easily quantifiable in a generic way).

2.3 System function and functional unit

The main **function** of the systems studied is to "Mitigate urban heat islands through the implementation of a measure, without regard to its temperature reduction performance.*"*

The quantification of this function is based on the implementation and continued application of this measure over a specified period. The **functional unit** chosen is defined as follows:

"The implementation, in 2010, and the continued application over a 30-year period of an individual urban heat island mitigation measure on a residential block of a large urban centre in the province of Quebec."

The **reference flows** refer to the quantity of products required to perform the function studied. In the present case, the individual UHI mitigation measures were chosen as reference flows (Table 2-2). All the material and energy requirements for their implementation and maintenance over the study period are included.

Table 2-2: Characteristics and reference flows

UHI mitigation measures	Characteristics
Protection of the building envelope	
1. Extensive green roof	Elastomeric bitumen membrane roof and adapted system. Roof dimensions: 7.6 m x 13.1 m (i.e. a 100 m² (1,076 ft²) house) including 1,200 perennial plants (reed-grass or sedums, for example). Assumed lifespan of 45 years. Replaces an asphalt and gravel roof.
2. Reflective roof	White elastomeric bitumen membrane roof and reflective coating. Same dimensions as the green roof. Assumed lifespan of 25 years. Replaces an asphalt and gravel roof.
Planting around buildings	
3. Green wall	Virginia creeper planted directly in the ground (hole 0.5 m deep), at the base of a standard wall 7.62 m (25 ft) long by 8 m high (two storeys). The plants climb directly on the brick wall.
4. Planting arrangement	Area of 25 m² in the form of a border in front of or on the side of a house (250 plants). 5% of the plants are replaced annually.
5. Tree	Planting and maintenance of a large tree (2 m). Excavation of 1 m³ (area of 1 m²).
Parking area	
6. Reflective surface	Parking area "resurfaced" with an ultrathin (75 mm) layer of Portland cement reinforced with polypropylene fibres. Area of 5.5 m x 2.6 m (14.3 m²)* Assumed 20-year lifespan. Replaces an asphalt parking area.
7. Permeable surface	Parking area covered with concrete paving stones including openings for quick drainage of the paved surface. Same area as the reflective surface. Assumed 20-year lifespan. Replaces an asphalt parking area.
Soil humidification	Installations capable of draining the water from a 100 m roof and runoff from a private parking area (14.3 m²).
8. Rain garden	Area of 25 m² or 28.6 m² (with or without capture of runoff from the parking area). Option applicable for houses with gutters and with fairly permeable soils. 1% of the plants are replaced annually.
9. Infiltration trench	Trench 12 m x 1.2 m x 1.1 m deep or 13 m x 1.2 m x 1.15 m deep (with or without capture of water from the parking area). Option applicable for houses with gutters and with fairly permeable soils. Assumed lifespan of 30 years.
10. Dry well	Well 1.7 m Ø x 2.5 m deep or 1.8 m Ø x 2.75 m deep (with or without capture of water from the parking area). Option applicable for houses with gutters and with fairly permeable soils. Assumed lifespan of 30 years.

* See Appendix B, Table B-1 for the choice of parking area dimensions.

For the purposes of the analysis, the respective lifespans of the various UHI mitigation measures were taken into account in order to determine their potential impacts over the 30-year period defined by the functional unit. For example:

- 0.67 extensive green roof (30 years/45-year lifespan)
- 1.2 reflective roof – elastomeric bitumen membrane (30 years/25-year lifespan)
- 1.5 parking area (30 years/20-year lifespan)

Hence, the quantity of materials and energy consumed and the emissions generated during the implementation, maintenance and dismantling of the measures were calculated prorated to the lifespan of each of the assessed options.

More details about the characteristics of the measures considered during the modelling are provided in Table B-2 (Appendix B).

2.4 Multifunctional processes and allocation rules

The LCA does not deal with the comparison of specific products or services, but rather with one or more functions fulfilled by these products or services. Therefore, multifunctional processes must be considered with care.

The UHI mitigation measures assessed encompass a wide variety of intrinsic functions. Apart from lowering the ambient temperature (which they all do to varying degrees), some measures are intended to protect the occupants of a house from bad weather (roofs), some are intended to promote soil humidification (retention trenches, rain gardens…), while others provide a parking space (permeable or reflective surfaces) or are intended to beautify the landscape (trees, planting in general).

These various "secondary"[2] functions cannot easily be integrated in the same LCA. However, some secondary functions that can be quantified relative to the baseline scenario have been modelled in such a way as to take into consideration the factors which can influence the environmental balance sheet of the options considered. This is the case of the following two parameters:

- **Avoided energy consumption:** this is the reduction in the energy requirements of a building (associated with air conditioning and heating) following the installation of a green roof or a reflective roof.
- **Avoided water treatment:** for the options leading to increased infiltration of precipitation in the soil, this is the reduction in the volume of water that ends up in the municipal sewers and has to be treated.

The other secondary functions were qualitatively assessed using a functional LCA matrix (see section 3.1).

It should be noted that no allocation rules were used. In all cases, the aspects of multifunctionality were treated by boundary expansion, in a manner consistent with the study objectives. Table 2-3 presented in the following section indicates the processes for which a boundary expansion was carried out.

2.5 System boundaries

[2] Although the primary function of a roof is to protect the occupants of a house, in the context of this analysis this is a secondary function.

The system boundaries identify the life cycle stages, processes and flows considered in the LCA and should include all activities relevant to the attainment of the study objectives and therefore necessary to carry out the studied function.

The following paragraphs provide a general description of the system boundaries and the temporal and geographical boundaries of the study.

2.5.1 General system description

Figure 2-1 illustrates the studied system boundaries. For each UHI mitigation measure, the subsystems include various activities defined in Table 2-3. More detailed documentation on the assessed life cycle stages is provided in Appendix B (in the form of a spreadsheet). The document includes a complete list of the material and energy flows creating the foreground of each subsystem.

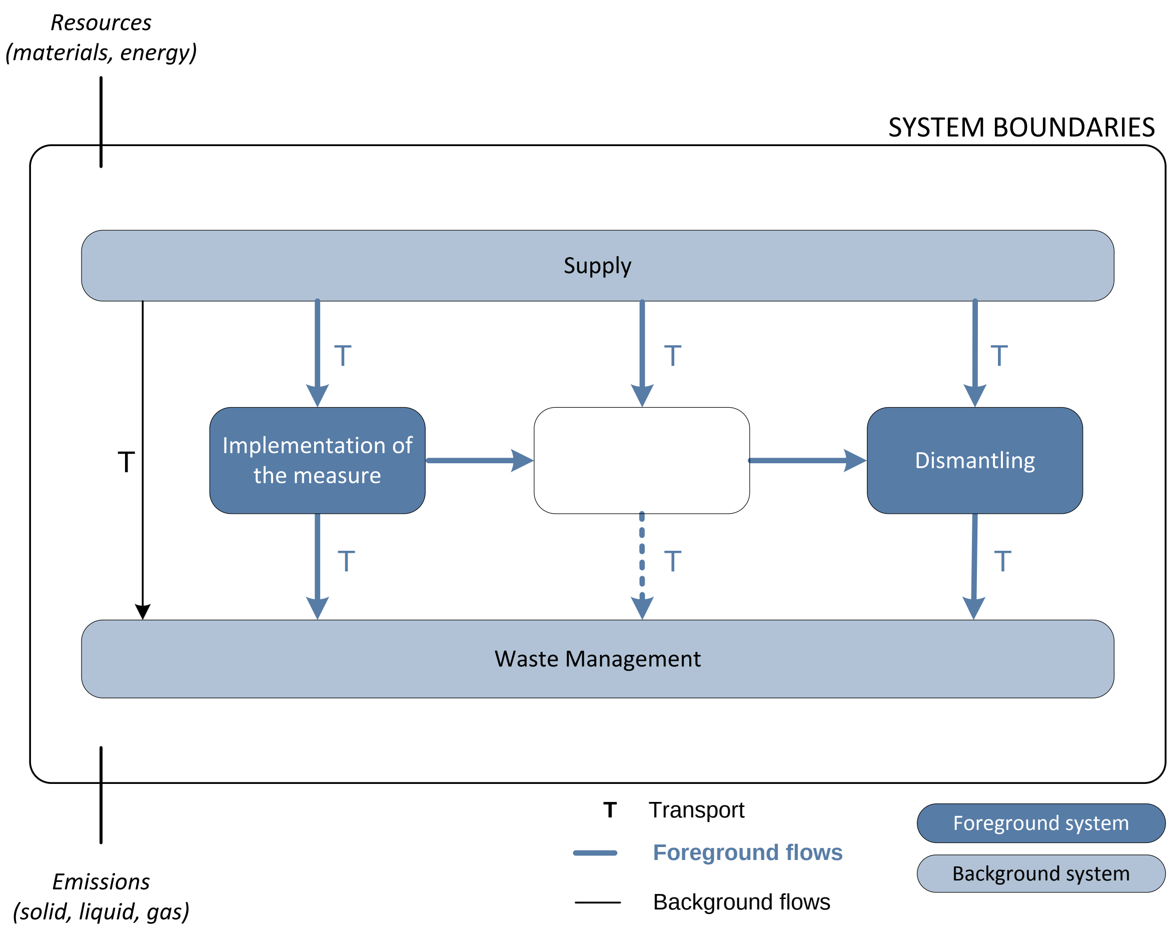


Figure 2-1: Main life cycle stages included in system boundaries.

It should also be noted that the various stages of the life cycle of the measures studied comprise the **foreground systems**, while all the supply and waste management processes involved in each of these stages constitute the **background systems**.

The "**supply**" and "**waste management**" background subsystems concern respectively, for each of the foreground subsystems, all the activities related to:

- The supply of resources (water, energy, chemicals, materials), including the extraction and processing of natural resources, as well as the various transport stages required culminating in delivery at the site of end use;
- The transport and treatment of the waste generated during the various stages of the life cycle studied.

Within each of these stages, the LCA also considers all identifiable "upstream" inputs to provide the most comprehensive view of the system. For example, when considering energy used for transportation, not only are the emissions and fuel used by the truck moving the products considered, but so are the additional processes and inputs needed to produce that fuel. In this way, the production chains of all inputs are traced back to the original extraction of natural resources.

Table 2-3 presents the activities included and excluded in the life cycle assessment of the UHI mitigation measures. Supply and waste management have been distributed among the life cycle stages to simplify the reading of the table.

No cut-off criteria were used. Therefore, all inventory data available were included into the system modeling.

Table 2-3: Processes included and excluded from the LCA

Life cycle stage	Process/Subprocess	Description
Implementation of the measure	Production and transport of the materials, plants and energy necessary for the installation	Production and transport of the main components/materials included; fuel consumed by the equipment included. The other resources and waste were ignored.
	Manufacture of the infrastructures and equipment for the installation	Included (in the generic data modules).
	Production and end-of-life management of packaging (bags, plastic film, boxes…)	*Ignored, except in the case of the flowerpots, accounted for in the production of the plants, and small quantities of black earth, assumed to be purchased in 30 L plastic bags (for green wall and tree).*
	Transport and landfilling of the soil excavated	Included.
	Baseline option replaced (boundary expansion)	Green/reflective roof: over 30 years, replaces 2 asphalt and gravel roofs with a lifespan of 15 years (including the production, transport and landfilling of the materials). Permeable/reflective surface: over 30 years, replaces 1.5 asphalt-paved parking area with a 20-year lifespan (production of materials, machinery, transport and landfilling).

Life cycle stage	Process/Subprocess	Description
Operation and maintenance over 30 years	Production and transport of the materials and energy required for maintenance	Included.
	Avoided energy consumption (boundary expansion)	Green/reflective roof: reduction of air conditioning/heating compared to the baseline scenario. For the other measures, no avoided energy consumption considered (assumed to be negligible).
	Avoided water treatment (boundary expansion)	Reduction of the rainwater that ends up in the municipal sewers compared to the baseline scenario: for all the options involving increased infiltration of precipitation in the soil or water retention (green roof).
	Change in albedo	*Excluded. Can have an effect on climate change (Schwaiger and Bird (2010); Bird and Woess-Gallasch (2008)). However, the quantification in kg CO_2 eq. is complex and depends on factors that vary in time and space.*
	CO_2 capture by the plants	*Excluded. Biogenic carbon will be returned to the atmosphere in a relatively short timeframe. Biogenic carbon is therefore not taken into account.*
Dismantling	Manufacture and operation of the equipment required for the dismantling	Main equipment (excavators and trucks) included.
	End-of-life transport and management of the materials	The main materials (gravel, concrete, growing medium, membranes, etc.) are assumed to be landfilled.
	Impacts avoided by the recycling/re-use of materials at the end of their life	***Metals** are assumed to be 100% recycled. A cut-off was applied – no impact attributed to the end-of-life management of metals.* *The re-use of the wood from the tree at the end of its life was also excluded, since this is impossible to determine in a generic context (composting, incineration with heat recovery, production of electricity or of alternative fuel…)*
	Site restoration	For constructed measures such as dry wells and infiltration trenches, restoration of the site to its initial condition was assumed (removal of the gravel and filling with earth). *In the case of greening measures (plant arrangement, tree, green wall, rain garden), no end-of- life management was considered, since this depends entirely on the subsequent use of the site.*
All stages	*Ancillary services (administration, promotion and other services)*	*Excluded.*

As presented in Table 2-3, certain processes, for example the effect of the change in albedo on climate change or the end-of-life management of greening measures, were excluded owing to the lack of data or the impossibility of modelling a representative generic case. It is not possible to know the effect of excluding these elements on the results.

2.5.2 Geographical and temporal boundaries

According to the functional unit, this study constitutes a representative LCA of the Quebec context in 2010. The UHI mitigation measures were therefore modelled in such a way as to meet this criterion.

It should be noted, however, that some processes within the system boundaries may take place anywhere or anytime, as long as they are needed to achieve the functional unit. For example, the processes associated with the supply, and the waste management can take place in Quebec or elsewhere in the world. In addition, certain processes may generate emissions over a longer period of time than the reference year. This applies to landfilling, which causes emissions (biogas and leachate) over a period of time whose length (several decades to over a century/millennium) depend on the design and operation parameters of the burial cells and how the emissions are modeled in the environment.

2.6 Life cycle inventory (LCI) data, sources and assumptions

LCI data collection mainly concerns the materials used, the energy consumed and the wastes and emissions generated by each process included in the system boundaries.

Since the purpose of this study was to provide general environmental data about various UHI mitigation measures, it was carried out based on **secondary data** (i.e. generic or theoretical data derived from commercial databases or the CIRAIG database, from information provided by contractors, reports of various studies or other published sources (see Appendix B)). In all cases, the data selected are representative of UHI mitigation measures applied in Quebec, without necessarily covering all the locally available options.

All the systems were modelled using the life cycle inventory (LCI) data modules available in the *ecoinvent* version 2.0 database (www.ecoinvent.ch/). This European database is particularly recognized by the international scientific community, since it by far surpasses the other commercial databases from both the quantitative (number of processes included) and qualitative (quality of the validation processes, completeness of the data, etc.) standpoints.

Whenever possible, generic datasets used in this study were adapted to increase their representativeness of the geographical context of the study. More specifically, for all activities taking place in Quebec, the generic datasets were adapted by replacing the original grid mixes (European) by:

- The Quebec grid mix for foreground processes, i.e. the processes directly related to the system studied (e.g. the consumption of electricity during the production of components manufactured in Quebec);
- The North American grid mix for the background processes, i.e. all the processes directly and indirectly related to the foreground processes (e.g. all the resources consumed for the production of plastic, steel, etc. required for the manufacture of the components). The North American grid mix is more appropriate here considering that the materials are not obtained exclusively in Quebec.

Hence, all the foreground processes that take place in Quebec (including transports) refer to background processes adapted to the North American energy context.

It should also be noted that all the data used were:

1) Checked regarding their temporal, geographical and technological representativeness;
2) Collected at the highest level of detail possible;
3) Documented according to the best practices available.

In cases where no source was available or involved variable parameters, **assumptions** were also used. The complete assumptions list relative to the systems is provided in Appendix B.

The SimaPro 7.2 software, developed by PRé Consultants (www.pre.nl), to assist the LCA system modeling, link the reference flows with the life cycle inventory database and compute the complete life cycle inventory of the systems. No cut-off criteria were used. All the available data were incorporated in the model.

2.7 Environmental impact assessment

2.7.1 IMPACT 2002+

The internationally recognized European life cycle impact assessment method IMPACT 2002+, version 2.05 (Jolliet et al., 2003) was chosen to conduct the life cycle impact assessments (LCIA) of the measures. In addition to providing the results for fifteen impact categories, IMPACT 2002+[3] permits aggregation of the data into four damage categories (Figure 2-2).

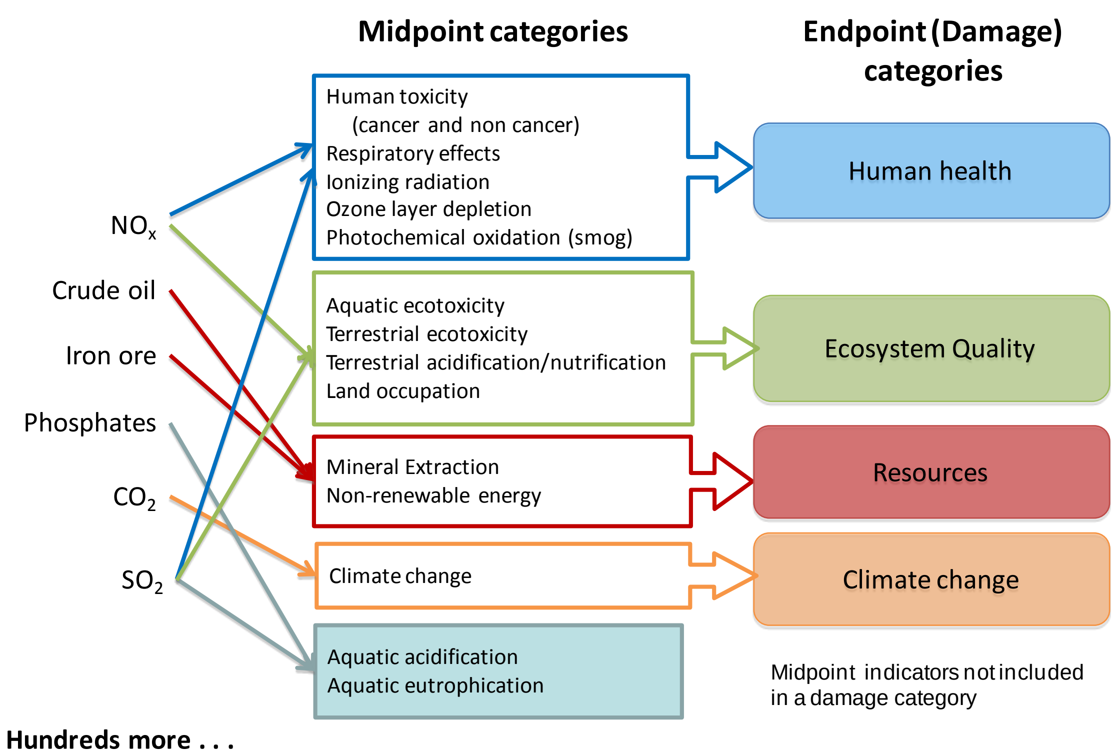


Figure 2-2: IMPACT 2002+ midpoint and endpoint categories.

[3] The presentation of the impact categories of the IMPACT2002+ method is usually available on the website www.sph.umich.edu/riskcenter/jolliet/impact2002+.htm#form2. Since the website is currently inaccessible [as of February 19, 2011], a summary taken from the site – in English only – is provided in Appendix C.

The aggregation of the midpoint indicators into damage (endpoint) categories provide results easier to understand and interpret for the layman, but also provide a rapid assessment of key environmental issues associated to the system under study.

Damage categories may be summarized as follows:

- **Human Health:** This category accounts for toxic substances (carcinogenic and non-carcinogenic), those that lead to respiratory problems, those that generate ionizing radiation and those that deplete the ozone layer. The damage score is expressed in DALY (disability-adjusted life years).
- **Ecosystem Quality:** This category accounts for aquatic and terrestrial ecotoxicity impacts, land acidification and nitrification and land use. It is expressed as the fraction of species that will potentially disappear (*potentially disappeared fraction – PDF*) in a given area and over a certain time period (PDF*m²*year/kg).
- **Climate Change:** This category accounts for the global warming potential of each GHG based on the model of the International Panel on Climate Change (IPCC, 1996) in kilograms of carbon dioxide equivalent (kg CO_2 eq.) based on infrared radiative forcing. The GHG potentials are estimated over a 500-year time horizon.
- **Resources:** This category accounts for non-renewable energy resource use and minerals extraction, expressed in megajoules (MJ).

It should be noted that:

- These categories do not cover all the possible environmental impacts associated with human activities. Several types of impacts, including noise, odours and electromagnetic fields, are not examined in this analysis. In addition, water use is not considered by the current characterization models.
- **Aquatic Eutrophication and acidification:** These impacts are not taken into account by the damage indicators of the IMPACT 2002+ method (damage relating to ecosystem quality). These two midpoint indicators where therefore considered in conjunction with the damage indicators.
- No normalization of results was carried out with the exception of the results presented in relative form (as a %), in relation to the reference system. No weighting of the damage categories was performed. However, the impact-to-damage conversion factors include an implicit weighting described in the IMPACT 2002+ method.
- Life cycle impact assessment results present potential and not effective environmental impacts. They are relative expressions (to the functional unit namely) which do not predict the final impact or risk on the natural media, exceeding standards or safety margins.

As was done for the inventory, the SimaPro 7.2 software was used to calculate the potential impacts associated with the emissions inventoried. This software also classifies the elementary flows according to the various impact categories and calculates the results of damage indicators.

A second assessment based on the ReCiPe method (Goedkoop et al., 2009) was carried out in the sensitivity analysis in order to verify whether the variability of the characterization models had a significant effect on the conclusions and, therefore, to test the robustness of the results obtained based on IMPACT 2002+.

2.8 Interpretation

This last phase of the LCA provides an opportunity to discuss the results obtained following the LCIA and to place them in perspective. It includes a comparison of the UHI mitigation measures to the baseline scenario, on the basis of the LCA environmental data and of a qualitative analysis of the secondary functions.

Given the objective of the study and its target audience, the discussion of the results is presented in Chapter 3 in simplified terms. The conclusions are nonetheless based on a complete and in-depth analysis of the inventory data and the LCIA. This includes, specifically:

- Data quality assessment and contribution analysis;
- Consistency and completeness analysis;
- Sensitivity and scenario analyses;
- Uncertainty analyses.

The methodology used for data analysis and interpretation, such as data quality assessment, consistency and completeness checks, sensitivity analyses and the uncertainty analyses are summarized here. But first, a clarification is provided concerning the inventory analysis.

2.8.1 Inventory analysis

The inventory results in terms of quantities of materials and energy associated with each of the studied systems are not presented in the body of this report (in Appendix B, the list of elementary flows aggregated for each of the life cycles is presented for information purposes). An exhaustive input/output analysis generally does not improve the understanding of the issues. Indeed, the inventory results contain too much information and on their own do not allow conclusions to be drawn. In order for the analysis of the life cycle inventory to be relevant, it must be conducted in parallel with the impact assessments. Thus, in accordance with Standard ISO 14044, the LCIA presented and discussed in Chapter 3 constitutes the interpretation of the LCI results, with the goal of better understanding its environmental scope. A contribution analysis also serves to identify the inventory flows which give rise to the main impacts.

