Environmental impact of the construction sector on life cycle: evidence of the insularity effect

Leslie Bertil, Jean-Philippe Praene, Fiona Sora, Vanessa Rakotoson

Environmental impact of the construction sector on life cycle: evidence of the insularity effect

Leslie BERTIL[1]*, Jean Philippe PRAENE[1], Fiona BENARD-SORA[1], Vanessa RAKOTOSON[1]
[1] Laboratory of Physics Engineering Mathematics for Energy, Environment and Building

[1]University of Reunion Island, 117 Rue du Général Ailleret, 97430 Le Tampon, France

*Corresponding Author: ayagapinleslie@gmail.com Tel: + (0) 262 06 93 937 706

Abstract

The construction sector is very energy- and carbon-intensive. Evaluating environmental impacts is relatively complex, but the consideration of these factors is crucial for a key mitigation strategy. The main purpose of this study was to analyze the impact of a single-family house under different geographical situations. To do so, a comparative study is proposed between France (continental location) and Reunion (insular context).
An Life Cycle Assessment approach has been used to define the impact at different steps of house construction. The specific emission was defined to take into account the mix of electricity generation, the import of materials, and the local manufacturing process. A comparative study was conducted between the French environmental Database INIES and factors created under GEMIS. This comparison provided some elements of validation of the defined processes for France. Thus, the adaptation of specific emission factors was possible for the Reunion case based on the same processes.
Among the first results obtained (civil works), an overview of the Global Warming Potential (GWP), which is defined per m^2 of residential house, was determined. The results for France and Reunion were 192.35 and 228.65 kg CO_2 eq/m^2, respectively. The difference of 18.87% highlights the effect of insularity due to the impact of building material import and mix of electricity. Thus, the greater impact of the construction sector in an island environment than in a continental environment is understandable because of products manufactured locally using a local mix of electricity. The energy vulnerability of an island area can have indirect consequences on the environmental quality of the territory.
This case study can be considered useful when defining a sustainable planning strategy that aims to reduce environmental effects. Finally, this article aspires to fill the gap in the field of LCA for the building sector in a subtropical climate.

Keywords
LCA
Environmental
Energy
Insularity
Construction

1. INTRODUCTION

The European Commission has set a long-term goal of reducing energy use and greenhouse gas (GHG) emissions. In 2015, GHG emissions in the EU-28 were recorded by 22% lower contrasted with 1990 levels, representing an absolute reduction of 1.265 billion tones of CO_2-equivalents, indicating that EU Member States will achieve and even solve the GHG targets set by 2020; it is also expected that the targets set for 2030 will be exceeded (European Commission, 2017).
The EU suggests, for a low-carbon to reduce GHG emissions to 80% below 1990 levels by 2050; the building sector (housing and office buildings) should contribute to at least 90% of this reduction (European Commission, 2012). To realize the objectives set by the European, it is of greater importance to implement new strategies for the reduction of environmental impacts, positioning on GHG emissions in the building sector. Limiting global warming requires decarbonization of the world economy which calls for a triple approach of combining efficiciency and renewable energy (Markovska, N *et al*, 2016). In the past two decades, society has begun to take an increasing interest in assessing the environmental impacts of anthropic activities such as transport, electricity generation or construction sector. Achieving the development of sustainable building projects currently involves assessments of the environmental impacts of any construction. The construction sector is well known as a large consumer of natural resources and widely contributes to greenhouse gases emission or other impacts (Carmine et al., 2018; Dimoudi and Tompa 2008).

This sector is a major consumer of natural resources, accounting for 32% of