2.8.2 Data quality analysis

The reliability of the LCA results and conclusions depends on the quality of the inventory data used. It is therefore important to ensure that these data meet certain requirements specified in accordance with the study objective.

According to the ISO standard, the data quality requirements should at a minimum ensure the **validity** of the data, which in the present study is equivalent to their representativeness with respect to age, geographic origin and technological performance. The data used should therefore be representative of:

- The period defined by the functional unit, namely the year 2010 and the subsequent 30 years (see section 2.3);
- The geographic context in which the measures studied are implemented, namely large urban centres in Quebec (see section 2.3);
- The technological characteristics of the processes that they describe.

Although no particular method is currently prescribed by the ISO, two criteria that affect the quality of the inventory were chosen to evaluate the data:

- **Reliability:** concerns the data sources, acquisition methods and verification procedures. Data is considered reliable when it has been verified and measured in the field. This criterion refers mainly to the quantification of economic flows.
- **Representativeness:** deals with geographic and technological correlations. Do all the data reflect reality? Data are considered representative when the technology is directly related to the field of study. This criterion relates mainly to the choice of the processes used to model the system.

A more detailed description of the criteria and the assessment of data quality are provided in Appendix D.

Concurrently with the assessment of the quality of the data used, the contribution of the processes (i.e. to what extent the processes modelled with these data contribute to the overall impact of the systems studied) was estimated. Indeed, data of inferior quality may be quite acceptable in the case of a process whose contribution is minimal. However, good quality data are preferable for processes that have a significant impact on the study conclusions.

In the context of this study, the contribution analysis was limited to observing the relative importance of the various processes modelled with respect to the potential overall impact assessed for each of the four damage categories mentioned in section 2.7, as well as for the two midpoint categories not characterized in terms of damage.

2.8.3 Consistency and completeness

Throughout the study, attention was paid to ensuring that all systems are represented in a manner consistent with the goal and scope of the study. In addition, during data collection and modelling, boundaries, assumptions, methods and data were applied in a similar way to all systems. There is therefore **consistency** among the studied systems with regard to data sources, their precision and their technological, temporal and geographic representativeness. The system expansion approach is also identical for all of the assessed options.

Owing to the fact that the assessed measures do not all have the same secondary functions, it was not possible to compare them from a strict LCA standpoint. That is why they were compared to the baseline scenario. Moreover, as mentioned in subsection 2.2.2, from a practical standpoint (that of a private individual who wishes to make a change to his property for example), some measures are considered equivalent:

- Green roof and reflective roof;
- Reflective surface and permeable surface for a private driveway.

These options were therefore compared for the benefit of the readers (Chapter 3).

Completeness was assured thanks to an attentive definition of the system boundaries and by systematic use of the expansion rules. For data gaps, sensitivity analyses were carried out to verify the effect of the hypotheses and approximations used. A second LCIA method was also used to validate the impact assessment results.

2.8.4 Sensitivity analyses and scenario analyses

Several parameters used for the system modelling presented some degree of uncertainty, more particularly associated with the assumptions and the use of generic datasets. Results obtained are linked to these parameters and their uncertainty is transferred to the conclusions.

Based on the main contributors (processes/parameter)s identified by the contribution analysis, sensitivity analyses were carried out on the following parameters:

- **Lifespan of green roofs:** Some publications claim that installing a green roof may double the lifespan of a new elastomer membrane (Dunnett and Kingsbury, 2005). However, green roofs have not existed in their current form long enough to allow these statements to be corroborated by experience. A sensitivity analysis comparing several lifespans (10, 20, 25, 30, 40 and 50 years) was carried out to determine at what point the potential impacts of a green roof become “equivalent” to those of the reference roof. A scenario analysis comparing a lifespan of 25 years (equivalent to an elastomeric bitumen membrane without plant cover) is also presented with the results.
- **Lifespan of reflective roofs:** Roofs covered with elastomeric bitumen membranes have an average lifespan of 21 years in Quebec (Perrier, 2010). However, white roofs, owing to the fact that they do not overheat, have a longer lifespan than their black equivalent (Perrier, 2011). Since no precise reference was found, a lifespan of 25 years was assumed. A sensitivity analysis comparing several lifespans (10, 15, 20, 25 and 30 years) was carried out to determine at what point the potential impacts of a reflective roof become “equivalent” to those of the reference roof.

Scenario analyses, where the variable parameters depend on the choices of the property owner implementing the measure, were also carried out:

- **Use of chemical fertilizers:** These fertilizers contain metals which migrate into the soil and groundwater following application. For this reason, their potential impact assessed by the characterization models (and particularly those of the IMPACT 2002+ method for the “Ecosystem Quality” category) is often very high. The use of organic fertilizers (bone powder and mycorrhizae for example) could most likely reduce these potential impacts, but the generic data to model their use were not available. Consequently, scenarios comparing the use of chemical fertilizers to installation and maintenance WITHOUT any fertilizer were compared for all the measures concerned.
- **Quantity of water captured by soil humidification measures:** Rain gardens, infiltration trenches and dry wells can be used to capture both roof water and runoff from the parking area. For these three measures, two scenarios were therefore compared, considering only roof water and roof water combined with water from the parking area.
- **Maintenance of the reflective roof:** To conserve its reflectivity, a white roof must be regularly maintained, otherwise the build-up of dirt significantly affects its albedo. According to the manufacturer’s recommendation, a new layer of reflective coating must be applied every five years on elastomeric bitumen membranes (as modelled in the base case). A no-maintenance scenario was also analyzed to measure the importance of the reflective coating on the potential impacts of this type of roof.

- **Type of reflective roof:** Elastomeric bitumen membranes share the market with ethylene propylene diene monomer (EPDM) membranes, which are quite different in that they are installed cold, are smooth (therefore, can be maintained by annual washing/scrubbing), are fully recyclable at the end of their life and have lifespans of up to 50 years according to some sources. Two scenarios involving an EPDM membrane with annual washing and lifespans of 40 and 25 years were analyzed.

The list of scenario analyses carried out for each of the measures is presented in Table 2-4.

Table 2-4: Scenario analyses

Measure	Base case	Scenario analysis
1. Green roof	A. 45-year lifespan With initial chemical fertilization and subsequently as needed	B. 45 years, without fertilization
		C. 25 years, initial chemical fertilization and subsequently as needed (worst case)
2. Reflective roof	A. White elastomeric bitumen membrane 25-year lifespan Reflective coating applied initially and every 5 years	B. White elastomeric bitumen membrane, no maintenance
		C. White EPDM membrane, 40-year lifespan
		D. White EPDM membrane, 25-year lifespan
3. Green wall	A. Chemical fertilization the first year	B. Without fertilization
4. Planting arrangement	A. Chemical fertilization the first year	B. Without fertilization
		C. Annual chemical fertilization
5. Tree	A. Chemical fertilization the first year	B. Without fertilization
6. Reflective surface	A. 20-year lifespan	N/A
7. Permeable surface	A. 20-year lifespan	N/A
8. Rain garden	A. Capture of roof water only Chemical fertilization the first year	B. Capture of roof water AND runoff from the **parking area** Chemical fertilization the **first year**
		c. Capture of roof water **Annual** chemical fertilization
		D. Capture of roof water AND runoff from the **parking area** **Annual** chemical fertilization
9. Infiltration trench	A. Capture of roof water only	B. Capture of roof water AND runoff from the parking area
10. Dry well	A. Capture of roof water only	B. Capture of roof water AND runoff from the parking area

The scenario and sensitivity analyses are presented in Chapter 3, in combination with the results of each measure.

2.8.5 *Uncertainty analysis*

There are two types of uncertainty related to the LCA model:

- Inventory data uncertainty, assessed with a Monte-Carlo simulation;
- Characterization models uncertainty, which translate inventory into environmental impacts.

Monte Carlo analysis

A Monte Carlo uncertainty analysis was carried out using the SimaPro 7.2 software in order to test the robustness of the results. The simulation allows assessing how the variability embedded in inventory data spreads over final results. Hence, results become probabilistic. The analysis has been performed for 750 iteration steps.

Out of the thousands of individual elementary flows inventoried in the elementary processes of the scenarios studied, the very large majority were taken from the *ecoinvent* database. Most of these flows have a variability which takes the form of a *lognormal* distribution around the central value specified (and used in the deterministic calculations), characterized by its standard deviation. However, these variabilities were not determined statistically using concrete measurements, but estimated by using a *pedigree matrix* describing the quality of the data based on its source, method of collection and geographic, temporal and technological representativeness (Weidema and Suhr Wesnæs, 1996).

In the same way, the variability of most data collected was represented by a lognormal distribution, the standard deviation of which was estimated using this same pedigree matrix. Certain data were also associated with a uniform or triangular statistical distribution, bounded by minimum and maximum values obtained from the literature. In total, 69% of data had an associated statistical distribution.

The Monte Carlo simulation involves the subtraction of two systems that one wishes to compare. Hence, the results indicate the probability that one option has indicators higher than the other.

For this study, for each measure that had several implementation scenarios, the variants were compared. In the case of the roofs and parking areas, the measures assessed were compared to the baseline scenarios. Finally, for the options deemed comparable, the uncertainty analysis was also carried out on the difference between a green roof and a reflective roof and between a permeable surface and a reflective surface.

The results of the uncertainty analysis were considered during the analysis of the results of each measure, although this is not mentioned in the body of the text.

Uncertainty relating to the characterization models

Since this second form of uncertainty cannot be quantified by means of an statistical analysis, guidelines proposed by the authors of the IMPACT 2002+ method were followed (Humbert et al., 2009). These guidelines establish thresholds of significance for different impact categories, below which it is not possible to make any conclusions concerning the best environmental performance of one option over another:

- 10% in terms of climate change, non-renewable energy and resources consumption;
- 30% in terms of respiratory effects due to inorganic substances (human health), acidification and eutrophication;
- An order of magnitude in terms of toxicological and ecotoxicological effects.

However, these guidelines depend on the correlation between the systems compared; two similar systems having thresholds of significance below those presented above. The interpretation proposed in Chapter 3 therefore takes these various aspects into account. A difference of 30% was considered significant for the *Human Health* indicator when the systems compared were not correlated.

2.9 Critical review

Because the results of this study are intended to be used to support a comparative assertion disclosed to the public, a critical review had to be conducted by a panel of interested parties, i.e. a committee composed of an LCA expert and other stakeholders.

The critical review panel was composed of four members (Table 2-5).

Table 2-5: Members of the critical review Committee

Name	Organization	Involvement/Area of expertise
Gontran Bage	LVM	Review panel chair, LCA expert
Marie Dugué	Vinci Consultants	Specialist, stormwater management
Patrice Godin	Montréal Urban Ecology Centre	Specialist, green roofs
Marie-Claire Martineau	La Vie en Vert	Specialist, greening options

In accordance with Standards ISO 14040 and 14044 (2006a, b), the goal of the critical review process were to check if:

- the methods used by CIRAIG to carry out the LCA are:
  - consistent with the 14044 International Standards,
  - scientifically and technically valid,
  - the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations of CIRAIG reflect the limitations identified and the goal of the study,
- the study report is transparent and consistent.

The critical review process was carried out in five stages, during January and February 2011:

1. Review of the preliminary LCA study (Martineau, 2010) by all the committee members.
2. Correction of the report and clarification of the points raised by the reviewers in step 1;
3. Review of the final study report by all the committee members;
4. Correction and clarification of the points raised by the reviewers in step 3;
5. Submission of the revised final report to the commissioner of the study.

The reviewers' comments for step 1 and 3 were provided to CIRAIG in the form of review reports.

3 Results

Owing to the fact that the assessed measures do not all have equivalent functions, it is not possible, strictly speaking, to compare the options. Indeed, they do not necessarily have the same temperature-lowering effectiveness and do not all have the same secondary functions. In addition, some options take into account impacts avoided compared to the baseline scenario. For example, it is assumed that the option to install a green roof or a reflective roof is considered by a home owner only when the roof has to be replaced. In these specific cases, the green roof or reflective roof therefore replaces the new asphalt and gravel roof which would have otherwise been installed (thus avoiding the production, transport and landfilling of the component materials). The other options assessed do not consider this avoidance. The same is true for the installation of permeable or reflective pavement in a private driveway, which avoids the installation of asphalt pavement.

In order to make it easier to put the assessed measures into perspective, an initial qualitative analysis of their functional profile is first presented. The environmental analysis of the options follows, according to the four types of applications defined in section 2.2.

3.1 Qualitative analysis of the secondary functions

Following the bibliographic review, a list of the functions performed by the various UHI mitigation measures was drawn up. Table 3-1 presents these functions, in association with the assessed measures. It should be noted that two factors, namely the avoided energy consumption and the avoided water treatment (described in section 2.4) are also among the secondary functions of the assessed measures, but are not presented in Table 3-1 since they were quantified in the environmental assessment which follows.

Table 3-1: Functional profile of the assessed UHI mitigation measures, compared to the baseline scenario

	"The implementation, in 2010, and the continued application over a 30-year period of an individual urban heat island mitigation measure on a residential block of a large urban centre in the province of Quebec"	UHI mitigation measures									
		1	2	3	4	5	6	7	8	9	10
Functional profile	Reduction of the ambient temperature	+	+	+	+	+	+	+	+	+	+
	Reduction in drainage and flooding problems associated with sewer overloading	++		+	+	+		+	++	++	++
	Aquifer recharge			+	+	+		+	++	++	++
	Creation of wildlife habitat	+		+	+	+			+		
	Improved air quality	+		+	+	+			+		
	Improved water quality	+							+		
	Reduction in ambient noise	+		+	+	+			+		
	Beautification of urban neighbourhoods			+	+	+			+		

Légende

1	Green roof
2	Reflective roof
3	Green wall
4	Planting arrangement (border)
5	Tree
6	Reflective pavement / surface
7	Permeable pavement / surface
8	Rain garden
9	Infiltration trench
10	Dry well

++	Strong link between a function and a component
+	Link between a function and a component
	No significant link

Compared to the baseline situation, implementation of UHI mitigation measures can therefore have several beneficial effects, which are discussed below.

As can be seen from this table, while all the assessed measures serve to lower the ambient temperature (to varying degrees that are difficult to quantify), other functions are shared by only a few options.

3.1.1 Sewer overloading and aquifer recharge

Owing to the fact that they become saturated with water at the beginning of a downpour, during heavy precipitation, green roofs help reduce stress on the sewer system which, in many municipalities, is still a combined sanitary and stormwater sewer. The greening measures, the permeable surface and the soil humidification measures are all options that also reduce the volume of rainwater that ends up in the municipal sewers.

However, during extreme precipitation events, the volume of water that must be treated at water treatment plants increases, which reduces the effectiveness of treatment. When the volume of water entering the treatment plant is too high, the combined storm/wastewater may also be discharged directly into the river without first being treated. The retention of water by green roofs or the infiltration of runoff water into permeable areas can therefore reduce the stress on filtration plants and thus reduce contamination of watercourses. However, in order to achieve this effect, a sufficient number of systems must be installed in a given municipality.

All these options, with the exception of green roofs, also promote aquifer recharge, by facilitating infiltration of precipitation into the ground.

3.1.2 Creation of wildlife habitats and air quality

All the measures involving the addition of plants to the urban landscape are appreciated by small animals. In particular, green roofs and trees provide habitats for birds. Plants also filter the ambient air, which has the effect of improving air quality.

3.1.3 Water quality

Green roofs and rain gardens are two measures that have the effect of ensuring some degree of filtration of rainwater by plants. In the case of a green roof, the water that is not retained is directed to the sewer system. Rain gardens absorb some of the rainwater from the roof and runoff from the parking area. In particular, they help to filter oils, greases and nutrients carried by runoff.

3.1.4 Noise reduction and beautifying urban neighbourhoods

Finally, the implementation of greening measures helps to reduce city noise and make neighbourhoods more pleasant to live in. Even a green roof, often invisible from the street, can provide a pleasant landscape for neighbours on higher floors.

These distinctions must therefore be borne in mind when comparing the environmental impacts assessed by the LCA, since, although a particular measure may have more potential impacts in terms of the quantifiable indicators, it can also provide services that the other measures do not.

3.2 Presentation of the analyses compared to the baseline scenario

The first objective of the study was to individually compare the UHI mitigation measures to a baseline situation, which corresponds to the *status quo* (taking no action). To this end, the results of indicator results (*Human Health*, *Ecosystem Quality*, *Climate Change*, *Resources* and the two midpoint categories *Aquatic Acidification* and *Aquatic Eutrophication*) are presented for each studied measure.

These results include:

- An **environmental load**, which consists of the impacts potentially generated by the implementation and maintenance of the measures, and by the transport and landfilling of the materials after dismantling. It is illustrated as potential positive impacts.
- An env**ironmental benefit**, associated with the processes potentially avoided by the measure compared to the baseline situation. This can include avoided water treatment, avoided energy consumption or even the reference roof or parking areas which would have been installed, but which are replaced by the assessed measures. The benefit is presented in the form of potential negative impacts.

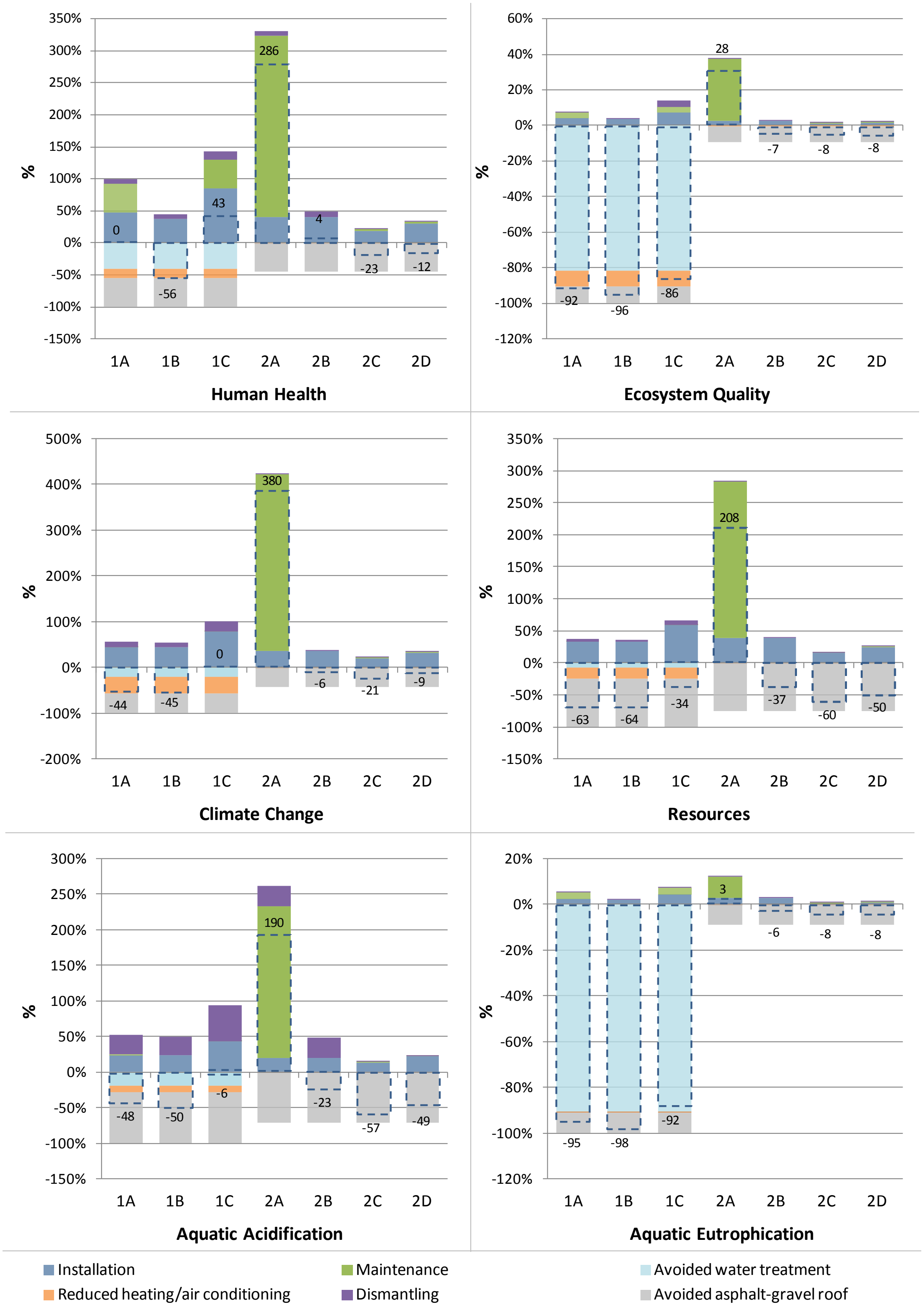
The difference between the total environmental load and the avoided impacts constitutes the **net potential impact (or net damage)**, illustrated in the graphs by boxes with dotted lines. A negative net result thus indicates that implementation of the measure represents an improvement compared to the baseline situation. Conversely, a positive result indicates that the measure represents more potential impacts/damage than the *status quo*.

It is important to point out that the environmental benefits such as heating savings associated with the installation of a green roof or the avoided water treatment by the measures which capture rainwater are uncertain assessments of potentially avoided impacts. The uncertainty associated with these benefits is sometimes significant, due to the fact that these are average estimates of factors that are highly influenced by the specifications and context of each installation (see section 3.7).

For this reason, the environmental results presented in the following sections are discussed by excluding and including the potential benefits. The various assessed scenarios are also discussed and the main processes contributing to the indicators are summarily described. It should be noted that the values are presented on a relative basis compared to the baseline scenario, which correspond to a 0% potential impact (and 100% corresponding to the score of the first measure compared).

3.3 Measures involving protection of the building envelope

Since green roofs and reflective roofs have the same function of protecting the building envelope and since both options are perceived as equivalent by a private individual wishing to replace the roof of his house, these measures were considered comparable from a practical perspective. Figure 3-1 therefore presents, for each indicator, the results associated with a green roof and with a reflective roof. Various lifespan and maintenance scenarios were analyzed for each. A second type of reflective membrane, a single EPDM layer, was also compared to the base model (multilayer elastomeric bitumen membrane).



1A. Green roof (45 years, chemical fertilization as needed)
1B. Green roof (45 years, no fertilization)
1C. Green roof (25 years, fertilization as needed- worst case)

2A. Elastomeric membrane (25 years, reflective coating every 5 years)
2B. Elastomeric membrane (25 years, no maintenance)
2C. White EPDM membrane (40 years, with annual washing)
2D. White EPDM membrane (25 years, with annual washing)

Figure 3-1: Comparison of a green roof and a reflective roof with the baseline scenario

The “maintenance” stage includes: fertilization in the case of a green roof, the addition of a layer of reflective coating every five years for the elastomeric bitumen membrane, and annual washing with soap and water for the EPDM membrane. Since EPDM membranes are very smooth, they can be washed easily to remove dirt, which reduces their reflectivity.In terms of **environmental loads**, we can see from these figures that:

- Not applying chemical fertilizers to a **green roof** improves the score of the *Human Health* and *Ecosystem Quality* indicators (1A and 1B), because of the avoided fertilizer emissions to water. If the roof water were to be captured by a system that promotes soil humidification, the *Ecosystem Quality* indicator would be further affected, owing to the avoided soil metal emissions.
- The membranes installed under the vegetation and the growing medium used to grow the plants share most of the environmental loads associated with the **installation of a green roof** (1A, 1B, 1C); the plants themselves have a moderate impact. When the lifespan of the roof is reduced from 45 years to 25 years, the potential impacts associated with the production, transport and landfilling of these materials at the end of their life increase proportionally.
- The **landfilling of materials** contributes significantly to the *Aquatic Acidification* indicator, as can be seen for green roofs (1A, 1B, 1C) and reflective elastomeric bitumen membranes (2A and 2B). EPDM membranes (2C, 2D) do not have this potential impact since they are entirely recyclable and were assumed to be recycled.
- **Maintenance of the reflective elastomeric bitumen membrane roof** contributes quite significantly to the scores for the majority of the indicators (*Human Health, Climate Change, Resources, Aquatic Acidification*). These potential impacts are due to the production of the reflective coating, which contains acrylic compounds and titanium dioxide.
- **Maintenance of the reflective roof with an EPDM membrane** (2C, 2D) by annual washing with soap and water has a negligible contribution to the environmental loads of this type of roof.
- For the **reflective roof**, the production and installation of the two compared membranes, namely elastomeric bitumen (2A, 2B) and EPDM (2C, 2D), have similar scores for all the indicators. However, the longer lifespan of the EPDM membrane (2C) reduces its environmental load proportionally.

In terms of the **environmental benefits:**

- These benefits include the avoided water treatment (maximum potential benefit for the green roof), the reduction in energy consumption associated with heating (for the green roof) and air conditioning (for all the roofs), and the avoided asphalt and gravel roof (baseline scenario), including installation and dismantling.
- If realized, the benefit associated with the **avoided water treatment** could entirely offset the environmental loads associated with the installation and dismantling of a green roof according to the *Ecosystem Quality* and *Aquatic Eutrophication* indicators and, to a lesser extent, the *Human Health* indicator (because of the chemicals used to treat the water, particularly sodium hydroxide).

- o Substituting a **multilayer asphalt and gravel roof** makes it possible to avoid potential impacts in all the assessed categories, not only because of the materials and energy for its installation, but also because of the transport and landfilling of the materials at the end of their life.
- o According to the assumptions and data used, the **air conditioning energy avoided by a white roof (regardless of type) and a green roof** is negligible over their life cycles. Notably, it is assumed that the reduction in air conditioning avoids the consumption of Quebec electricity, derived primarily from hydroelectric power, which has little potential impact on the assessed indicators.
- o It is difficult to estimate the reduction in **energy consumption associated with heating** as a result of the installation of a green roof. This reduction depends on various factors including the initial insulation of the roof and of the building envelope in general, as well as the building location. Based on collected data and assumptions used, the heating avoided by the green roof generates potential benefits particularly in the *Human Health, Ecosystem Quality, Climate Change and Resources* categories. This is due to the fact that natural gas or fuel oil are often used for residential heating. The production and combustion of these fossil fuels is thereby avoided.

When we consider instead the **net potential impacts**, we can see that:

- Considering all the potential benefits, installing a green roof is preferable to installing a standard asphalt and gravel roof for all the indicators, except *Human Health* (because of the production of the waterproof membrane, the growing medium and the use of chemical fertilizers).
- If we exclude fertilization and the benefits associated with the avoided water treatment and the reduction in energy consumption, a green roof is preferable to a standard asphalt and gravel roof for the *Resources* and *Ecosystem Quality* indicators, but becomes disadvantageous in terms of the *Climate Change* and *Human Health* indicators, since the potential impacts of the production of the growing medium and membranes exceed those of the reference roof.
- The addition of a reflective coating every five years makes a reflective roof less advantageous than the standard roof in all the assessed categories.
- An EPDM membrane has fewer potential impacts than an elastomeric bitumen membrane in all the categories assessed.
- Installing a reflective roof without maintenance (or with annual washing with soap and water only) is preferable to installing a standard asphalt and gravel roof for five out of six indicators. This results in a very slight increase for the *Human Health* indicator (associated with production of the membranes).

It should be pointed out that green roofs cannot be installed on all buildings. The structure of older buildings is often inadequate to support the additional weight represented by the water-soaked growing medium.

In general terms, we can conclude that…

For **roofs:**

- An extensive green roof or a reflective elastomeric bitumen membrane roof are generally preferable to an asphalt and gravel roof, when maintenance is reduced (i.e. without chemical fertilization or reflective coating).
- A membrane with the longest possible lifespan should be chosen, in order to reduce the potential impacts associated with the production, transport and landfilling of the materials.
- In the case of an extensive green roof, it is preferable not to use chemical fertilizers on a regular basis, particularly if the roof water is diverted to a rainwater capture system, in order to prevent discharge of metals into water and soil.
- In the case of reflective roofs, it is preferable to opt for a membrane that can be maintained by simple washing with soap and water. The application of a reflective coating on a regular basis has significant potential impacts on the environment. If a white elastomeric bitumen membrane is installed, it is therefore better to allow it to lose its reflectivity than to apply layers of reflective product.
- White EPDM membranes have fewer potential impacts than asphalt and gravel roofs owing to their longer lifespan, ease of maintenance and the fact that they are fully recyclable at the end of their life.

In addition to these factors, it should be borne in mind that an extensive green roof is able to retain light rain and delay the arrival of water in sewers during heavy rains, which helps reduce stress on the sewer system and water treatment plants. The plants on the roof also improve air quality and reduce ambient noise, in addition to creating habitat for birds.

However, green roofs cannot be installed everywhere. The structure of older buildings is often inadequate to support the additional weight represented by the water-soaked growing medium.

3.4 Measures involving planting around buildings

Figure 3-2, Figure 3-3 and Figure 3-4 present, respectively, the results for a green wall, a planting arrangement and a tree, according to several fertilization scenarios. It will be recalled that the results cannot be compared, since they are calculated in relative terms compared to the first scenario (A) of each measure.

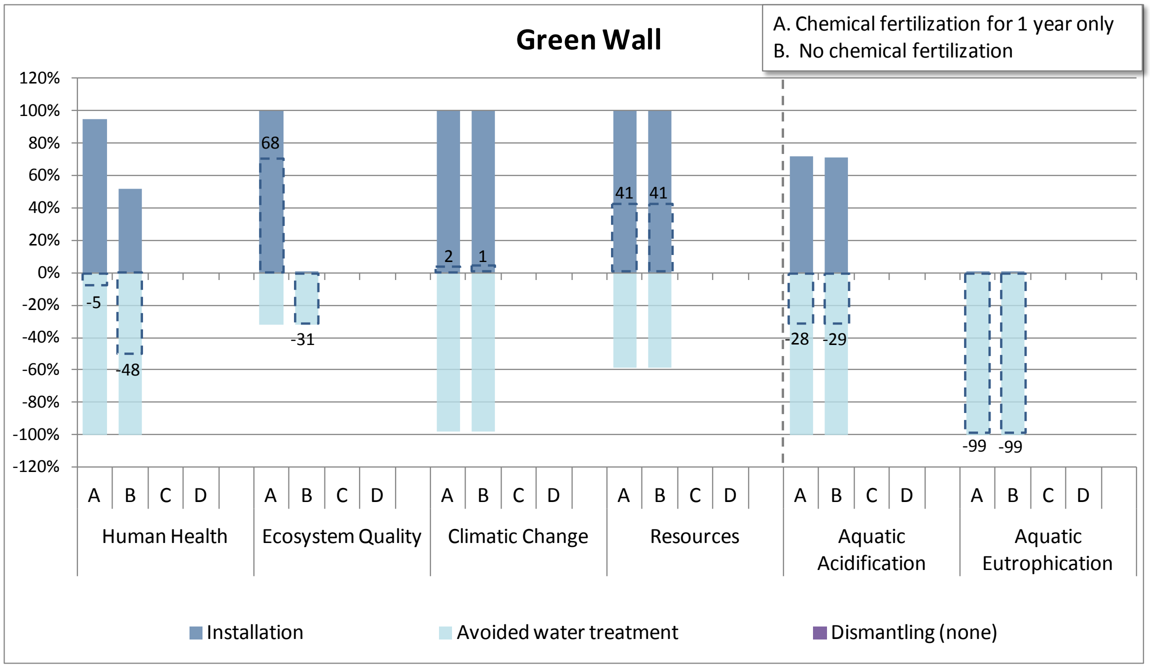


Figure 3-2: Comparison of a green wall with the baseline scenario

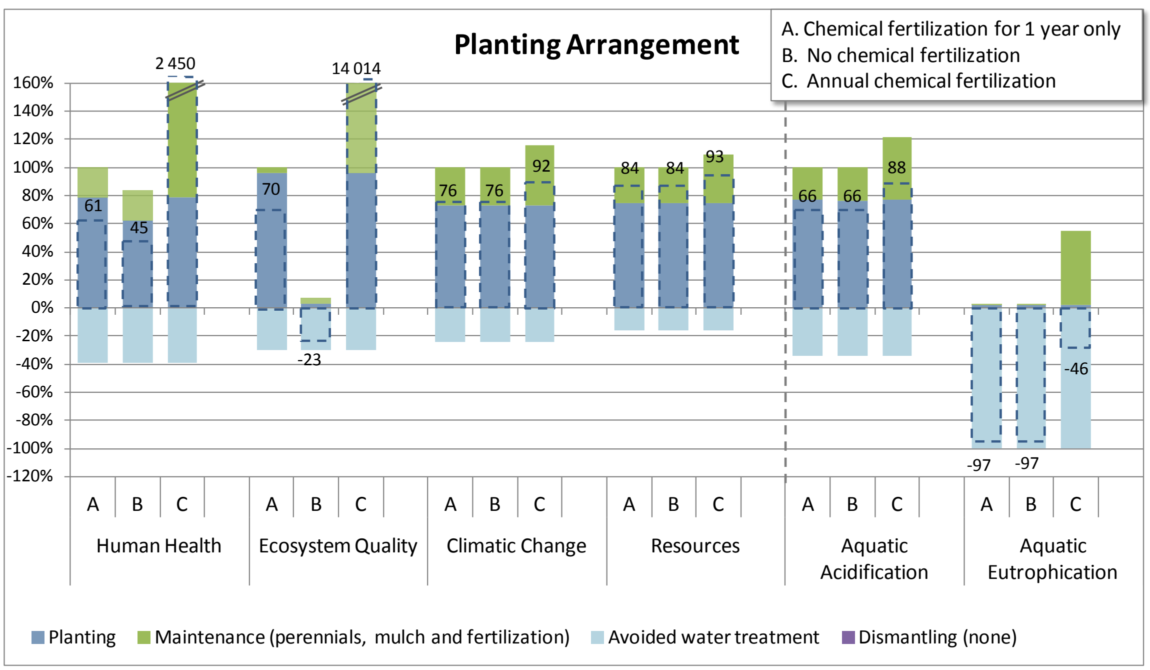


Figure 3-3: Comparison of a planting arrangement with the baseline scenario

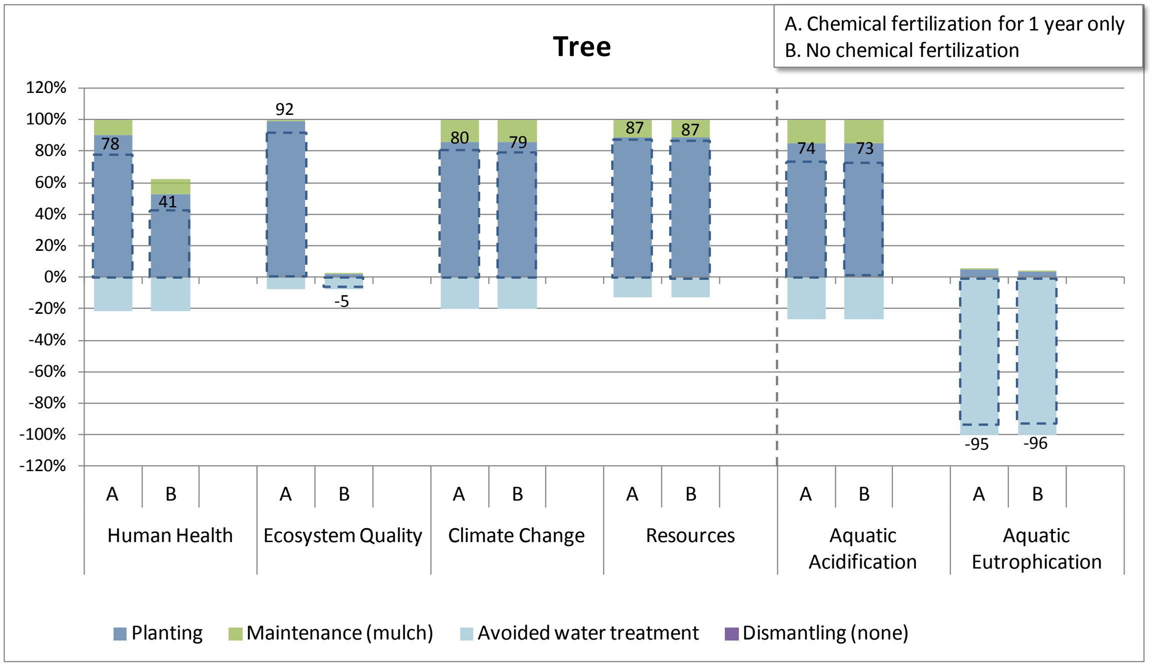


Figure 3-4: Comparison of tree planting with the baseline scenario

In terms of **environmental loads,** we can see from these figures that:

- Not applying chemical fertilizers (at the time of planting only or on a regular basis) improves the *Human Health* and *Ecosystem Quality* indicators, because of the soil metal emissions avoided. The IMPACT 2002+ characterization method used is extremely sensitive to this type of emission and tends to overestimate its potential impact. Nonetheless, the validation of the results by another assessment method, ReCiPe, confirmed that regular use of chemical fertilizers (several times a year) generates significant potential impacts.
- The added black earth and the transport and landfilling of the excavated soil are also included in the potential impacts of these measures. Re-use of the earth on site, when possible, would further reduce the *Climate Change, Resources* and *Human Health* indicators associated with the combustion of fuel for transport.
- Mulch and water have a negligible contribution to the indicators.

In terms of the **environmental benefits,** the avoided water treatment indicated constitutes the maximum potential benefit. Where applicable, it could entirely offset the environmental loads according to several indicators in the case of a green wall. For planting arrangements and trees, the avoided water treatment particularly reduces the *Ecosystem Quality* and *Aquatic Eutrophication* indicators (because of the chemicals used to treat the water, particularly sodium hydroxide).

The **net potential impact** of the considered indicators shows that the greening measures do not, on the whole, result in a reduction of the potential environmental impacts compared to the baseline situation. In fact, planting and maintaining vegetation requires a consumption of materials and energy that is not entirely offset by the measurable benefits. However, it is important to bear in mind that this type of measure offers several non-quantified secondary functions, such as an improvement in air quality, a reduction in city noise and neighbourhood beautification, to name but a few.

Moreover, the potential impacts and benefits associated with the end-of-life management of the greening measures were not taken into account in the analysis. In the case of green walls and planting arrangements, there is not really any end-of-life management attributable to the measure. The plants can simply be removed and re-used, composted or thrown away, which does not involve any impact given the “biogenic” nature of the materials.

The case of a tree is more complex. Both its lifespan and end-of-life management are extremely context-dependent. Once cut down, the wood from the tree can be re-used in various ways, ranging from firewood for the fireplace, feedstock for a biofuel plant, to composting to mulch. The potential benefits associated with the life cycle of a tree would be very different depending on the assumed end-of-life re-use. Since the purpose of the study was not to compare the energy and material recovery options of the wood, dismantling was therefore excluded. However, it should be borne in mind that some of the benefits associated with the re-use of the tree at the end of its existence are subtracted from the environmental loads.

In general terms, we can conclude that…

For **greening measures**, it is preferable:

- Whenever possible, to keep the existing earth rather than disposing of it off-site and having new earth delivered.
- To reduce the use of chemical fertilizers insofar as possible.

In addition, greening areas that were originally paved increases the quantity of water that infiltrates into the soil, which facilitates natural aquifer recharge and reduces the problems of sewer overloading. Plants improve air quality and reduce ambient noise, in addition to creating habitat for birds and beautifying urban neighbourhoods.

However, it should be noted that when a tree is planted, its foliage does not provide significant shade. It will become an effective UHI mitigation measure only when it reaches maturity.

3.5 Measures involving environmentally-friendly paving materials/surfaces for parking areas

Figure 3-5 presents the results for the two types of parking surfaces assessed, reflective and permeable.

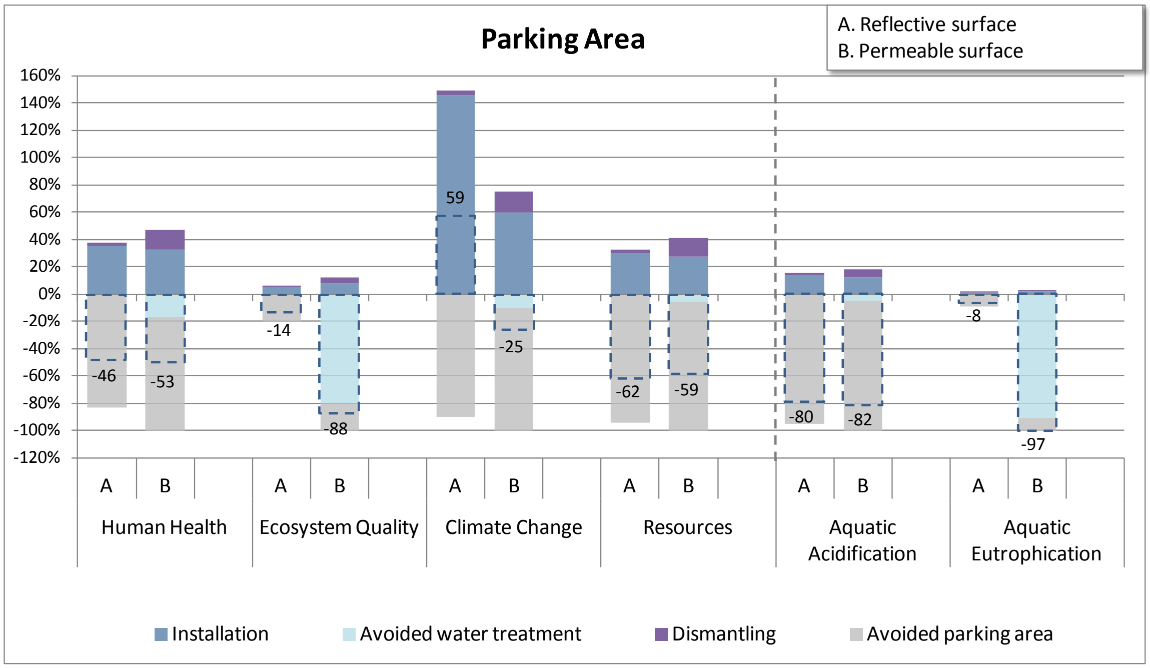


Figure 3-5: Comparison of a parking area with the baseline scenario

In terms of **environmental loads,** we can see from this figure that:

- The impacts of installing a reflective surface on a parking area are determined mainly by the production of the cement used to "resurface" the old asphalt. The effect is particularly significant in terms of the *Climate Change* indicator because of the CO_2 emissions at the cement plant, but also for the *Human Health* and *Resources* indicators.
- For the permeable surface, cement is also one of the ingredients used to manufacture the paving stones and the same indicators are affected, but the production and transport of the gravel used for the various foundation layers also account for more than a third of the score of the assessed indicators.
- Dismantling, including the machinery for excavating the surface, transport and landfilling in a dry disposal site (DDS), makes a moderate contribution to the life cycles of both options.

In terms of the **environmental benefits:**

- These benefits are the avoided water treatment (maximum potential benefit for the permeable surface) and the avoided asphalt parking area (baseline scenario), including installation and dismantling.

- If it was real, the benefit associated with the avoided water treatment could entirely offset the environmental loads associated with the installation and dismantling of the permeable surface according to the *Ecosystem Quality* and *Aquatic Eutrophication* indicators (because of the chemicals used to treat the water, particularly sodium hydroxide).
- Substituting an asphalt-paved parking area makes it possible to avoid potential impacts in all the assessed categories, not only because of the materials and energy for its installation, but also because of the transport and landfilling of the debris at the end of its life.

When we consider the **net potential impacts**, we can see that:

- Since a **reflective surface** generally results in fewer environmental loads than the baseline scenario, it is preferable to an asphalt-paved parking area for all the indicators except *Climate Change* (since the production of Portland cement generates greater impacts than asphalt).
- A **permeable surface** is preferable to an asphalt-paved parking area in all the impact/damage categories assessed, since the installation and end-of-life management of the permeable paving stones presents less environmental loads than an asphalt-paved parking area, whether or not the avoided water treatment is considered.
- According to the considered indicators, a permeable surface is preferable to a reflective surface for the *Climate Change* indicator. If the maximum benefit associated with the avoided water treatment is applied, the *Ecosystem Quality* and *Aquatic Eutrophication* indicators also favour the permeable surface. For the other categories, the uncertainty is too great to draw a conclusion in favour of either option.

Moreover, the runoff from the parking area that penetrates into the soil may contain pollutants such as oils and greases which can contaminate the soil and the water table. The potential impact associated with these substances was not assessed.

It should be noted that there are other types of permeable and reflective parking areas (crushed gravel, plastic grids that allow grass to grow, reflective paving stones, etc.). These options were not assessed, but it appears from the results obtained that it is generally advantageous to replace an asphalt driveway with options that require less materials (to produce, transport and landfill at the end of their life) and energy for installation and dismantling.

In general terms, we can conclude that…

For **parking areas:**

- Permeable concrete paving stones have fewer potential impacts than an asphalt-paved parking area.
- Permeable concrete paving stones also have more benefits compared to reflective surfaces ("resurfacing" with Portland cement) for the *Climate Change* indicator.
- Other types of permeable and reflective surfaces are available on the market. Although they were not analyzed, it appears that it is generally advantageous to replace an asphalt driveway with options that require less materials and energy.

Installing a permeable surface on areas that were originally paved increases the quantity of water that infiltrates into the soil, which facilitates natural aquifer recharge and reduces the problems of sewer overloading. However, this water may contain pollutants that can eventually contaminate soil and groundwater with oils and greases, and the potential impact associated with these substances was not assessed.

3.6 Soil humidification measures

Because they are not entirely equivalent, the various soil humidification measures were not compared. However, each was assessed according to two installation scenarios: the first whereby only the roof water is captured and the second combined with runoff from the parking area.

Figure 3-6 presents the results for a rain garden, according to several scenarios of fertilization and quantity of water captured.

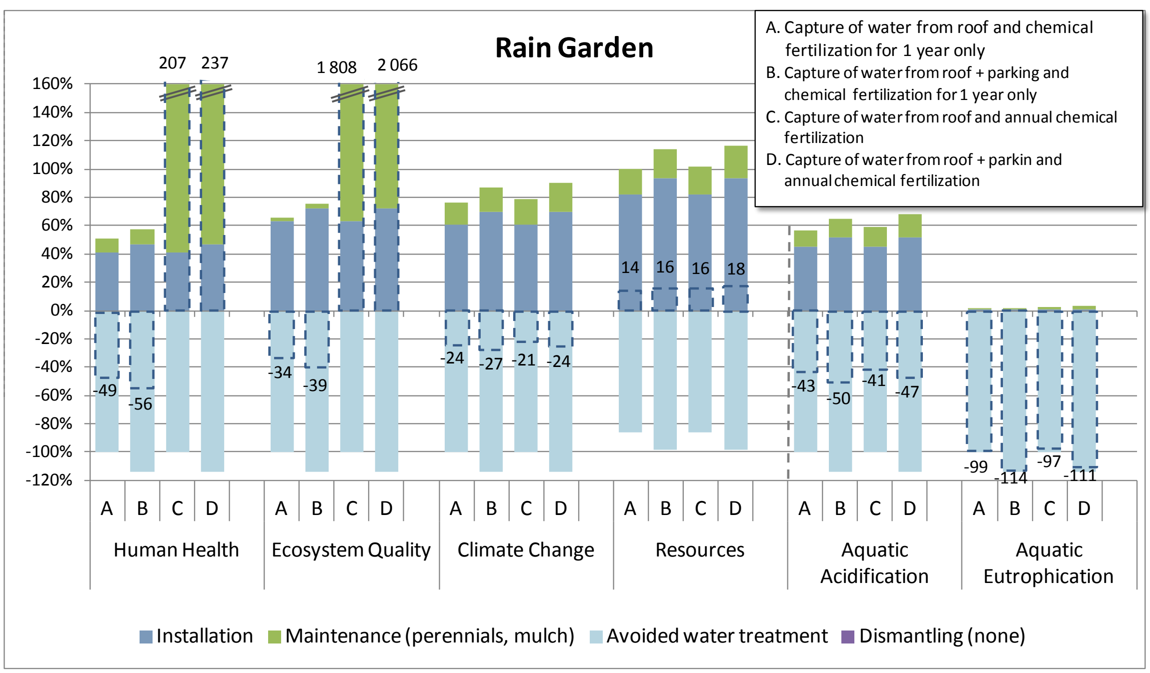


Figure 3-6: Comparison of a rain garden with the baseline scenario

In terms of **environmental loads**, we can see from this figure that:

- Not applying chemical fertilizers on an annual basis in the **rain garden** significantly reduces the scores of the *Human Health* and *Ecosystem Quality* indicators, because of the avoided soil metal emissions. As mentioned earlier, the IMPACT 2002+ characterization method used is extremely sensitive to this type of emission and tends to overestimate its potential impact. Nonetheless, the validation of the results by another assessment method, ReCiPe, confirms that regular use of chemical fertilizers generates significant potential impacts.
- The black earth, the transport and landfilling of the excavated soil are also taken into account in the potential impacts of this measure. Re-use of the earth on site, when possible, would further reduce the *Climate Change, Resource* and *Human Health* indicators associated with the combustion of fuel for transport.
- Mulch and water have a negligible contribution to the indicators, while the production of perennials represents a fairly limited impact.
- Capturing runoff from the parking area in addition to roof water requires that the garden be larger, which proportionally increases the quantity of earth excavated, black earth transported, etc.
- The potential impacts associated with the end-of-life management of the rain garden were not taken into account, since there is not really any end-of-life management attributable to the measure. The plants can simply be removed and re-used, composted or thrown away, which does not involve an impact given the "biogenic" nature of the materials. It is assumed that contaminants from the runoff water have not become concentrated in the plant tissues.

In terms of the **environmental benefits,** the avoided water treatment represents a maximum potential benefit. It is proportional to the increase in the quantity of water captured by the rain garden.

Considering the net potential impacts, we can see that:

- Opting for a rain garden that captures water from the parking area in addition to water from the roof does not appear to be a major factor. In fact, the environmental loads and the benefits associated with the avoided water treatment are proportional to the volume of water captured. It is therefore not possible to draw any general conclusions concerning the benefits of capturing a larger or smaller volume of water.
- Excluding the scenarios involving annual fertilization and considering the maximum potential benefits of the avoided water treatment, the installation of a rain garden represents an advantage relative to the *status quo* for almost all the indicators. However, the uncertainty associated with the avoided water treatment does not enable us to conclude that the environmental loads attributable to the installation and maintenance of the rain garden would be effectively offset.

As is the case for the greening measures discussed above, planting and maintaining vegetation requires a consumption of materials and energy that is not entirely offset by the measurable benefits. However, it is important to bear in mind that this type of measure offers several non-quantified secondary functions, such as an improvement in air quality, water filtration, a reduction in city noise and neighbourhood beautification, to name but a few.

Figure 3-7 and Figure 3-8 present the results, respectively, for infiltration trenches and dry wells, according to two scenarios of quantity of water captured. It will be recalled that the results cannot be compared, since they are calculated in relative terms compared to the first scenario (A) of each measure.

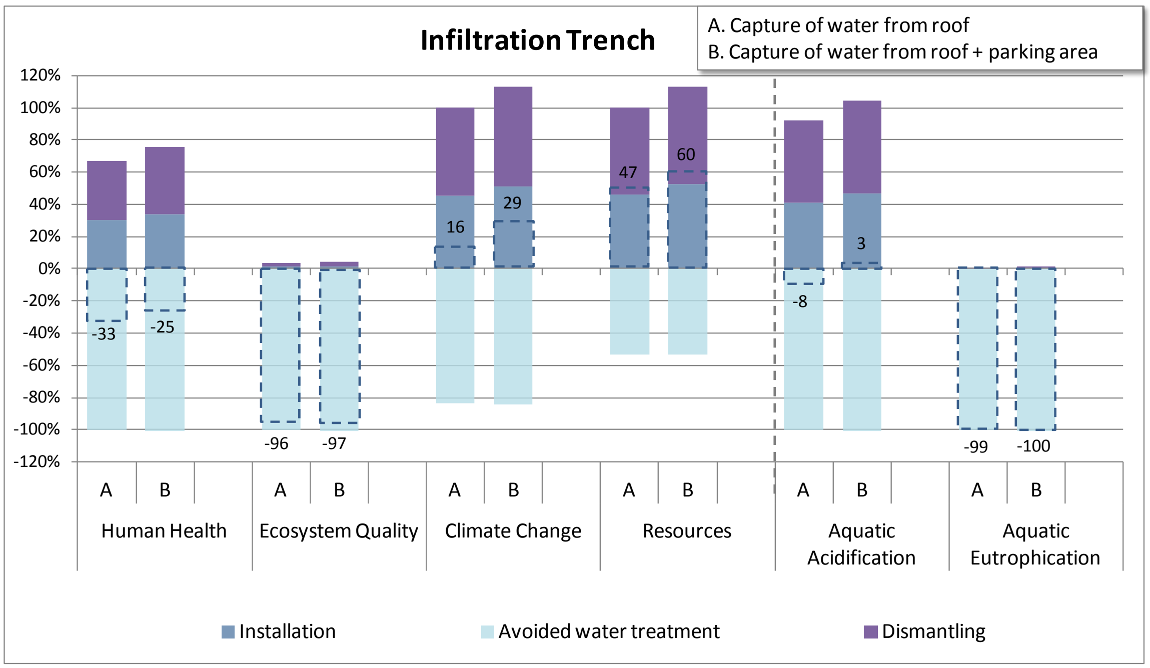


Figure 3-7: Comparison of an infiltration trench compared to the baseline scenario

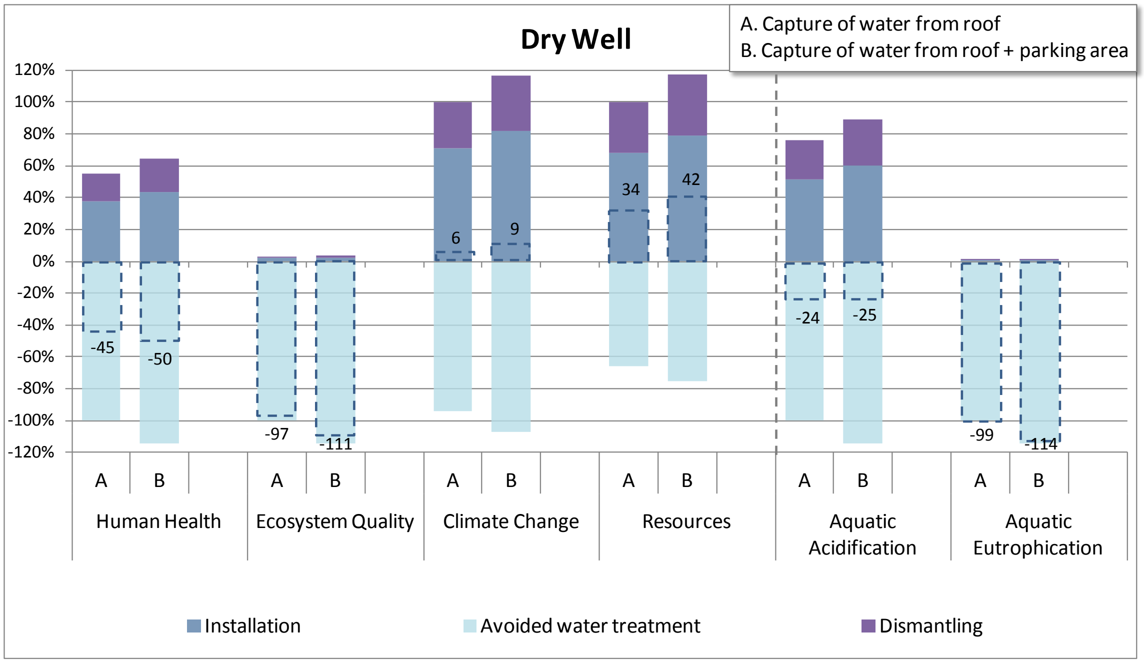


Figure 3-8: Comparison of a dry well compared to the baseline scenario

In terms of **environmental loads**, we can see from these figures that:

- The gravel used and the transport and landfilling of the excavated soil account for the potential impacts of these two measures.
- In the case of a dry well, the aluminum cover also contributes to all the damage and impact categories assessed.
- The transport and landfilling of the gravel in a DDS account for approximately half of all the damage/impacts attributable to the dismantling of these constructed measures. The other half is due to the transport of black earth to fill the holes. In cases where the subsequent use of the site permits, leaving the gravel in place and covering it with the chosen surface would significantly reduce the score of all the assessed indicators.

In terms of the **environmental benefits,** the volume of water diverted from the sewer system, which otherwise would have been channelled to the municipal wastewater treatment plant, represents a maximum potential benefit, which is proportional to the increase in the quantity of water captured by the trench and the dry well and applies to all the assessed indicators.

Considering the net potential impacts, we can see that:

- If the maximum benefit associated with the avoided water treatment is applied, the *Human Health, Ecosystem Quality and Aquatic Eutrophication* indicators are favourable to the installation of a trench or of a dry well compared to the *status quo*.

- o Opting for a dry well which can capture and retain water from the parking area in addition to water from the roof does not appear to be a major factor. In fact, the difference between the two installation scenarios is not great enough to prefer one option over the other given the uncertainty. There is therefore no reason to prefer the capture of larger volumes of water on the basis of these results.
- o In the case of the infiltration trench, it appears preferable to reduce the size of the trench and capture less water, since the loads associated with its installation and dismantling exceed the potential benefit attributable to the avoided water treatment. The only parameter is volume. The origin of the water (from the roof or from the parking) does not influence the results, since the pollutant load of the water was not taken into consideration during the modelling.

Implementing a constructed rainwater capture and retention measure therefore requires a consumption of materials and energy which is not entirely offset by the measurable benefits. However, it is important to bear in mind that this type of measure offers non-quantified secondary functions, such as recharge of the water table and reducing the problem of sewer overloading.

One last non-quantified factor must also be considered concerning the capture of the water from a parking area, namely the fact that this runoff may contain pollutants, oils and greases, which can eventually contaminate soils and aquifers. The rain garden plants can filter out some of these contaminants, but the potential impact and benefit associated with these substances were not quantified.

In general terms, we can conclude that…

For **rain gardens,** it is preferable to:

- Keep the existing earth rather than disposing of it off-site and having new earth delivered.
- Reduce the use of chemical fertilizers insofar as possible.

In addition, as it is the case for planting arrangements, plants improve air quality, water filtration and reduce ambient noise, in addition to creating habitat for birds and beautifying urban neighbourhoods.

For constructed measures such as **dry wells and infiltration trenches:**

- The soil excavated during installation should if possible be re-used at the same site or nearby in order to reduce the impacts associated with its transport and landfilling.
- The dismantling of these structures at the end of their life contributes to nearly half of their potential impacts. In cases where the subsequent use of the site permits, leaving the gravel in place and covering it with the chosen surface would significantly improve the environmental performance of these measures by reducing the transport and landfilling of gravel and by avoiding the transport of earth to fill the hole.

Finally, for all the soil humidification measures, capturing runoff increases the quantity of water that infiltrates into the soil, which facilitates natural aquifer recharge and reduces the problems of sewer overloading. However, runoff from the parking area may contain pollutants, oils and greases, which can eventually contaminate the soil and aquifers. The rain garden substrate can filter out some of these contaminants, but the potential impact and benefit associated with these substances were not quantified.

3.7 Inventory data quality

The results concerning the inventory data quality are summarized in Appendix D of this report.

The results of this analysis show that the majority of the stages and processes modelled used good-quality data (deemed sufficiently representative for the case studied). None of the data were rated as very good quality, not having undergone a detailed verification by experts in the field. However, the information sources used were chosen based on their representativeness of the Quebec context and age.

Certain data rated as medium or low quality are still acceptable, since their impact on the system is minor and having higher quality data would not change the results. This is the case of the processes associated with growing plants in a greenhouse, the air conditioning energy avoided by green and reflective roofs, the propane for installation of the elastomeric bitumen membranes, the mulch, the potable water for irrigating the plants, as well as the machinery used to implement certain measures.

However, the processes that make a significant or very significant potential contribution to the systems were in most cases modelled using good-quality data – since an effort was made to obtain the required data. Some of these processes nonetheless had to be modelled using generic European data, since Quebec data did not exist or were not found; they consequently represent a limitation and reduce the certainty with which the conclusions can be drawn.

The main data that represent a limitation are associated with the following processes/ parameters:

- **Fertilization:** The modelling of the actual emissions into the environment (soil and water) is complex since the potential impacts of the fertilizers are in large part related to the fate of the metals in the soil, and therefore depend on the specific characteristics of the site where the fertilizer is spread. The current characterization models overestimate the potential damage to the *Human Health* and *Ecosystem Quality* indicators. For all the measures involving fertilization, scenario analyses with and without use of chemical fertilizers were therefore carried out.
- **Reduced heating associated with the installation of a green roof**: It is difficult to estimate the energy savings on an average basis for residential buildings in urban Quebec, since these savings depend on several specific parameters (the insulation of the roof and of the rest of the building envelope and the geographic location, for example). Several assumptions, which are however considered conservative, were therefore used to calculate the reduction in energy consumption of the buildings after installation of a

green roof. In order to measure the effect, the analysis of the results is discussed by including and excluding this potential benefit.

- In the case of the **water treatment avoided** by the measures that capture rainwater, all of the following factors affect the assessment of the avoided impact:
  - The sanitary and storm sewer must be combined. In areas where rainwater is handled by a separate system, the water is not sent to the water treatment plant, but is discharged directly into the river (therefore no avoided treatment).
  - During extreme rain events, the sewer system does not have sufficient capacity to allow all the water captured to be directed to the water treatment plant. A portion of the combined stormwater/wastewater is therefore discharged directly into the receiving watercourses for a short period of time (which reduces the avoided water treatment).
  - The baseline situation considers that the surface is initially asphalt-paved (or impermeable to the natural infiltration of rainwater). In cases where a greening measure or precipitation capture measure is implemented in an area that already allows the water to percolate toward the water table, the avoided water treatment is reduced or even cancelled.
  - The data used to represent the water treatment is from a Swiss source. The treatment process may therefore not be representative of the type of treatments used in major Quebec cities.

In order to measure the effect, the analysis of the results is discussed by including and excluding this potential benefit.

- **Landfilling of soil and materials in a dry disposal site (DDS) or landfill site:** Generic European data were used since Quebec data were unavailable and given the great complexity of modelling the emissions and potential impacts attributable to the landfilling of materials. Caution should therefore be exercised regarding the results concerning landfilling.

3.8 Sensitivity analyses

In addition to the scenario analyses carried out for each UHI mitigation measure assessed, three separate sensitivity analyses were performed.

3.8.1 Impact assessments with the ReCiPe method

As mentioned previously, the LCIA was carried out with a second method, ReCiPe (Goedkoop et al., 2009) in order to verify whether the variability of the characterization models had a significant influence on the conclusions and, therefore, to test the robustness of the results obtained using IMPACT 2002+.

With respect to the main contributors, the results obtained with the ReCiPe method (H) generally confirm those obtained with the IMPACT 2002+ method, and the trends were the same for the various indicators assessed.

However, the ReCiPe method (H) yields somewhat different results owing to the different way it models potential impacts. It appears that:

- The potential benefit from the avoided water treatment is not as great according to this method.
- The potential impact of fertilization on the *Human Health* and *Ecosystem Quality* indicators is less pronounced.
- Growing trees in a nursery generates a benefit in terms of the *Ecosystem Quality* indicator, since it makes it possible to create and maintain a wooded area. This advantage, not considered by IMPACT 2002+, means that planting a tree becomes more favourable than the baseline scenario for this indicator, regardless of whether or not fertilization is used.

The results obtained with the ReCiPe method in terms of *Climate Change* and *Resources* are similar to the results obtained with the IMPACT 2002+ method. In addition, when several scenarios are compared, there is no reversal of the conclusions.

On the whole, the sensitivity analysis with the ReCiPe (H) LCIA method therefore confirms the results of the study and attests to their robustness.

3.8.2 Lifespan of a green roof

A sensitivity analysis comparing several lifespans (10, 20, 25, 30, 40 and 50 years) was carried out to determine at what point the potential impacts of a green roof become "equivalent" to those of the reference roof.

It appears that a green roof is preferable to a standard asphalt and gravel roof as soon as its lifespan exceeds 25 years, for all the indicators, except when there is regular fertilization. In this case, the *Human Health* damage category (assessed according to IMPACT 2002+) indicates that it would take 45 years for a green roof to become preferable to a standard roof. It should be recalled that this indicator of the IMPACT 2002+ method is particularly sensitive to fertilizer emissions.

Since the lifespan of an elastomeric bitumen membrane is approximately 25 years and since the plant layer has the effect of prolonging its longevity, it appears that green roofs always have lower impacts than standard roofs. In order for the conclusions obtained in this study to be reversed, the lifespan of a green roof would have to be shorter than that of an unprotected elastomeric bitumen membrane, which seems somewhat unrealistic.

3.8.3 Lifespan of a reflective roof

A sensitivity analysis comparing several lifespans (10, 15, 20, 25 and 30 years) was carried out to determine at what point the potential impacts of a reflective elastomeric bitumen membrane roof become "equivalent" to those of the reference roof.

When we consider maintenance involving the addition of a layer of reflective surface every five years, the reflective roof always has more potential impacts than the reference roof, regardless of its lifespan.

Without maintenance, the elastomeric bitumen membrane roof is preferable when its lifespan exceeds:

- 28 years for the *Human Health* indicator
- < 10 years for the *Ecosystem Quality* indicator

- 22 years for the *Climate Change* indicator
- 14 years for the *Resources* indicator
- 17 years for the *Aquatic Acidification* indicator, and
- < 10 years for the *Aquatic Eutrophication* indicator.

Hence, if a white elastomeric bitumen membrane roof has a lifespan of 21 years (the average for coloured elastomer membranes), rather than the 25 years assumed, the *Climate Change* indicator would be favourable to the standard roof rather than to the reflective roof. The conclusions concerning the other categories assessed would remain unchanged.

The same exercise was carried out with the EPDM membrane. It appears that as soon as this type of roof has a lifespan exceeding 20 years, it has fewer potential impacts than the reference roof, all indicators combined. Assuming a lifespan of 40 years (considered realistic given the observations of existing roofs) or of 25 years (conservative hypothesis) therefore does not modify the conclusions of the analysis.

3.9 Applications and limitations of the LCA

This LCA aims to inform the public and the organizations working in the field about the potential impacts and environmental benefits associated with various UHI mitigation measures throughout their life cycle. It also aims to enable the INSPQ to enhance its assessment of urban heat island mitigation measures by incorporating aspects of environmental performance based on the "life cycle" approach. The analysis was carried out from a comparative perspective relative to a baseline scenario where no UHI mitigation measures are taken. Any conclusions drawn from this study outside of its original context should be avoided.

The study results may be used to:

- Individually compare the UHI mitigation measures to a baseline situation, which corresponds to the *status quo* (i.e., taking no action);
- Identify the key parameters that reduce the impacts or increase the potential benefits of the measures assessed;
- Draw up, using the calculation table, a preliminary classification of the UHI mitigation scenarios (involving combinations of various individual measures) according to their potential overall environmental performance.

However, the main limitations which may be noted concern:

- The fact that the measures assessed do not have equivalent functions. It is therefore not possible, strictly speaking, to compare the options. Indeed, they do not necessarily have the same temperature-lowering effectiveness and do not all involve the same secondary functions.
- There are sometimes several variants or models of the same measure. The assessment was conducted by selecting one option for each measure (except in the case of the reflective roof where a second variant was analyzed). The modelling data are therefore not necessarily representative of all of the cases.
- The results and conclusions are only applicable to residential-scale UHI mitigation measures. Commercial and institutional projects require different design criteria which would necessitate an adaptation of the systems analyzed.

- Not all the options take into account the same avoided impacts relative to the baseline scenario.
- The completeness and validity of the inventory data used, as illustrated by the data quality assessment (section 3.7), in particular, the large number of estimates and assumptions concerning the dimensions and the choices made to model the options. For several of the assessed options, there is some variability concerning the specific conditions associated with the implementation site.
  - The completeness and validity of the impact assessment method used, namely because it does not cover all chemicals inventoried, nor all environmental impacts associated with human activities. Specifically:
    - The impact categories "cancer", "non-cancer" and "Ecotoxicity" are not measures of the risk associated with systems under study. Since the various emissions are aggregated in time and space to create an inventory in which a single stream is associated with each of the listed substances (i.e. the total mass emitted by all processes that produce it), it is not possible to know the place nor the timing of emissions and, therefore, identify the quantity to which a given region is exposed.
    - The potential impacts of fertilizer use are in large part associated with the fate of the metals in the soils. However, toxic emission assessment models used to characterize the metals have been "adapted" from models developed for the characterization of organic compounds. They do not take into account the speciation of the compounds, which are dependent of the specific environmental conditions at the emission site (all metals are considered 100% bioavailable). Thus, the potential impact of metals emitted to soil is currently overestimated for the “terrestrial/aquatic ecotoxicity" and the "human toxicity cancer/non cancer" categories.
    - The interpretation of the characterization results can only be based on the results obtained, that is to say substances for which a characterization factor exists in the method database. These characterization factors convert the inventoried elementary flows into midpoint and endpoint units, but several elementary flows could not be converted into impact scores since no characterization factor was available. These flows have therefore not been considered during the evaluation phase of potential impacts.
    - Unlike the environmental risk assessment conducted in a regulatory context, which uses a conservative approach, LCA seeks to provide the best possible estimate (Udo de Haes et al., 2002). The LCIA tries to represent the most probable case, i.e. that the models (of transport and fate of contaminants in the environment and of toxic effects on biological receptors) do not attempt to maximize exposure and environmental damage (the worst case scenario approach).

Finally, LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

3.10 Use of the results

One of the goals of this study was also to rank, if possible, certain comparable measures according to their potential overall environmental performance and to permit the comparison of UHI mitigation projects (involving combinations of various individual measures).

3.10.1 Ranking of the measures

The wide range of functions of the assessed UHI mitigation measures make it impossible to rank all the options according to their environmental performance. In addition, based on the results obtained, it is not possible to rank the measures belonging to the same type of application. Indeed, depending on the specific conditions (lifespan, type of maintenance, use of fertilizers, etc.), the results can lead to the same measures being ranked differently. A ranking of the measures without consideration of these variabilities would therefore almost certainly lead to erroneous or questionable decisions.

3.10.2 Comparison of UHI mitigation projects

In cases where the assumptions formulated are applicable (see the list in Appendix B), it is possible for decision-makers to compare different implementation scenarios of measures that they consider equivalent in terms of heat reduction, since the results are linear.

Table 3-2 presents the results of the damage and impact indicators obtained with the LCIA IMPACT 2002+ method for each of the measures on an individual basis. These results are provided in absolute values compared to the baseline situation (whose measured impact would be zero). The options for which the indicators are less than zero (grey-shaded boxes) indicate an environmental benefit compared to the baseline scenario.

Given the significant uncertainty associated with the water treatment avoided by the measures which promote infiltration of precipitation in the soil, it was decided to assume 50% of the potential benefit estimated in the calculation table which follows. For the rest, the hypotheses presented in Appendix B were used.

Use of the calculation table

For example, to compare the planting of five trees with a green wall (7.6 m long), it is sufficient to multiply the tree indicator results by five. If the wall is longer or shorter, it is possible to adjust the results by a rule of three. The same is true for all the greening measures for which the basis of assessment is surface area.

The potential impacts of the roofs and parking areas whose areas differ from the reference values (100 m² and 14.3 m², respectively) will also be modified proportionally. Only the soil humidification measures are a little more difficult to adjust. Indeed, they were modelled based on the assumption of capturing the water from a 100 m² roof, with or without runoff from a parking area. However, the quantity of water absorbed is not directly proportional to the size of the installation or to the quantity of construction materials used. In cases where the goal is to compare humidification measures (rain garden, trench or dry wells) of very different dimensions from those modelled here, it may be necessary to recalculate the potential impacts using the data specified.

Finally, it is essential to bear in mind that not all the measures have the same functions and that, in some cases, avoided impacts were considered (standard asphalt and gravel roof, asphalt-paved parking …).

Table 3-2: Basis of comparison for determining the implementation scenarios of UHI mitigation measures

UHI mitigation measures		Indicator scores - IMPACT 2002+ method					
		HH	EQ	CC	R	AA	AE
		(DALY)	(PDF.m².an)	(kg CO_2 éq.)	(MJ)	(kg SO_2 éq.)	(kg PO_4 éq.)
1. Extensive green roof, 100 m²	With chemical fertilization every 2 years	6,36E-04	-4,58E+03	-1,14E+03	-7,31E+04	-1,21E+01	-3,22E+00
	Whitout chemical fertilization	-1,12E-03	-4,91E+03	-1,18E+03	-7,36E+04	-1,28E+01	-3,43E+00
2. Reflective roof, 100 m²	Elastomeric bitumen membrane, coating every 5 years	9,02E-03	2,51E+03	1,29E+04	2,55E+05	6,00E+01	2,22E-01
	Elastomeric bitumen membrane, no maintenance	1,26E-04	-6,03E+02	-1,82E+02	-4,50E+04	-7,28E+00	-3,93E-01
	EPDM membrane, annual washing with soap	-7,38E-04	-7,31E+02	-7,20E+02	-7,30E+04	-1,80E+01	-5,25E-01
3. Green wall	With initial chemical fertilization	3,14E-05	1,03E+03	2,00E+01	5,71E+02	2,30E-01	3,39E-03
	Whitout chemical fertilization	1,43E-06	-1,84E+02	1,98E+01	5,69E+02	2,28E-01	2,29E-03
4. Planting arrangement	With initial chemical fertilization	9,63E-04	7,32E+03	9,24E+02	1,83E+04	5,11E+00	-9,86E-01
	With annual chemical fertilization	3,06E-02	1,21E+06	1,09E+03	2,01E+04	6,46E+00	9,47E-02
	Whitout chemical fertilization	7,66E-04	-6,99E+02	9,23E+02	1,83E+04	5,10E+00	-9,93E-01
5. Tree	With initial chemical fertilization	7,50E-05	1,27E+03	4,50E+01	9,30E+02	2,77E-01	-3,79E-02
	Whitout chemical fertilization	4,34E-05	-1,78E+01	4,48E+01	9,28E+02	2,75E-01	-3,90E-02
6. Reflective surface		-7,23E-04	-2,70E+02	8,25E+02	-2,03E+04	-2,14E+01	-1,09E-01
7. Permeable surface		-7,02E-04	-9,03E+02	-2,76E+02	-1,84E+04	-2,13E+01	-6,89E-01
8. **Rain garden, without chemical fertilization**	Capture of water from roof (100 m²)	-1,83E-04	-5,94E+03	3,32E+02	1,03E+04	6,96E-01	-5,21E+00
	Capture of water from roof and parking area (115 m²)	1,59E-05	9,47E+03	8,83E+02	1,70E+04	5,43E+00	6,05E-02
9. Infiltration trench	Capture of water from roof (100 m²)	4,00E-04	-6,24E+03	9,05E+02	2,22E+04	4,57E+00	-5,33E+00
	Capture of water from roof and parking area (115 m²)	6,00E-04	-6,24E+03	1,11E+03	2,61E+04	5,85E+00	-5,37E+00
10. Dry well	Capture of water from roof (100 m²)	9,49E-05	-4,89E+03	5,71E+02	1,27E+04	2,20E+00	-4,15E+00
	Capture of water from roof and parking area (115 m²)	1,36E-04	-5,58E+03	6,80E+02	1,50E+04	2,70E+00	-4,75E+00

4 Conclusion

The goal of this study is to better inform the public and the organizations working in the field about the impacts and potential environmental benefits represented by various UHI mitigation measures throughout their life cycle.

In all, ten options were analyzed. All are aimed at individuals who may wish to make modifications to their home or their private property. They were modelled by documenting their consumption of materials and energy and by quantifying their environmental emissions relative to a baseline scenario in which no UHI mitigation measures are taken.

It should be recalled that assessing the effectiveness of the measures was not the objective of the analysis. Their temperature reduction potential was therefore not considered. The results provide an initial assessment of the measures on an individual basis (planting a tree, installing a green roof, etc.).

Following the assessment of the measures using the basic assumption and the results of the sensitivity analyses, certain conclusions and recommendations were formulated for the four types of applications that have common functionalities, i.e. the measures involving: 1) protection of the building envelope (roofs); 2) planting around buildings; 3) parking area and 4) soil humidification by rainwater capture and retention. Insofar as possible, the non-quantifiable functions of the options were also taken into consideration. The conclusions were focused on the practical aspects, so as to provide guidance for choosing, implementing and maintaining a UHI mitigation measure.

In conclusion, it should be noted that the assessment of urban heat island mitigation measures is a complex task, given the number of social, environmental and economic aspects involved. Several parameters, such as the quality of life of residents, and integration into the landscape, are elements that are not easily quantifiable, but which must nonetheless be taken into account. In this context, the LCA is not sufficient to decide which of a range of measures is the best, but it does help provide a better understanding of the impacts associated with the various options and, consequently, permits better informed decision-making.

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Appendix A:
Life Cycle Assessment (LCA) Methodology

APPENDIX A:
LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

TABLE OF CONTENTS

Life cycle assessment (LCA) methodology is regulated by the International Organisation for Standardisation (ISO), and, more specifically, by the ISO 14 040 standard. An introduction to the LCA methodology has been provided in the report. The following sections present certain LCA terms and their definitions and the main methodological aspects of the method's four phases.

A.1 Terms and definitions

Attribute-driven life cycle assessment (LCA-A): Assessment that aims to attribute to a product system the fair share of the impacts for which it is responsible.

Characterization factor: Factor based on a characterization model that is used to convert the life cycle inventory results into a common indicator category unit.

Consequence-driven life cycle assessment (LCA-C): Assessment that aims to analyze the consequences of a product system (or of a decision that impacts this system) on other systems.

Consistency check: Process begun before the conclusions are drawn and which makes it possible to verify that the hypotheses, methods and data are applied consistently throughout the study and remain in keeping with the objectives and scope of the study.

Completeness check: Process to verify whether the information in the previous phases of the life cycle is sufficient enough to draw conclusion that are in keeping with the objectives and scope of the study.

Critical review: Process to ensure the consistency between a life cycle assessment and the principles and requirements of the international standards that regulate life cycle assessment.

Elementary flow: Material or energy that enters the studied system and which was taken from the environment without previous transformation by man or the material or energy that exits the studied system and which is emitted into the environment without any subsequent transformation by man.

Elementary process: Smallest part of the life cycle inventory that is taken into account and for which input and output data is quantified.

Emissions: Emissions released into the air, water and soil.

Energy flow: Input or output of an elementary process of a product system expressed in energy units.

Functional unit: Quantified performance of a product system meant to be used as a reference unit in a life cycle assessment.

Impact category: Category that represents the environmental points to which the result of the life cycle inventory are assigned**.**

Impact category indicator: Quantifiable representation of an impact category (note: it is also sometimes referred to as *indicator category*).

Input: Product, material or energy flow entering an elementary process (note: the products and materials include raw materials, intermediate products and co-products).

Intermediary flow: Product, material or energy flow that impacts the elementary processes of the product system studied.

Life cycle assessment (LCA): Compilation and assessment of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle.

Life cycle impact assessment (LCIA): Phase of the life cycle assessment that aims to understand and assess the extent and significance of the potential environmental impacts of the product system throughout its life cycle.

Life cycle interpretation: Life cycle assessment phase during which the results of the inventory or impact assessment (or both) are assessed in light of the objectives and scope of the study so as to establish conclusions and recommendations.

Life cycle inventory (LCI): Life cycle assessment phase that involves input and output compilation and quantification for a given product system throughout its life cycle.

Output: Outgoing product, material or energy of an elementary process (note: the products and materials include the raw materials, intermediate products, co-products and emissions).

Process: All of the correlated or interactive activities that transform the inputs into outputs.

Product flows: Input or output of one product system into another.

Product system: All of the elementary processes, including the elementary and product flows, that fulfill one or several of the defined functions and which serve as a model for a product's life cycle.

Raw material: Raw or secondary material used to manufacture a product.

Reference flow: Measure of the outputs of the processes of a given system that are necessary to carry out the function as it is expressed in the functional unit**.**

Results audit: Part of the interpretation phase of the life cycle that establishes the level of certainty of the life cycle assessment results (note: the audit includes the completeness, sensitivity and consistency checks and all other forms of validation that may be required, in keeping with the objectives and scope of the study).

Sensitivity analysis: Systematic procedure to estimate the effects of the method and data choices on the results of the study.

Sensitivity check: Process to verify if the information obtained from a sensitivity analysis is reliable enough to establish conclusions and formulate recommendations.

System boundary: Set of criteria that specify which elementary processes are included in the product system.

Uncertainty analysis: Systematic procedure that makes it possible to research and quantify the uncertainty that the cumulated effects of the imprecision of the model, uncertainty of the inputs and variability of the data introduce into the life cycle inventory results.

A.2 LCA Phase I: Defining the objectives and scope of the study

The first phase of the LCA consists in defining the objectives and scope of the study to determine its rationale and the methods that will be used to reach these objectives (i.e., the study model that defines the methodological framework that the subsequent phases of the LCA must conform to).

The application and target audience must also be clearly determined, since these factors will set the depth and breadth of the study.

As stipulated by ISO, LCA are carried out by honing the models that describe the key elements of the physical systems. The product system[1] represents all of the human activities considered in the study. The impact assessment is based on the models (environmental mechanisms) that link the environmental interventions of these activities and their potential environmental effects.

ISO defines a **product system** as all of the elementary processes linked by the matter and energy flows that fulfill one or several functions. The focus of the LCA is characterized by its functions and not only in terms of its final products. This makes it possible to compare products that do not have the same functional performance per product unit (e.g.: a one-time use Styrofoam cup and a ceramic cup used more than once) because the quantification of the functional performance by the **functional unit** creates a reference based on which the compared inputs and outputs are mathematically standardized (e.g.: drinking two cups of coffee per day during one year). The specificity of the functional unit is the starting point at which the boundaries of the product system are defined because they determine the elementary processes that must be included in order to fulfill the function. The more precise the functional unit, the more restrictive the system boundaries will be.

An **elementary process** (or unit process) is defined by ISO as the smallest part of the product system for which data is collected (i.e., it can represent a specific chemical process or an entire factory that includes many sub-processes). An elementary process is characterized by its inputs and outputs. If the elementary process represents more than one sub-process, then its inputs and outputs are aggregated.

ISO stipulates that the elementary processes are linked to natural ecosystems (or ecospheres) by **elementary flows** and to economic systems (or technospheres – the part of the ecosphere that was transformed through human activities) by **product flows** (Figure A-1). There are also **intermediate product flows** between the processes of the studied system. The elementary flows are therefore taken directly from the environment or emitted directly into the environment and contribute to the impact categories, while the product flows (matter, energy or service including the co-products, sub-products and waste) are used to determine the intensity of the modeled processes.

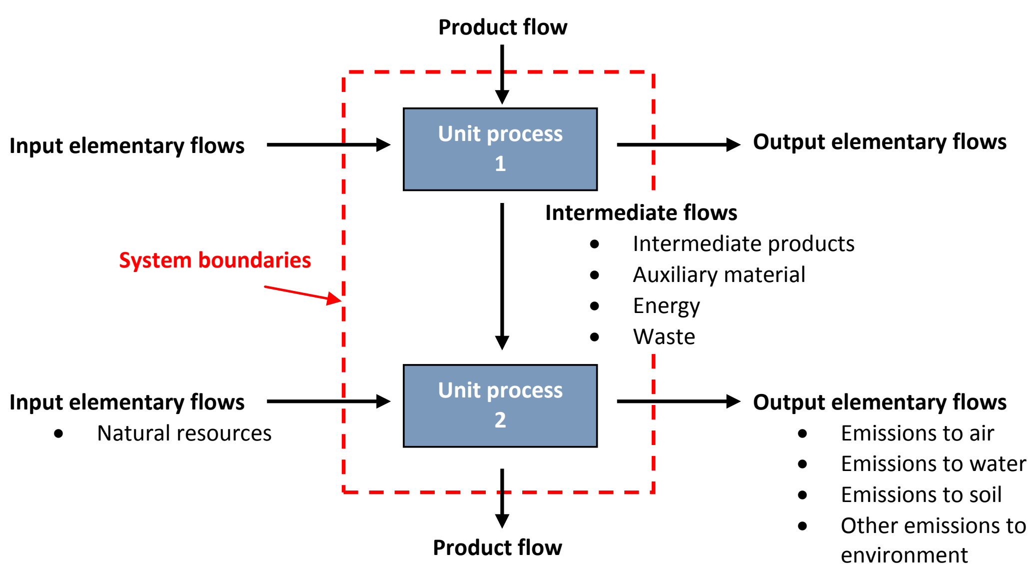

Figure A-1: Boundaries and elementary processes of a product system.

[1] The term *product*, when used alone, includes product systems and service systems.

Using a flow chart that illustrates the elementary processes and their interrelations (materials and energy flows) makes it possible to follow up on the product system boundaries.

According to ISO, it is best to model the product system so that the inputs and outputs at the boundaries are elementary flows. In many cases, however, time, resources and data are insufficient to conduct a complete study. Decisions must then be made on the elementary processes and flows[2] that should be initially included in the study. ISO also stipulates that it is not necessary to quantify the inputs and outputs that will have little impact on the broad conclusions of the study and suggests flow inclusion criteria (e.g.: contributions over a given threshold to the mass or energy balances or environmental relevance).

The list of all of the elementary flows and processes to be modeled can be adjusted when new information is acquired and the decisions that lead to these system boundary modifications must be clearly presented.

Once the list of the elementary processes included in the product system is complete and in order to build the system inventory and continue the assessment of the potential impacts, the relevant process data (i.e., the inputs and outputs) must be collected. However, prior to this collection, criteria pertaining to the data's quality (time, geographic and technological boundaries, precision and completeness), source (specific or generic), type (measured, calculated or estimated), nature (deterministic or probabilistic) and level of aggregation must be determined so as to remain focussed on the objectives of the study.

A.3 LCA Phase II: Inventory assessment

The second phase of the LCA, life cycle inventory assessment (LCIA), consists in quantifying the elementary flows that cross the product system boundaries.

The calculation process used to complete the inventory is presented in Figure A-2.

[2] Because the quantified elementary flows are the inputs of the impact assessment, the choice of impacts will affect the choice of elementary flows to follow.

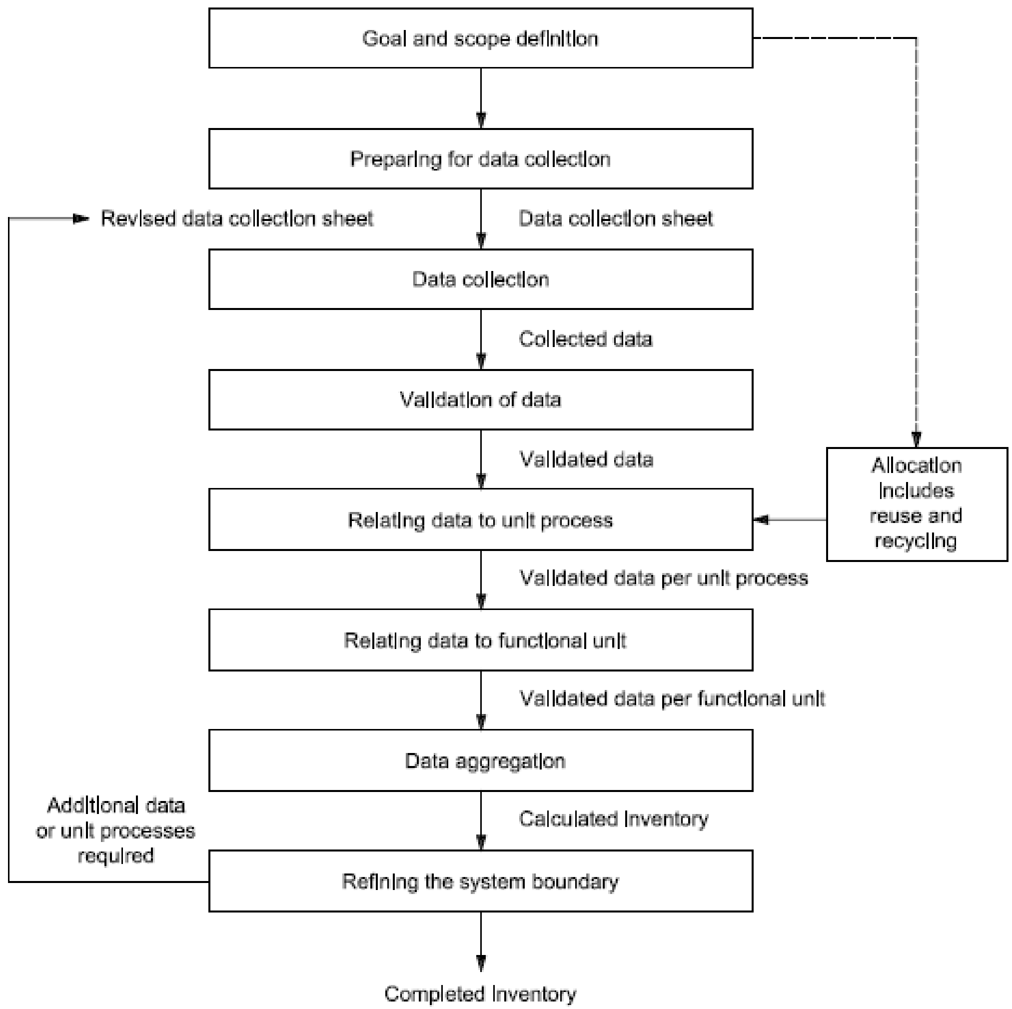

Figure A-2: Inventory calculation.
(from ISO 14 044, 2006)

A.3.1 Data category descriptions

The data used in the LCIA can be classified according to its source (specific or generic), type (measured, calculated or estimated), nature (deterministic or probabilistic) or level of aggregation.

A.3.1.1 Classification based on source

Specific or primary data

Specific data is collected from the installations that are linked to the elementary processes included within the boundaries of the system. The analyst overseeing data collection has direct access to the data during collection or a direct control over the collection process (i.e., the method used). Unless it is to characterize the installations included in the study, this type of data is not recommended because it lacks representativeness. It should be used only if 1) no other data source is available or 2) a sufficient number of installations in the same industrial sector provide data with which it is then possible to calculate representative industrial averages (which can then be used as generic data in other studies).

Generic or secondary data

Generic data is obtained from published sources (i.e., commercial databases, specialized literature). The analyst does not have access to the data during collection. Sufficient metadata[3] to provide information on the collection method or data variability is not usually available.

A.3.1.2 Classification based on type

Measured data

The measured data is from real installations and gathered through a monitoring program or random sampling. It could therefore be possible to obtain information on the variability and distribution of the data.

Calculated data

The calculated data is taken from the models in order to represent the processes or phenomena. Its quality therefore depends on the validity of the models. The data can be validated by or supplemented with measured data.

Estimated data

The estimated data includes information based on professional judgement or rules of thumb. It is only used when no other type of data is available.

A.3.1.3 Classification based on nature

Deterministic data

The deterministic data is represented by discrete values (i.e., measures, calculation results or estimates) for each of the characterized parameters (flows). It is therefore impossible to know the precision and variability of the reported data. .

Probabilistic data

The probabilistic data is represented by value ranges or probability distribution functions (e.g.: triangular, normal, lognormal) for each of the characterized parameters (flows). They therefore account for the imprecision and variability of a parameter and make it possible, in the interpretation phase, to eventually assess the uncertainty of the results obtained during the inventory and impact assessment phases.

A.3.1.4 Classification based on the level of aggregation

The level of aggregation of the data refers to the number of elementary processes that are represented by a same datum. When completely disaggregated, the data for a specific life cycle phase or product system is available for each individual process included in the phase or system. This same data can also be completely aggregated into a single datum that describes the phase of the system considered (all of the elementary flows of a same substances are summed up in a single flow). There is therefore information loss when the level of aggregation is increased because it is then no longer possible to know the individual contribution of each of the aggregated elementary flows. It is sometimes difficult to establish the level of aggregation (and the list of the aggregated processes) of the generic data in commercial databases.

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[3] Information with the inventory data and which provides facts on the data itself (e.g.: its origin, the collection method used and the boundaries of the elementary process being described).

A.3.2 Data collection

Depending on the complexity of the products studied (i.e., the number and nature of the elementary processes included within the boundaries), the amount of data to be collected is often quite large. Using commercial inventory databases eases the process by providing data on several elementary processes (e.g.: materials and energy production, transport). These databases are mainly European and are therefore not representative of the Canadian context. They can, however, be adapted to the Canadian context if the data is sufficient disaggregated and if the information needed to do so is available[4]. The methodology used for data collection must be clearly presented.

A.3.3 Data validation

The data collected for each of the elementary flows can be validated by 1) assessing the data based on the quality criteria established when defining the objectives and scope of the study and 2) carrying out mass or energy balances or comparative assessments of the emission factors. If obvious irregularities are determined, alternative data that meets with the previously established criteria is required.

The availability and quality of the relevant data (e.g.: data deficiencies, generic rather than specific averages) will limit the exactitude of the LCA. Specific North American inventory data is currently missing and this will affect the results of studies carried out in Canada.

The lack of a uniform documentation format[5], which can sometimes result in only a small amount of documentation for commercial inventory data, can also hinder data collection and validation, making it difficult to assess the data's quality and ability to meet the set criteria.

ISO stipulates that treating missing and forgotten data usually brings about a justified *non-zero* data value, a *zero* data value if it is justified or a value calculated based on the communicated values from the elementary processes that rely on a similar technology.

A.3.4 Linking the data and the elementary process

Once the inputs and outputs of each elementary process have been determined, they are quantified based on a reference flow established for each of the processes (e.g.: 1 kg or material or 1 MJ of energy). ISO states that if an elementary process has more than one product (e.g.: an oil refinery produces a mix of commercial petroleum hydrocarbons) or input (e.g.: a landfill site receives municipal waste made up of different products) or if it recycles the intermediate products or raw materials waste, the materials and energy flows and their environmental emissions must then be allocated to different co-products or co-inputs according to the rules set out when the objectives and scope were defined. ISO also suggests a series of principles and processes to follow when making these allocations.

The ISO allocation rules are listed below in order of importance.

1. It is best to avoid allocation whenever possible by:
   - Subdividing the multifunctional processes into two or more sub-processes (when certain sub-processes are specific to only one of the co-products);

[4] Production data on certain materials in Europe may refer to other transport, energy or materials production processes (e.g.: for intermediate or auxiliary products). The data that describes these other elementary processes can be replaced with data that described these same processes, if available, from a source that is more specific to the Canadian or North American contexts, thus increasing the geographic representativeness of the European data.

[5] This type of format would create a level of documentation that is sufficient and uniform enough for the generic data from commercial inventory databases. ISO 14 048 (2002) is a step in the right direction.

- Broadening the boundaries so as to include the functions of the other systems (potentially) substituted by the co-products (and by allocating an environmental credit that is equal to the avoided impact of the substituted functions to the system being studied).

2. When it is impossible to avoid allocation, it is best to divide the input and output flows of the multifunctional processes between the various co-products so as to reflect the underlying physical relationships (e.g.: mass or energy).

3. When a physical relationship cannot be established, it is best to distribute the inputs and outputs so as to reflect their other relationships (e.g.: the economic value of the co-products).

A.3.5 Linking the data and the functional unit

The inputs and outputs of all of the elementary processes included in the product system are then standardized according to the functional unit and aggregated. ISO states that the level of aggregation must be sufficient enough to meet the objectives of the study and that the data categories (i.e.: individual or grouped substances of natural resources or environmental emissions) should only be aggregated of they refer to equivalent substances or similar environmental impacts.

A.4 LCA Phase III: Impact assessment

The third phase of the LCA, the life cycle impact assessment (LCIA) consists in interpreting the results of the life cycle inventory assessment of the product system so as to understand their environmental significance.

Inventory assessment makes it possible to quantify the exchanges between the product system and the environment. Depending on the study, the information will be of greater or lesser importance (i.e., certain natural resource and emissions flows into the environment can be quantified) and its practical use can become unclear. During the LCIA phase, certain environmental issues, called impact categories, are modeled and category indicators are used to condense and explain the results.

ISO stipulates that the methodological framework of the LCIA contains mandatory and optional elements (Figure A-3).

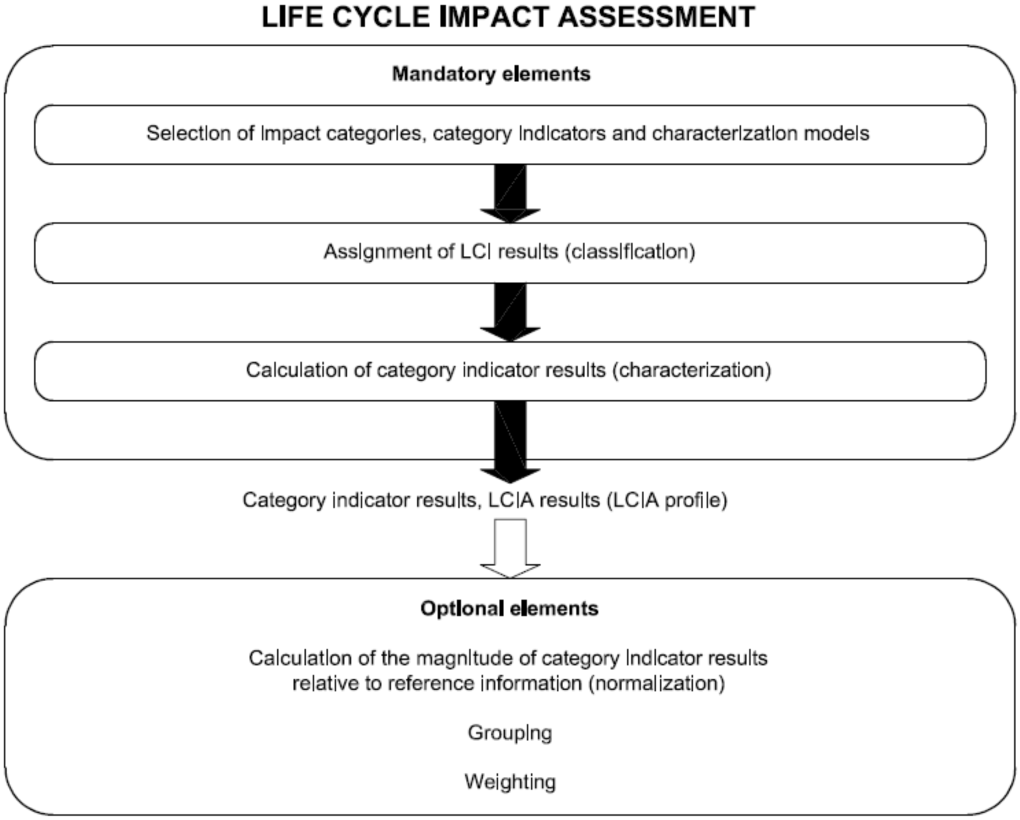

Figure A-3: Elements of the LCIA phase.
(From ISO 14 040, 2006)

A.4.1 Impact category and characterization model selection

The first step is selecting the **impact categories** that represent the problematic environmental issues considered in the study. Each category is identified by a final impact (i.e., an attribute or aspect of the natural environment, human health or natural resources). An **environmental mechanism** (i.e., a causality chain) is then established to link the inventory results to the final impact and a **category indicator** is chosen at a specific place in the mechanism to act as a quantifiable representation of the category. For example, Figure A-4 illustrates the environmental mechanism for the global warming category.

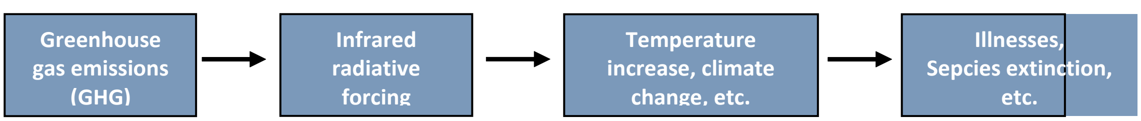

Figure A-4: Environmental mechanism for the global warming impact category.

A **characterization model** is then developed to determine the **characterization factors** that will then be used to convert the relevant inventory results into category indicator results according to their relative contributions to the impact category. For example, for the global warming category, the characterization factors represent the global warming potential of each of the greenhouse gases (in kg of CO_2-equivalent/kg of gas) and can be calculated based on the IPPC model. The inventory results that have been converted into a common unit can then be aggregated into a single **category indicator result** for each impact category. An example of the terms to describe the global warming category of the LCIA is presented in Table A-1.

Table A-1: Example of the terms used in LCIA

Term	Example	Unit
Impact category	Global warming	--
Inventory results	Amount of greenhouse gases (GHG) per functional unit	kg of gas
Characterization model	Basic 100-year model established by the Intergovernmental Panel on Climate Change (IPCC)	--
Category indicator	Infrared radiative forcing	W/m^2
Characterization factors	Global warming potential for (GWP_{100}) for each GHG	kg of equivalent CO_2 / kg of gas
Category indicator results	Sum of the characterized inventory results (i.e., multiplied by their respective characterization factors)	kg of equivalent CO_2 / functional unit
Final impacts per category	Illnesses, species extinctions, etc.	--
Environmental relevance	Infrared radiative forcing is indirect data on potential climate effects that depends on the absorption of the integrated atmospheric heat generated by the emissions and the distribution of this absorption over time.	--

(Adapted from ISO 14 044, 2006)

ISO stipulates that:

- The impact categories, indicator categories and characterization models should be accepted at the international level (i.e., they should be based on an international accord or approved by a knowledgeable international organization;
- The choice of impact categories must reflect a complete group of environmental points and how they pertain to the product system studied, taking into account the objectives and scope of the study;
- The characterization model for each indicator category should be scientifically and technically valid and based on a distinct environmental mechanism that is identifiable and/or a reproducible empirical observation;
- The choice of values and hypotheses made when selecting the impact categories, category indicators and the characterization models be minimized.

The impact categories often considered in LCA are:

- Global warming
- Acidification
- Photochemical smog
- Ozone layer depletion
- Eutrophication
- Human toxicity

- Ecotoxicity
- Land use
- Abiotic resource use
- Water use

Because no single widely-accepted LCIA method exists, there is no single list of impact categories that is generally recognized and used (Udo de Haes *et al.*, 2002). A compromise must therefore be reached between the foreseen applications of the results and the applicability and practicability of the choice of categories and models.

As for the inventory databanks, most of the LCIA methods are European and introduce a bias when considering the Canadian context. This is particularly important for the regional (photochemical smog, eutrophication, acidification) and local (human toxicity, ecotoxicity, land use) impact categories. Because these categories are influenced by the environmental conditions of the receptor area, the characterization models should normally take these characteristics into account[6]. For these impact categories, the CIRAIG has developed a Canadian LCIA method, LUCAS (Toffoletto *et al.*, 2005), based on the American model, TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) (Bare *et al.*, 2003). This method has the advantage of relying on characterization models that have been adapted to the North American context.

Also, the IMPACT 2002+ (Jolliet *et al.*, 2003) method proposes human toxicity factors for each continent. And, as presented by Rochat *et al.* (2006), though the substances emitted on different continents are linked to impacts that can be deferred by up to two orders of magnitude, the relative impact (ranking) of these substances remains the same overall. The authors therefore conclude that:

- Generic characterization factors calculated for a continent like those in most LCIA methods are normally valid for other continents on a comparative basis;
- Characterization factors that are specific to the receptor areas must be used when the study is focussed on absolute results or when a comparison is made between scenarios that involve emissions in very different receptor areas.

A.4.2 Classification and characterization of the inventory results

Once the impact categories have been selected, the inventoried elementary flows (those that are classified) are put into categories according to their predicted effects. Some can be exclusive to one category and others can be in several categories when serial or parallel effect mechanisms are being considered.

The categorized inventory results are then converted using characterization factors and the common units of the indicator categories. The converted results for each category are aggregated to obtain a numerical indicator result. All of the indicator results make up the LCIA profile.

Two elements should be noted regarding the LCIA profile:

1. The calculated range of the impacts considered only represents a potentiality since it is based on models that describe the environmental mechanisms and which therefore simplify reality[7].

[6] The characterization models used for the impacts with global repercussions (global warming, ozone depletion, abiotic resource use and water use) are the same no matter where the emissions or resource extraction occurs.

[7] The divergence between the models' predictions and reality are increased mostly because they are based on the European context. This is particularly significant for regional and local impacts such as acidification and ecotoxicity.

2. The undefined substances (i.e., those that do not have a characterization factor because of a lack of data – (eco)toxicological data, for example) that are not included in the calculations increase the uncertainty of the results.

A.4.3 Optional elements

ISO stipulates that calculating the range of the category indicator results in relation to reference information (normalization) leads to a better understanding of the relative range of each indicator result of the product system. The reference information can consist in:

1. The total emissions or resource uses for a given geographic zone (global, regional or local);
2. The total emissions or resource uses for a given zone (global, regional or local) per inhabitant or a similar measurement;
3. A reference scenario such as another product system.

This optional step can be useful during the consistency check, for example. It also has the advantage of converting all of the category indicator results into the same unit (person-equivalent, for example), which is a pre-requisite for the optional elements below.

According to ISO:

1. **Grouping** consists in classifying the impact categories into one or several series, as predefined in the definition of the objectives and scope. This can involve sorting on a nominal basis (e.g.: per characteristic, such as emissions and resources or global, regional or local spatial scales) and/or an order based on a given hierarchy (e.g.: high, medium, low priority);
2. **Weighting** is the process of converting the indicator results of the various impact categories by using numerical factors. It can include the aggregation of the weighted indicator results into a single score.

These optional elements involve choosing values and different individuals, organizations or societies may therefore have preferences and thus obtain different grouping and weighting results from the same characterized indicator results.

The methodology (i.e., the selection of the impact categories, category indicators, characterisation models and optional elements) used to carry out the assessment of the potential impacts must be clearly presented when defining the objectives and scope of the study.

A.5 LCA Phase IV: Results interpretation

The objectives of the fourth phase of the LCA, the interpretation phase, are to assess the results, establish conclusions, explain the limitations and provide recommendations based on the results of the preceding phases of the study and to then report these results in a transparent way that is in keeping with the criteria set out with the objectives and scope.

Ideally, the interpretation is carried out in a way that considers the three other LCA phases. Defining the objectives and scope and interpreting the life cycle should constitute the framework of the study and the inventory and impact assessments should provide information on the product system.

According to ISO, interpreting the life cycle includes three elements:

1. Identifying the significant points based on the results of the inventory and impact assessment phases in view of the objectives and scope of the study;

2. Carrying out a verification that takes the completeness, sensitivity and consistency checks into account;
3. Determining the conclusions and recommendations and writing up a report.

The goal of the verification process is to establish and strengthen the credibility and reliability of the results. The **completeness check** aims to guarantee that all of the relevant information and data necessary to the interpretation of the results are available and complete. The **sensitivity check** is conducted to verify the reliability of the results and conclusions by determining whether or not they are affected by the uncertainty of the data and methodological choices (e.g.: inclusion criteria, allocation methods or category indicators). The **consistency check** determines whether or not the hypotheses, methods and data are consistent with the objectives and scope of the study and if they have been applied consistently throughout the study or to the compared product systems (when comparing various alternatives).

Results interpretation is hindered by the deterministic nature of the inventory and impact assessment data generally available, since it impedes the statistical and quantitative analysis of the uncertainty of the results that is associated with the use of this type of data. This affects the certainty of these deterministic results. The conclusions and recommendations could lack precision or even be erroneous because it is impossible to quantify the variability of these results or determine if there is a significant impact difference between the two alternatives. The methodology (i.e., types of controls) that will be used to guide the interpretation phase must be clearly detailed when defining the objective and scope.

A.6 REFERENCES

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Appendix B:
Inventory Data Sources and Assumptions

Table B-1: Main data sources used in compiling the foreground LCI

UHI mitigation measures	Data sources
Protection of the building envelope	
1. Extensive green roof	Soprema Nature system. Data provided by Soprema. • Sopralène FLAM 250 waterproof membrane: Technical Data Sheet 040206CAN1E • Components of the SBS modified bitumen membranes: www.soprema.ca/openFile.aspx?ID=283 • Coltack adhesive: Technical Data Sheet 070627CAN1E • Sopradrain ECO-5 drainage panel: LEED Data Sheet + Technical Data Sheet 080208CAN2E • Microfab root barrier: LEED Data Sheet + Technical Data Sheet 040907CAN3E • Sopraflor X growing medium (low water requirement). • Growing plants in a greenhouse: see green wall. Green roof lifespan: Kosareo and Ries (2006); Dunnett and Kingsbury (2005) Number of plants/m²: Expert opinion (reviewer) Rainwater retention capacity: CMHC (2001), Mentens (2005), Teemusk (2007) Avoided energy consumption: OEE (2009a and 2009 b), CMHC (2006), Liu and Baskaran (2003, 2005) Rate of heat loss through the roof of a house in Quebec: AEE (Web site) Modelling of the growing medium: see Appendix C.
2. Reflective roof	Soprema Soprastar™ system. Data provided by Soprema. • Soprafix waterproof membrane: Technical Data Sheet 06-05/2.6-en (Soprafix HP) • Components of the SBS modified bitumen membranes: www.soprema.ca/openFile.aspx?ID=283 • Soprastar white cap sheet membrane: Technical Data Sheet 080311CAN2E • Soprastar RNOVA reflective coating: Technical Data Sheet 090716SCAN1E (*www.soprema.ca/EN/openfile/665/e-mam29a.aspx*), components: Soprastar R'Nova Technical Data Sheet, transport distance: LEED Data Sheet. Average lifespan of elastomeric bitumen membranes: Perrier (2010), Perrier (2011). For the data on EPDM membranes, see Appendix C. Avoided energy consumption: http://www.coolroofs.org/coolroofing.html, Synnefa et al. (2007); Suehrcke et al. (2008).
Planting around buildings	
3. Green wall	**Growing plants in a greenhouse** Energy consumption (heating, ventilation, lighting…): • Areas and operating expenses of specialized greenhouse flower and plant producers, Quebec 2008: www.statcan.gc.ca/pub/22-202-x/2008000/t005-eng.htm and www.statcan.gc.ca/pub/22-202-x/2008000/t015-eng.htm • Relative importance of the energy sources used to heat greenhouses in Quebec (2008): www.agrireseau.qc.ca/horticulture-serre/documents/L%27efficacit%C3%A9%20%C3%A9nerg%C3%A9tique%20dans%20le%20secteur%20serricole.pdf • Price of electricity, industrial sector, Quebec 2008: www.mrnf.gouv.qc.ca/energie/statistiques/statistiques-energie-prix-electricite.jsp

UHI mitigation measures	Data sources
	• Price of light fuel oil, Quebec 2008: www.regie-energie.qc.ca/energie/prodpetro/Mazout_Ens_Qc_2008.pdf • Price of natural gas, Quebec 2008: www.nrcan.gc.ca/eneene/pdf/janjan2008-eng.pdf Fertigation in greenhouse, components of the growing medium: CIRAIG 2010 data. Type of containers assumed: polypropylene pots 8 cm x 8 cm x 8 cm (approx. 500 cm³). Mass and volume measured. **Final planting** Bulk black earth (estimated by: excavation and transport) Number of plants: http://fr.noistop.be/files/noistop/Brochure/Noistop%20 Green%20BE%28FR%29%20Vers%201-5_noSpread.pdf
4. Planting arrangement	**Growing plants in a greenhouse:** see Green wall. **Final planting** Bulk black earth (estimated by: excavation and transport) Ecoinvent process: Excavation, hydraulic digger/RER
5. Tree	**Growing a tree in a nursery**: Data on growth in a nursery and in the field taken from Couillard et al. (2009). All packaging (production and end-of-life management) was ignored. Removal of roots; capture of biogenic CO_2; storage in cold room and removal of spagnum peat moss excluded. Modelling of harvesting was very approximative, since Christmas trees are cut rather than dug up for transplantation.
Parking areas	
6. Reflective surface	Resurfacing conditions: "Guidelines for Portland Concrete Inlay or Overlay" in Winkelman (2005). Thickness of cement: http://www.fhwa.dot.gov/pavement/concrete/pubs/07025/07025.pdf Quantity of polypropylene in reinforced cement: http://findarticles.com/p/articles/mi_qa5360/is_201001/ai_n52370365/ Asphalt scarification: http://www.decovan.be/downloads/Brochure%20FR-200.pdf Density of Portland cement: http://wiki.answers.com/Q/What_is_the_density_of_Ordinary_Portland_Cement Lifespan of a pavement resurfacing: http://www.concreteparking.org/Whitetopping/
7. Permeable surface	Subterra™ paver system - Permacon technical guide: http://www.permaconpro.ca/uimages/pro_support/Permacon_GT09_e.pdf Density of gravel: http://www.simetric.co.uk/si_materials.htm
Soil humidification (which allows runoff to be retained or captured)	
8. Rain garden	Dimensions and components of a rain garden: Bannerman and Considine (2003)
9. Infiltration trench	Summary dimensions of the trench, gravel porosity: Grand Lyon (2008a) Materials required and configuration: Grand Lyon (2008b) No geotextile used in Quebec: Information provided by reviewer
10. Dry well	Summary dimensions of the dry wells, gravel porosity: Grand Lyon (2008a). No geotextile used in Quebec: Information provided by reviewer.

Reference systems	
Standard asphalt and gravel roof	• Components of a multilayer asphalt and gravel roof: www.guideperrier.com/article1306-1755/Refaire-une-membrane-multicouches-d-asphalte-et-gravier • Properties of felt: www.nrc-cnrc.gc.ca/eng/ibp/irc/cbd/building-digest-95.html and www.emcobp.com/upload/products/Publications/res/green/ ORGANIC_FELT_%28fr%29.pdf
Avoided rainwater treatment	• Average rainfall in Montreal: Environment Canada, Climate Normals 1971-2000, Montreal Lafontaine Station: http://climate.weatheroffice.gc.ca/climate_normals/index_e.html • Ecoinvent process: Treatment, sewage, to wastewater treatment, class 1/CH
Asphalt-paved residential parking area	Bitume Québec (2009) Asphalt modelling: CIRAIG data. Lifespan of an asphalt surface: http://www.guideperrier.com/article1437-1745/Realisation-d-un-stationnement-d-asphalte-residentiel
Dimensions of a residential parking area	Dimensions selected: 5.5 m x 2.6 m (14.3 m²). Average value obtained from the following sources: • City of Toronto: Dimensions of 5.6 m x 2.6 m (14.56 m²). Taken from http://www.toronto.ca/zoning/parking.htm. • City of Montreal, borough of Ville-Marie: Dimensions of 5.5 m x 2.75 m (15.13 m²). Taken from http://www11.ville.montreal.qc.ca/sherlock2/servlet/template/sherlock%2CAfficherDocumentInternet.vm/nodocument/24484;jsessionid=33F75E3DEACB3D95B8C679C22298162C • Canadian Parking Association (CPA): Dimensions of 5.4 m x 2.5 m (13.5 m²). Taken from http://www.canadianparking.ca/publications/theparker/archive/2010/Q2/ParkingDimensions_eng.pdf

Table B-2: Assumptions and values defining the assessed measures

Assumptions and details of the characteristics considered * Sensitivity or scenario analyses were conducted on the assumptions indicated in italics.
1. Extensive green roof

- Modelled based on the SopraNature system (Soprema™).
- No major change in the structure of the building is required. It is assumed that the extensive green roof can be installed on an existing building. N.B.: Older homes in Montreal or other Quebec urban centres may require structural reinforcement before a green roof can be installed. These cases are not considered in the present analysis.

Elastomeric bitumen membrane:

- All the materials comprising the elastomeric bitumen membrane are virgin (information provided by Soprema).
- Torch welding: it was assumed that a 10 kg propane tank is required.

Planting system:

- Aluminum roof drain guard (15 cm x 45 cm x 45 cm, assumed thickness 2 mm).
- Composition of the growing medium modelled (made with 66% recycled materials):
  - Crushed brick (not compressible, recycled post-consumption material): 60% v/v. Crushed brick is presumed be demolition waste. Only the energy required for crushing is considered.
  - Blond peat: 10% v/v
  - Expanded perlite (not compressible): 10% v/v
  - Sand: 15% v/v
  - Green compost (recycled material) 5% v/v. The ingredients of the compost are presumed to be pruning waste, dead leaves, etc.
- Perennials grown in a greenhouse: 12 plants/m² (average between 9 and 14 plants/m² depending on the type of plant)
- *45-year lifespan (Kosareo and Ries, 2006). According to Dunnett and Kingsbury (2005), the lifespan of a standard roof equipped with a green roof is at least doubled.**
- The planting includes slow-release fertilization, approximated by a standard fertilization with a 20-20-20 type all-purpose chemical fertilizer for the first two years.
- *After the initial period, fertilization is carried out as needed. It is assumed that fertilization is carried out every five years. Slow-release fertilization, approximated by a standard fertilization with a 20-20-20 type all-purpose chemical fertilizer**

Avoided water treatment (maximum):

- Based on the average rainfall in Montreal of 830 mm/year (Environment Canada).
- According to the literature consulted, 50% to 85% of the seasonal precipitation falling on an extensive green roof is retained on site and would have otherwise been captured by the municipal sewer system (CMHC, 2001; Mentens et al., 2005; Teemusk et al., 2007). It was therefore assumed that treatment of 70% (average value) of the seasonal precipitation is avoided by a green roof.
- The fact that green roofs delay the arrival of precipitation in the municipal sewer system during violent storms, and thus help prevent overloading of the water treatment plant and the opening of the overflow valves (leading to the discharge of untreated water directly to the river), was not quantified in this analysis. However, to take advantage of this effect, it is necessary that a large number of rainwater management measures be implemented in the same area, which exceeds the context of this study.

Avoided energy:

- No published Quebec data were found. Several studies (in particular those of the NRC – Liu and Baskaran (2003, 2005)) show that green roofs improve the thermal performance of roofs (reduced heat gains in summer and heat losses in winter). A study carried out in western Canada indicates a reduction in energy demand due to heat transfers of 83-85% during the summer and spring and 40-44% during the fall and winter, for an overall annual average of 66%. The results of the research by Liu and Baskaran (2003, 2005) also indicate that in Toronto and Ottawa, extensive green roofs provide an overall reduction (over more than a year) of 47% to 50% in heat exchanges between the outside and inside of the building, i.e. 70% to 90% in summer and 10% to 30% in winter (Liu and Baskaran, 2003). Given the similarity between the climate in northern Ontario and large urban centres in Quebec, it appears that these conclusions could be used in the context of the present modelling. However, there is no quantifiable correlation between a reduction in heat exchanges and the resulting energy savings for heating or air conditioning. This aspect was very clearly pointed out by the representatives of Soprema roofs contacted for the study. In fact, the heat exchanges measured apply only to the roof. The reduction in energy consumption is dependent on a number of factors, such as the insulation of the walls, the number and type of windows, etc. To correlate the reduction in heat loss through the roof and the energy savings, the fraction of the heat lost through the roof was used (AEE, Web site).

In light of these considerations, the energy avoided by a green roof was estimated as follows:

- Distribution of residential heating energy sources in Quebec: 16% fuel oil; 12% natural gas; 72% electricity (2007 data, estimated excluding bivalent systems, heat pumps, wood, coal and propane (OEE, 2009a)). Average energy intensity: 0.58 GJ/m².yr.
- 11% of the heat losses of an average Quebec house are attributable to the roof (AEE, Web site). It is assumed that the same rate of loss applies to air conditioning.
- Air conditioning provided by electrical source only (assumed). Average energy intensity for residential air conditioning: 30.9 MJ/m².yr (OEE, 2009a).
- 35% of homes are equipped with an air conditioner (INSPQ, 2008).
- The energy avoided (heating and air conditioning) applies only to a single floor, directly under the roof.
- In Quebec, for an average residence, installing a green roof results in a reduction of approximately 2% (i.e. 11% of 20%) in winter energy consumption for heating, as well as a reduction of approximately 9% (i.e. 11% of 80%) in summer energy consumption for air conditioning.

During dismantling, it is assumed that all the components are removed manually and disposed of in a container using a tube (no use of crane or machinery). The materials removed are transported (50 km) to an engineered landfill site (ELS).

2. Reflective roof

- Modelled based on the Soprastar (Soprema™) system including a Soprafix™ impermeable base sheet, a Soprastar HD™ white cap sheet membrane (surface of white reflective slate flakes) and a RNOVA™ reflective coating (white acrylic latex elastomer coating). There are other types of reflective membranes, but they were not analyzed.
- A scenario involving a white EPDM membrane was also analyzed. See Appendix C for details.

Elastomeric bitumen membrane:

- All the materials comprising the elastomeric bitumen membrane are virgin (according to a Soprema representative).
- Torch welding: it was assumed that a 10 kg propane tank is required.

Reflective system:

- Reflective coating (RNOVA™) applied to the entire roof surface (initial Solar Reflectance Index (SRI): 112).
- All the materials comprising the reflective system are assumed to be virgin, as is the case for the elastomeric bitumen membrane (information provided by Soprema).
- To maintain the SRI of the roof, it is recommended that the reflective coating be re-applied as needed (approximately every five years according to the Soprema representative). The maintenance modelled therefore includes an application of RNOVA™ coating every five years.
- 21-year lifespan (average for an elastomeric bitumen membrane).

Maintenance: Prado and Ferreira (2005) demonstrated that a reflective roof loses 15% of its effectiveness during the first year of installation. It must therefore be maintained, i.e. scrubbed or hosed down in order to conserve its properties. In the case of the Soprastar membrane, Soprema suggests applying a layer of RNOVA reflective coating every five years.

Avoided energy:

- No Quebec data were found. Paroli and Gallagher (2008) report that white roofs reduce the energy demand in summer, but can be disadvantageous in winter, since the solar heat is then dissipated into the atmosphere. They add that “However, since the sun is low in the sky, the potential heat value lost through reflectivity may not be critical. Plus, since the days are short, less energy is hitting the roof, which means less reflectivity is taking place. And when there is snow on the roof, reflectivity due to the membrane does not occur.” Synnefra et al. (2007) demonstrated that in summer in New York a roof with a solar reflectance of 0.85 reduces the air conditioning load by 46%

Assumptions and details of the characteristics considered
* Sensitivity or scenario analyses were conducted on the assumptions indicated in italics.

compared to a conventional "black" roof (reflectance of 0.2). Given the similarity between the New York and Montreal summer climates, these conclusions would have been applicable in the context of the present modelling. However, maintaining consistency between the calculation and modelling methods used for a green roof and a white roof make the use of this data problematic. Consequently, a search was conducted for data dealing with heat flows in a white roof. Suehrcke et al. (2008) report a net heat gain avoided by white roofs in an Australian context. According to these authors, installing a white roof reduces heat gain through the roof in summer by approximately 30%. **This result obviously depends on the insulation of the roof**. However, this data makes it possible to calculate the avoided energy in a manner consistent with a green roof.

- In light of these considerations, the energy avoided by a reflective roof was estimated as follows:
  - No savings or increase in energy consumption associated with heating.
  - Air conditioning provided by electrical source only (assumed). Average energy intensity for residential air conditioning: 30.9 MJ/m².yr (OEE, 2009a)
  - 35% of homes are equipped with an air conditioner (INSPQ, 2008).
  - The air conditioning energy avoided applies only to a single floor, directly under the roof.
  - In an average residence in Quebec, installing a reflective roof results in approximately a 3% (i.e. 11% of 30%) reduction in summer energy consumption for air conditioning.

During dismantling, it is assumed that all the components are removed manually and disposed of in a container using a tube (no use of crane or machinery). The materials removed are transported (50 km) to an engineered landfill site (ELS).

3. Green wall

- Growing the plants in a greenhouse: infrastructure ignored.
- Virginia creeper plants spaced 0.5 m apart.
- Excavation carried out manually.
- The original soil cannot be used to grow plants. It is landfilled in a dry disposal site and replaced by black earth to a depth of 15 cm (0.57 m³).
- *Fertilization (20-20-20 type all-purpose chemical fertilizer) is carried out during planting**.
- Watering (0.5 L/plant) 10 times during the first year only.
- Maintenance does not involve any consumption of energy or materials (stems cut with a pruner, no use of mulch or fertilizer).
- Lifespan not considered, since the stems can be used for propagation by cuttings without resorting to new greenhouse-grown plants.
- **Avoided water treatment (maximum):** all the precipitation absorbed by the soil at the base of the green wall would have otherwise been captured by the municipal sewer system.
- **Avoided energy**: since no data were found on the quantity of air conditioning energy potentially avoided by the presence of vegetation on the outside walls of a house, this parameter was ignored.
- Dismantling does not involve any consumption of materials or energy (manual labour) and the plants are re-used. No impact associated with restoration of the site, since this depends entirely on the subsequent use.

4. Planting arrangement

- Growing the plants in a greenhouse: infrastructure ignored.
- Plants planted every 0.10 m². Composed mainly of perennials adapted to the Quebec climate.
- Excavator required to prepare the border to a depth of 0.5 m (excavation of 12.5 m³).
- The original soil cannot be used to grow plants. It is landfilled in a dry disposal site and replaced by black earth to a depth of 50 cm (12.5 m³).
- *Implementation of the measure includes initial fertilization (approximated by a 20-20-20 type all-purpose chemical fertilizer)**, watering of 0.5 L/plant and addition of 1.25 m³ (25 m² x 5 cm) of cedar mulch.
- Every year, 5% of the plants are replaced (annuals or dead plants)

Assumptions and details of the characteristics considered * Sensitivity or scenario analyses were conducted on the assumptions indicated in italics.
o Maintenance includes watering (0.25 L/plant, 10 times a year and the addition of 1.25 m³ (25 m² x 5 cm) of cedar mulch every two years. *Fertilization (20-20-20 type all-purpose chemical fertilizer, five times a year) was also assessed.** o **Avoided water treatment (maximum):** all the precipitation absorbed by the planted area would have otherwise been captured by the municipal sewer system. o **Avoided energy:** since no data were found on the quantity of air conditioning energy potentially avoided by the vegetation planted around a house, this parameter was ignored. o Dismantling does not involve any consumption of materials or energy (manual labour) and the plants are re-used. No impact associated with restoration of the site, since this depends entirely on the subsequent use.
5. Tree
o Growth in a nursery estimated equivalent to that of a Christmas tree (Couillard et al., 2009). Includes four years of growth in a nursery and 10 years in the field. o Large tree (2 m) delivered with root ball. o Excavator required to prepare the site (1 m³). o The original soil (1 m³) cannot be used to grow plants. It is landfilled in a dry disposal site. o 25% of the hole is filled with black earth (0.25 m³). o *Initial fertilization (approximated by a 20-20-20 type all-purpose chemical fertilizer)** and generous watering (20 L) are carried out during planting. Watering without fertilizer (10 L, 25 times a year during the first two years) is also included in the implementation stage of this measure. o Maintenance includes only the addition of 0.05 m³ of cedar mulch (1 m² x 5 cm) every two years. No fertilization is necessary once the tree is established (Montreal Botanical Garden, 2008). It is assumed that pruning is done manually. The transport and end-of-life management of the cut branches are excluded. o Lifespan of the tree not specified. Assumed to be more than 30 years. o **Avoided water treatment (partial):** all the precipitation absorbed by the soil at the base of the tree (1 m) would have otherwise been captured by the municipal sewer system. Trees also provide a water retention effect (during light rain) by intercepting precipitation in the foliage. However, this aspect was not modelled given the specific nature of the volumes of water retained (type of tree, maturity, period of the year, intensity of the rain…). o **Avoided energy**: since no data were found on the quantity of air conditioning energy potentially avoided by the presence of a tree near a house, this parameter was ignored. o The end-of-life management of a tree is complex to model in a generic context. First of all, its lifespan can extend well beyond the 30 years covered by the study. And should it have to be cut down, the energy required for its transport is extremely variable, depending on the size and density of the tree (which depends on the species and the characteristics of the site). Finally, there are several options for re-use of the wood: it can be chipped and used as mulch, composted, used as firewood in a home fireplace or in an incinerator/gasifier with heat recovery, for production of electricity or even production of alternative fuel. All these possibilities represent very different environmental loads and benefits which, if they were quantified, would not be representative of the average of trees cut down in urban areas in Quebec. Given all this uncertainty, it was deemed preferable not to model their end-of-life management.
6. Reflective surface
o The type of reflective surface studied involves resurfacing an existing asphalt-paved parking area with a "thin" (75 mm) layer of white Portland cement (whitetopping). There is a growing number of other types of reflective surfaces (light-coloured gravel or high-albedo pavers), but they were not analyzed o The technology includes scarification of the old surface, Portland cement reinforced with polypropylene fibres (3 kg/m³). o Asphalt scarification is carried out with a manual milling machine which consumes 5 litres of diesel to cover the parking area. o It was estimated that the energy necessary to apply the cement layer is considered equivalent to that required for asphalt finishing (0.190 MJ/m²). o No metal reinforcing. Saw cuts were ignored. o Density of Portland cement: 1.44 t/m³. o Maintenance does not involve any consumption of materials or energy. o 20-year lifespan.

Assumptions and details of the characteristics considered * Sensitivity or scenario analyses were conducted on the assumptions indicated in italics.

- **Avoided water treatment:** the reflective surface does not change the quantity of water captured by the municipal sewer system.
- **Avoided energy**: no air conditioning energy is avoided by the presence of reflective pavers near a house.
- During dismantling, only the superficial layer of cement is removed and sent to a DDS. It is assumed that the underlying asphalt-paved layer can be resurfaced again.

7. Permeable surface

- Modelling based on the Subterra (Permacon™) pavers, assuming an installation that permits complete infiltration. There are other types of permeable surfaces, but they were not analyzed.
- The system as implemented does not involve installation of any concrete curbs, geotextile or drain. All the water infiltrated is assumed to be absorbed by the soil (implying that the underlying soil has a permeability of 15 mm/h).
- Concrete pavers 80 mm thick with 6% opening (for the drainage of the paved surface).
- Joint filling material: gravel (1-10 mm); Installation bed: 50 mm gravel layer (1-10 mm); Foundation: 100 mm gravel layer (3-25 mm); Sub-foundation: 100 mm of coarse gravel. All the gravel was modelled by the Ecoinvent process “Gravel, crushed, at mine/CH”.
- Density of the concrete pavers: 2,300 kg/m³
- The compaction of the foundation and of the installation bed is equivalent to the preparation of the granular foundation for the reference asphalt-paved parking areas.
- The pavers are installed manually.
- Maintenance does not involve any consumption of energy or materials (no replacement of pavers).
- 20-year lifespan.
- **Avoided water treatment (maximum):** all the precipitation falling on the surface of the parking area is absorbed by the soil and would have otherwise been captured by the municipal sewer system. N.B.: The water from the parking area which penetrates into the soil may contain pollutants and thus contaminate the soil and water table. This aspect was not quantified, but was taken into account in the interpretation.
- **Avoided energy**: no air conditioning energy is avoided by the presence of permeable pavers near a house.
- During dismantling, the concrete pavers and the layers of gravel are excavated and sent to a DDS.

8. Rain garden

- Growing the plants in a greenhouse: infrastructure ignored.
- Rain garden designed to collect the roof water and, where applicable, runoff from a private parking area. Dimensions depend on the specific conditions of the site. For the modelling, the dimensions were calculated based on the following considerations:
  - Site with 5% slope, silty soil (not sand or clay).
  - Roof fitted with gutters: all the water collected by the 100 m² roof is directed to the rain garden + the water falling on the 14.3 m² parking area.
  - The parking area (if there is one) is designed so that all the precipitation runs off into the trench.
- Dimensions obtained:
  - 25 m² to collect the roof water only;
  - 28.6 m² to collect water from the roof and the parking area.
- Excavator required to prepare the rain garden. Although the finished installation is 0.15 cm deep relative to the initial level of the site, it was estimated that an excavation of 0.65 m was necessary to replace the original soil with black earth to a depth of 0.5 m.
- Part of the original soil is used to create the berm (i.e. 4.3 m³ or 3.75 m³ depending on whether or not there is a parking area), the rest cannot be used to grow plants. It is landfilled in a dry disposal site.
- Plants planted every 0.10 m². Composed mainly of perennials adapted to the Quebec climate.
- *Implementation of this measure includes initial fertilization (approximated by a 20-20-20 type all-purpose chemical fertilizer)**, watering of 0.5 L/plant and addition of 5 cm of cedar mulch over the entire the surface of the garden.
- Since these are perennials, it is assumed that only 1% of the plants are replaced annually (dead plants).

Assumptions and details of the characteristics considered * Sensitivity or scenario analyses were conducted on the assumptions indicated in italics.
o Maintenance includes *fertilization (chemical fertilizer all-purpose of type 20-20-20, once a year)** and the addition of 5 cm of cedar mulch over the entire the surface of the garden every two years. o **Avoided water treatment (maximum):** ▪ All the precipitation from the roof directed to the rain garden is absorbed by the soil. Conversely, if the rain garden did not exist, all the water would have been directed to the municipal sewer system. ▪ All the precipitation falling directly on the planted area or from the parking area (where applicable) is absorbed and would have otherwise been captured by the municipal sewer system. ▪ The fact that the rain garden delays the arrival of precipitation in the municipal sewer system during violent storms, and thus avoids the overloading of the water treatment plant and the opening of the overflow valves (leading to the discharge of untreated water directly to the river), was not quantified in this analysis. However, to take advantage of this effect, it is necessary that a large number of rainwater management measures be implemented in the same area, which exceeds the context of this study. o **Avoided energy:** since no data were found on the quantity of air conditioning energy potentially avoided by the presence of planting arrangements (such as a rain garden) around a house, this parameter was ignored. o Dismantling does not involve any consumption of materials or energy (manual labour) and the plants are re-used. No impact associated with restoration of the site, since this depends entirely on the subsequent use. o The plants do not have concentrated contaminants from the runoff in their tissues.
9. Infiltration trench
o Trench designed to collect the roof water and, where applicable, runoff from a private parking area. Dimensions depend on the specific conditions of the site. For the modelling, summary dimensions were calculated based on the following considerations: ▪ The parking area (if there is one) is designed so that the precipitation all runs off into the trench. ▪ Hydraulic conductivity of 10^{-5} m/s (e.g. soil composed of coarse to fine sand). N.B.: This conductivity is the necessary limit to permit infiltration of the water into the soil according to the dimensions used. ▪ Trench filled with medium to coarse gravel, porosity of 0.4. ▪ Water table more than 2-3 m deep (to respect the minimum thickness of 1-2 m between the top of the water table and the bottom of the infiltration structure). ▪ Extreme daily rainfall of 60 mm (based on rainfall data in Montreal, Environment Canada), falling in 3 hours. ▪ Roof fitted with gutters: all the water collected by the 100 m^2 roof is directed to the trench + the water falling on the 14.3 m^2 parking area. o Dimensions obtained (based on the necessary storage volume of the trench (Grand Lyon, 2008a): ▪ To collect the roof water only: length: 12 m, depth: 1.1 m; width: 1.2 m ▪ To collect water from the roof and the parking area: length: 13 m, depth: 1.15 m; width: 1.2 m o Excavator required to prepare the trench (15.8 m^3 or 17.9 m^3). o The original soil (15.8 m^3 or 17.9 m^3) is landfilled in a dry disposal site. o Uncovered trench (without vegetated surface or pavers). o Maintenance does not involve any consumption of materials or energy. o Assumed lifespan of 30 years (i.e. over the study period considered, it is not necessary to make major modifications to the installations). o **Avoided water treatment (maximum):** ▪ All the precipitation from the roof directed to the infiltration trench is stored and absorbed by the soil. Conversely, if the trench did not exist, all the water would have been directed to the municipal sewer system. ▪ All the precipitation falling directly on the surface of the trench or from the parking area (where applicable) is absorbed and would have otherwise been captured by the municipal sewer system. ▪ The fact that the infiltration trench delays the arrival of precipitation in the municipal sewer system during violent storms, and thus avoids the overloading of the

Assumptions and details of the characteristics considered

* Sensitivity or scenario analyses were conducted on the assumptions indicated in italics.

water treatment plant and the opening of the overflow valves (leading to the discharge of untreated water directly to the river), was not quantified in this analysis. However, to take advantage of this effect, it is necessary that a large number of rainwater management measures be implemented in the same area, which exceeds the context of this study.

- **Avoided energy**: no air conditioning energy is avoided by the presence of an infiltration trench near a house.
- During dismantling, the gravel is excavated and sent to a DDS. Earth is transported to fill the hole and restore the site its “initial” state.

10. Dry wells

- Well designed to collect the roof water and, where applicable, runoff from a private parking area. Dimensions depend on the specific conditions of the site. For the modelling, summary dimensions were calculated based on the following considerations:
  - Hydraulic conductivity of $5x10^{-5}$ m/s (e.g. soil composed of coarse to fine sand). N.B.: This conductivity is the necessary limit to permit infiltration of the water into the soil according to the dimensions used.
  - Well filled with medium to coarse gravel, porosity of 0.4.
  - Water table more than 2-3 m deep (to respect the minimum thickness of 1-2 m between the top of the water table and the bottom of the infiltration structure).
  - Extreme daily rainfall of 60 mm (based on the rainfall data in Montreal, Environment Canada), falling in 3 hours.
  - Roof fitted with gutters: all the water collected by the 100 m² roof is directed to the rain garden + the water falling on the 14.3 m² parking area.
- Dimensions obtained (determined based on the necessary storage volume of the well, Grand Lyon (2008a)):
  - To collect the roof water only: diameter: 1.7 m, depth: 2.5 m.
  - To collect water from the roof and the parking area: diameter: 1.8 m, depth: 2.75 m.
- Excavator required to prepare the well (5.9 m³ or 7 m³).
- The original soil (5.9 m³ or 7 m³) is landfilled in a dry disposal site.
- Aluminum cover (diameter of the well, assumed to be 5 mm thick).
- Maintenance does not involve any consumption of materials or energy.
- Assumed lifespan of 30 years (i.e. over the study period considered, it is not necessary to make major modifications to the installations).
- **Avoided water treatment (maximum):** all the precipitation from the roof directed to the well is stored and absorbed by the soil. Conversely, if the well did not exist, all the water would have been directed to the municipal sewer system.
- The fact that the dry well delays the arrival of precipitation in the municipal sewer system during violent storms, and thus avoids the overloading of the water treatment plant and the opening of the overflow valves (leading to the discharge of untreated water directly to the river), was not quantified in this analysis. However, to take advantage of this effect, it is necessary that a large number of rainwater management measures be implemented in the same area, which exceeds the context of this study.
- **Avoided energy**: no air conditioning energy is avoided by the presence of a dry well near a house.
- During dismantling, the gravel is excavated and sent to a DDS. Earth is transported to fill the hole and restore the site its “initial” state.

General assumptions

- Density of the soil: 1.8 t/m³ (no expansion factor was used between the soil in place and the excavated soil).
- Density of gravel (all dimensions combined): 1,700 kg/m³
- Density of diesel: 0.847 kg/l
- Density of the earth: 1,250 kg/m³ (http://fr.wikipedia.org/wiki/Masse_volumique)
- When transport distances are not known, average distances were assumed:
  - 100 km for the transport of the components and raw materials to the production plants. (Ecoinvent process “Transport, Lorry >32 t, EURO3/RER”)
  - 50 km for the transport of the equipment and the delivery of the materials to the site where the measure is to be implemented. (Ecoinvent process “Transport, Lorry 16-32t, EURO3/RER”)
- The current Quebec grid mix will remain unchanged over the entire time period covered by the study (30 years).

Assumptions and details of the characteristics considered

* Sensitivity or scenario analyses were conducted on the assumptions indicated in italics.

Reference roof (multilayer asphalt and gravel)

- Lifespan: 15 years.
- No maintenance considered (no addition of gravel or asphalt).
- During dismantling, all components of the multilayer asphalt and gravel roof are transported (50 km) to an engineered landfill site (ELS).

Reference parking area (asphalt)

- Density of asphalt: 2,350 kg/m³
- Asphalt pavement including 68% aggregates, 23% sand, 3% limestone and 6% bitumen.
- Lifespan: 20 years.
- No maintenance considered (no use of sealant or cleaner).
- During dismantling, the foundation gravel and the used asphalt are transported (50 km) to an engineered landfill site (ELS).

Appendix C:
Impact Assessment (LCIA) Method

IMPACT 2002+

The LCIA methodology IMPACT 2002+ (Jolliet et al. 2003) proposes a combined midpoint/damage-oriented approach. Figure A shows the overall scheme of the IMPACT 2002+ framework, linking all types of LCI results via 14 midpoint categories (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction) to four damage categories (human health, ecosystem quality, climate change, resources). An arrow symbolizes that a relevant impact pathway is known and quantitatively modelled based on natural science. Impact pathways between midpoint and damage levels that are assumed to exist, but that are not modeled quantitatively due to missing knowledge are represented by dotted arrows.

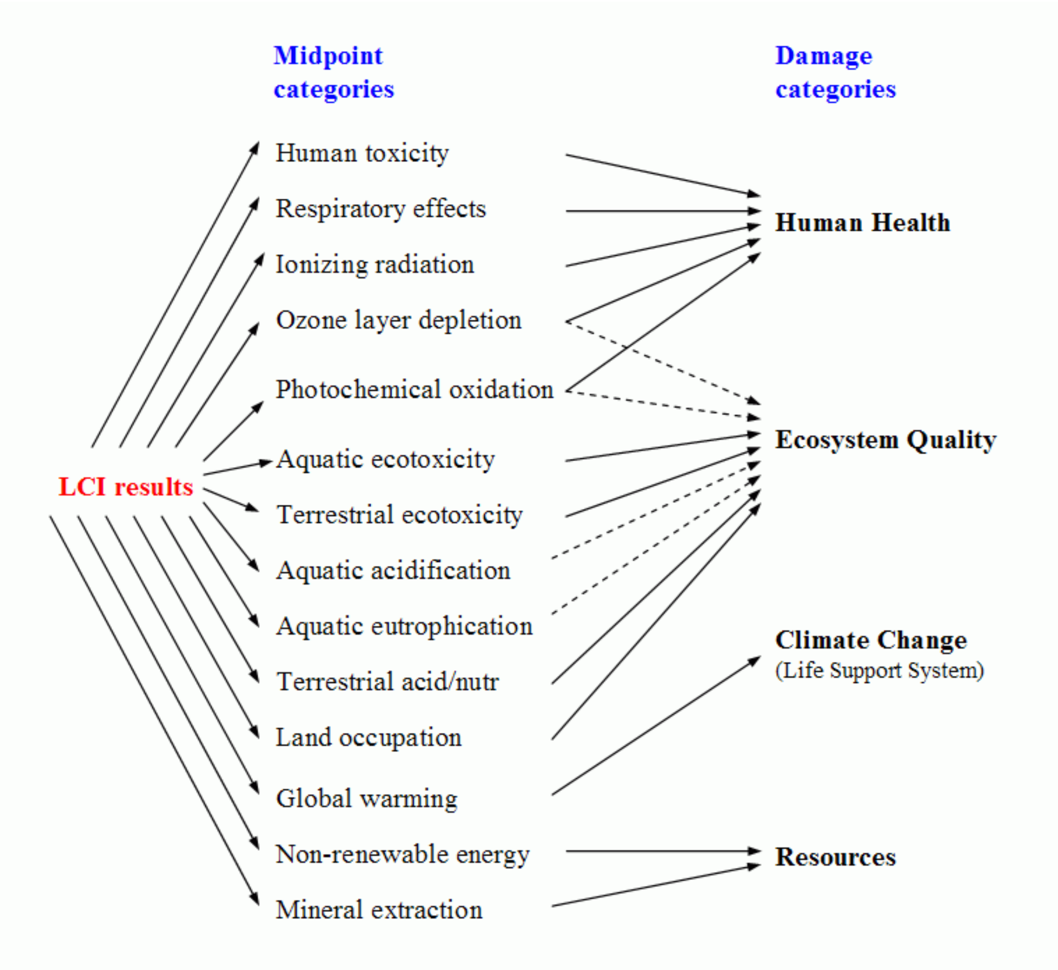

Figure A: Overall scheme of IMPACT 2002+, linking the life cycle inventory results (LCI) and the damage categories, via the midpoint categories.

New concepts and methods for the comparative assessment of human toxicity and ecotoxicity were developed for the IMPACT 2002+ methodology. For other categories, methods have been transferred or adapted mainly from the Eco-indicator 99 (Goedkoop et al. 2000) and the CML 2002 (Guinée et al. 2002) methods, from the IPCC list (IPCC 2001), the USEPA ODP list (EPA) and ecoinvent database (ecoinvent Centre, 2005).

By the following we shortly describe the main assessment characteristics for midpoint and damage categories, as well as related normalization factors.
Midpoint categories are:

1. Human Toxicity measures the impact on human life related to carcinogen and non-carcinogens toxic effects caused by pollutants emitted into the environment and eventually reaching the humans through air inhalation, drinking water and food ingestion. Carcinogen and non-carcinogens are separated in two indicators in the analysis realised in the present study.
2. Respiratory Inorganics are air pollutants such as fine particles that affect human lungs. These pollutants are massively released by heavy industries and road traffic.
3. Ionizing Radiation measures the impact on human life caused by substances emitting ionizing radiations. These substances are mainly released by the nuclear energy sector.
4. Ozone Layer Depletion measures the potential in reducing the stratospheric ozone layer and thus the increase in UV light reaching the earth. It can therefore generate impact on human life such as skin cancer and cataract, and damage terrestrial life and aquatic ecosystems. The pollutants destroying the ozone layer, such as CFCs are emitted by some specific industrial processes, in need, for example, for strong cooling systems.
5. Photochemical Oxidation measures the effects on human health (and eventually on crop growth) associated with tropospheric ozone formation (also called summer smog formation). Pollutants responsible for trophosperic ozone such as NOx and Volatiles Organic Carbons (VOCs) are mainly emitted by road traffic and industrial activities.
6. Aquatic Ecotoxicity measures the effects on fresh water ecosystems in term of loss in biodiversity caused by toxic emissions emitted into the environment.
7. Terrestrial Ecotoxicity measures the effects on terrestrial ecosystems in term of loss in biodiversity caused by toxic emissions emitted into the environment.
8. Aquatic Acidification literally refers to processes increasing the acidity in aquatic systems that may lead to declines in fish populations and disappearances of species. These substances such as airborne nitrogen (NOx and NH_3) and sulfur oxides (SOx) are mainly emitted by heavy oil and coal combustion for electricity production, and by road traffic.
9. Aquatic Eutrophication measures the potential of nutrient enrichment of the aquatic environment, which generates a growth of biomass that pushes this ecosystem population out of balance: decrease of oxygen leads to further fish kills and disappearance of bottom fauna. These nutrients are mainly associated with phosphorus and nitrogen compounds in detergents and fertilizers.
10. Terrestrial Acidification and Nutrification measure the potential change in nutrient level and acidity in the soil leading to a change of the natural condition for plant growth and competition. A reduction of species are observed with an excess of nutrients and a decrease in forest health by soil acidification (effect on biodiversity). Acidifying and nutrifying substances such as NOx, SOx and NH_3 are massively released by heavy industries and road traffic.
11. Land Occupation measures the reduction of biodiversity caused by the use of land. Agriculture (farming) is the main contributor to this category.
12. Global Warming covers a range of potential impacts resulting from a change in the global climate. It is the measured heat-trapping effect of a greenhouse gas (GHG) released in the atmosphere. CO_2 emitted by fossil fuel combustion is the main GHG.

13. Primary Non-Renewable Energy measures the amount of energy extracted from the earth contained in the fossil energy carrier (coal, oil and natural gas) or uranium ore. These resources are subject to depletion. Electricity, heat and fuel production and consumption are the main consumer of fossil fuels and uranium ore.
14. Mineral Extraction measures the surplus of energy associated with the additional effort required to extract minerals from lower concentration ore mines.

The indicators of each midpoint impact category have units expressed in kg of substance equivalent that are linked to the following 4 damage indicators (Table A2 and A3):

- human health (DALY). Human toxicity (carcinogenic and non-carcinogenic effects), respiratory effects (inorganics and organics), ionizing radiation, and ozone layer depletion all contribute to human health damages.
- ecosystems quality (PDF·m^2·yr), measure how far the anthropogenic processes affect the natural development of the occurrence of species within their habitats. Their impact can directly be determined as a Potentially Disappeared Fraction over a certain area and during a certain time per kg of emitted substance, expressed in [PDF.m^2.year/kg emitted]. It includes the contribution of terrestrial acidification/nitrification, land occupation and terrestrial + aquatic ecotoxicity.
- resources depletion (MJ primary non-renewable energy) and. The two midpoint categories contributing to this endpoint are mineral extraction and non-renewable energy consumption. Damages due to mineral resource extraction are specified according to Eco-indicator 99, with the concept of surplus energy (in [MJ]). This is based on the assumption that a certain extraction leads to an additional energy requirement for further mining of this resource in the future, caused by lower resource concentrations or other unfavorable characteristics of the remaining reserves (Goedkoop et al. 2000).
- climate change (kg CO_2 equivalent into air). From the authors' point of view, the modeling up to the damage of the impact of climate change on ecosystem quality and human health is not accurate enough to derive reliable damage characterization factors. The interpretation, therefore, directly takes place at midpoint level, which can be interpreted as damage on life support systems that deserve protection for their own sake. The global warming is considered as a stand-alone endpoint category with units of [kg-eq CO_2], which is normalized in the next step. The assumed time horizon is also 500 years to account for both short-term and long-term effects as there is little evidence that global warming effects will decrease in the future

Table A2: Number of substances covered, source and units of IMPACT 2002+ (v2.1).

LCI coverage	Midpoint category	Reference	Midpoint reference substance	Damage unit	Damage unit	Normalized damage unit
769	Human toxicity (carcinogens + non-carcinogens)	IMPACT 2002	kg chloroethylene$_{-eq}$	Human Health	DALY	point
12	Respiratory (inorganics)	Ecoindicator 99	kg chloroethylene$_{-eq}$			
25	Ionizing radiations	Ecoindicator 99	kg PM2.5$_{-eq}$			
95	Ozone layer depletion	USEPA and Ecoindicator 99	Bq Carbon-14$_{-eq}$			
130	Photochemical oxidation	Ecoindicator 99	kg CFC-11$_{-eq}$			
393	Aquatic ecotoxicity	IMPACT 2002	kg ethylene$_{-eq}$	Ecosystem Quality	PDF·m^2·yr	
393	Terrestrial ecotoxicity	IMPACT 2002	kg triethylene glycol$_{eq}$ into water			
5	Terrestrial acidification/ nutrification	Ecoindicator 99	kg triethylene glycol$_{eq}$ into soil			
15	Land occupation	Ecoindicator 99	m^2 organic arable land			point
10	Aquatic acidification	CML 2002	kg SO_{2-eq}	*n/a*	*n/a*	*n/a*
10	Aquatic eutrophication	CML 2002	kg SO_{2-eq}	*n/a*	*n/a*	*n/a*
77	Global warming	IPCC 2001 (500 yr)	kg CO_{2-eq}	Climate Change (life supporting functions)	kg CO_{2-eq} into air	
9	Non-renewable energy	Ecoinvent	MJ/kg crude oil$_{-eq}$	Ressource depletion	MJ primary non-renewable energy	
20	Mineral extraction	Ecoindicator 99	MJ/kg iron$_{-eq}$			

Table A3: Units of midpoint impact categories and conversion factors between the midpoint categories and the damage categories of IMPACT 2002+ (v2.1).

Midpoint category	Damage factor	Unit
Carcinogens	2.80^{E}-6	DALY/kg chloroethylene$_{-eq}$
Non-carcinogens	2.80^{E}-6	DALY/kg chloroethylene$_{-eq}$
Respiratory (inorganics)	7.00E-4	DALY/kg PM2.5$_{-eq}$
Ionizing radiations	2.10E-10	DALY/Bq Carbon-14$_{-eq}$
Ozone layer depletion	1.05E-3	DALY/kg CFC-11$_{-eq}$
Photochemical oxidation	2.13E-6	DALY/kg ethylene$_{-eq}$
Aquatic ecotoxicity	5.02E-5	PDF·m^2·yr/kg triethylene glycol$_{-eq}$ into water
Terrestrial ecotoxicity	7.91E-3	PDF·m^2·yr/kg triethylene glycol$_{-eq}$ into soil
Terrestrial acidification/nutrification	1.04	PDF·m^2·yr/kg SO_{2-eq}
Aquatic acidification	1	kg SO_{2-eq}/kg SO_{2-eq}
Aquatic eutrophication	1	kg $PO_4^{---}{}_{-eq}$/kg $PO_4^{---}{}_{-eq}$
Land occupation	1.09	PDF·m^2·yr/m^2 organic arable land
Global warming	1	kg CO_{2-eq}/kg CO_{2-eq}
Non-renewable energy	45.8	MJ/kg crude oil$_{-eq}$
Mineral extraction	5.10E-2	MJ/kg iron$_{-eq}$

The normalization is performed by dividing the impact scores by the respective normalization factors (cf. Table A4). A normalization factor represents the total impact of the specific category divided by the total European population. The total impact of the specific category is the sum of the products between all European emissions and the respective damage factors.

The normalized characterization factor is therefore determined by the ratio of the impact per unit of emission divided by the total impact of all substances of the specific category, per person per year. The unit of all normalized characterization factors is therefore [point/unit$_{emission}$] = [pers·yr/unit$_{emission}$], i.e. it is the impact caused by a unitarian emission, which is equivalent to the impact generated by the given number of persons during 1 year. Additional details are provided by Humbert et al. (2005).

Table A4: Normalization factors relative to the four damage categories for Western Europe

Damage categories	Normalization factors	Units
Human Health	0.0071[48]	DALY/point
Ecosystem Quality	13’700	PDF.m^2.yr/point
Climate Change	9’950	kg CO_2 into air/point
Resources	152’000	MJ/point

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Appendix D:
Inventory Data Quality Assessment

D.1 Data quality assessment criteria

Table D-1 presents the data qualification criteria used. These criteria concern the reliability and representativeness of the data. It should be noted that this study is simplified with the objective of not making life cycle impact assessment process overly complex, but represents an excellent overview of the type of inventory data collected.

Table D-1: Data quality criteria (quantity and process)

Score	Qualification criteria – Reliability (quantity)
1	Measured or calculated and verified data on site. – *This data meets the Reliability/precision criteria required for the study.*
2	Verified data, partly from assumptions OR Measured data but not verified (documents provided by the client or literature) – *This data is considered sufficiently accurate/reliable by the working team for the study.*
3	Non verified data, partly from assumptions OR Estimated data (good estimation performed by an expert) – *This data is considered usable by the working team, but its precision/reliability could be improved.*
4	Data grossly estimated – *This data does not meet the precision/reliability criteria for the study.*
Score	**Qualification criteria – Representativeness (process)**
1	On site data (directly linked to the scope) - *This data meets the Representativeness criteria required for the study.*
2	Good geographical/technological representativeness of the selected process - *This data is considered sufficiently representative by the working team for the study.*
3	Data related to the same process or material but referring to another technology (i.e. process from generic database) - *This data is considered usable by the working team, but its representativeness could be improved*.
4	Data whose geographic and technological representativeness are inadequate. The data is not easily accessible, another process is used to approximate the figures (proxy) - *This data does not meet the Representativeness criteria for the study.*

D.2 Results – contribution and data quality

Table D-3 summarizes the data quality assessment results.

The *Reliability* criterion refers to the quantification of the flows (materials and energy, transport distances, waste) while the *Representativeness* criterion refers to the geographic and technological validity and completeness of the selected generic data modules (processes). Finally, the potential contribution to the impacts refers to the effect that the process has on the results. A colour code was added and is presented in Table D-2.

Table D-2: Contribution and data quality criteria

Contribution		Quality	
0-5%	Potentially low or negligible contribution	1	Meets the criterion for the case studied
6-10%	Potentially moderate contribution	2	Deemed sufficiently representative
11-50%	Potentially significant contribution	3	Deemed useable, but could be improved
51-100%	Potentially very significant contribution	4	Does not meet the criterion for the case studied

It should be recalled that, as a general rule, a score of “1” corresponds to a very good assessment, while a score of “4” indicates data which should be improved in order to meet the various quality criteria. Thus, the processes for which the data quality is considered limited or insufficient are highlighted in red (score “4”) and the processes which can be improved are highlighted in orange (score “3”).

A range of values is presented for contribution and indicates the minimum and maximum contribution of the process assessed according to the six indicators considered (i.e. *Human Health, Ecosystem Quality, Climate Change, Resources, Aquatic Acidification* and *Aquatic Eutrophication*). The overall contribution of the process assessed (colour of the box) was established based on its maximum contribution, all indicators combined.

Table D-3: Contribution of the processes and data quality

Life cycle stage / Process	Contributionto the overall impact of the measure	Quality	
		Reliability (Quantity)	Representativeness (Process)
1. Extensive green roof (45 years, fertilization as needed)	100%		
Insatllation	2-43%	2	2
Maintenance	9-89%	3	3
Dismantling (100% landfilled - ELS*)	0-18%	2	3
Avoided asphalt and gravel roof	5-90%	2	2
Installation	100%		
Growing medium*	22-56%	2	2
Membranes*	22-48%	2	2
Fertiliszation, all purpose fertilizer	0-21%	2	3
Growing perennials in a greenhouse*	4-15%	2	2
Propane	0-1%	4	3
Maintenance	100%		
Avoided water treatment	29-96%	3	4
Reduced heating	1-68%	4	2
Fertilization, all purpose fertilizer	1-45%	2	3
Reduced air conditioning	0-2%	4	2
2. Reflective roof (25years, elastomeric bitumen membrane with maintenance)	100%		
Insatllation	5-13%	2	3
Maintenance	45-83%	2	3
Dismantling (100% landfilled - ELS*)	0-9%	2	3
Avoided asphalt and gravel roof	9-42%	2	2
Installation	100%		
Membranes*	70-91%	2	3
Reflective coating (initial 2 layers)*	7-29%	2	3
Propane	1-2%	4	3
Maintenance	100%		
Reflective coating (1 layer/5 years)*	99-100%	2	3
Reduced air conditioning	0-1%	4	2
3. Green wall (Fertilization for 1 year)	100%		
Insatllation	1-76%	2	2
Maintenance (100% avoided water treatment)	24-99%	3	4
Dismantling (excluded)	N/A	N/A	N/A
Installation	100%		
Black earth*	1-49%	2	2
Fertilization, all purpose fertilizer	0-99%	2	3
Landfilling in a DDS*	0-43%	2	3
Growing of perennials in a greenhouse*	0-10%	2	2
Potable water	0-1%	2	2

* The processes followed by an asterisk include, in addition to production, the transport of materials to the site where the measure is to be implemented.

Table D-3: Contribution of the process and quality of the data (cont'd)

Life cycle stage / Process	Contributionto the overall impact of the measure	Quality	
		Reliability (Quantity)	Representativeness (Process)
4. Planting arrangement (fertilization for 1 year)	100%		
Planting	2-97%	2	2
Maintenance	3-98%	3	3
Dismantling (excluded)	N/A	N/A	N/A
Planting	100%		
Black earth*	1-43%	2	2
Fertilization, all purpose fertilizer	0-97%	2	3
Landfilling in a DDS*	1-52%	2	3
Growing of perennials in a greenhouse*	1-10%	2	2
Excavator	0-1%	2	2
Mulch*	0-2%	2	2
Potable water	0-1%	2	2
Maintenance	100%		
Avoided water treatment	38-99%	3	4
Growing of perennials in a greenhouse*	0-26%	2	2
Mulch*	1-34%	2	2
Potable water	0-1%	2	2
5. Tree (fertilization for 1 year)	100%		
Planting	4-99%	3	2
Maintenance	1-96%	4	4
Dismantling (excluded)	N/A	N/A	N/A
Planting	100%		
Fertilization, all purpose fertilizer	0-98%	2	3
Landfilling in a DDS*	1-71%	2	3
Black earth*	0-19%	2	2
Tree, field cultivation (10 years)	1-11%	3	3
Excavator	0-2%	2	2
Mulch*	0-1%	2	2
Potable water	0-1%	2	2
Maintenance	100%		
Avoided water treatment	53-99%	4	4
Mulch*	1-47%	2	2

* The processes followed by an asterisk include, in addition to production, the transport of the materials to the site where the measure is to be implemented.

Table D-3: Contribution of the processes and quality of the data (cont'd)

Life cycle stage / Process	Contributionto the overall impact of the measure	Quality	
		Reliability (Quantity)	Representativeness (Process)
6. Reflective surface	100%		
Insatllation	9-61%	2	2
Maintenance (none)	N/A	NA	N/A
Dismantling	1-3 %	2	2
Avoided asphalt parking area	38-89%	2	2
Installation	100%		
Portland cement*	96-100%	2	2
Polypropylene fibres*	0-4%	2	2
Machinery	0-1 %	4	3
Dismantling	100%		
Landfilling of gravel in a DDS*	96-99%	2	3
Excavator	1-4%	2	2
7. Permeable surface	100%		
Installation	2-34%	2	3
Maintenance (100% avoided water treatment)	4-88%	3	4
Dismantling	1-10%	2	2
Avoided asphalt parking area	9-81%	2	2
Installation	100%		
Gravel*	33-58%	2	2
Cement pavers*	42-67%	2	3
Machinery	0-1 %	3	3
Dismantling	100%		
Landfilling of gravel in a DDS*	97-99 %	2	3
Excavator	1-3 %	2	2
8. Rain garden (water from roof, fertilization for 1 year)	100%		
Installation	1-55%	2	3
Maintenance	45-99%	3	4
Dismantling (none)	N/A	N/A	N/A
Installation	100%		
Fertilization, all purpose fertilizer	0-97%	2	3
Black earth*	1-43%	2	2
Landfilling in a DDS*	1-52%	2	3
Growing of perennials in a greenhouse*	0-9%	2	2
Excavator	0-2 %	2	2
Mulch*	0-2 %	2	2
Potable water	0-1 %	2	2
Maintenance	100%		
Avoided water treatment	83-100%	3	4
Mulch*	0-15%	2	2
Growing of perennials in a greenhouse*	0-2 %	2	2

* The processes followed by an asterisk include, in addition to production, the transport of the materials to the site where the measure is to be implemented.

Table D-3: Contribution of the processes and quality of the data (cont'd)

Life cycle stage / Process	Contributionto the overall impact of the measure	Quality	
		Reliability (Quantity)	Representativeness (Process)
9. Infiltration trech (water from roof)	100%		
Installation	0-30%	2	3
Maintenance (100% avoied water treatment)	35-99%	2	3
Dismantling	0-35%	2	3
Installation	100%		
Gravel*	12-24%	2	2
Landfilling of gravel in a DDS*	44-53%	2	3
Excavator	0-2 %	2	2
Dismantling	100%		
Black earth*	43-5 1%	2	2
Landfilling of gravel in a DDS*	48-57 %	2	3
Excavator	0-1 %	2	2
10. Dry well (water from roof)	100%		
Installation	0-41%	2	2
Maintenance (100% avoied water treatment)	40-99%	3	4
Dismantling	0-19%	2	3
Installation	100%		
Gravel*	38-40 %	2	2
Aluminum cover*	31-33 %	3	2
Landfilling in a DDS*	22-29 %	2	3
Excavator	0-1%	2	2
Dismantling	100%		
Black earth*	43-5 1%	2	2
Landfilling of gravel in a DDS*	48-57 %	2	3
Excavator	0-1 %	2	2

* The processes followed by an asterisk include, in addition to production, the transport of the materials to the site where the measure is to be implemented.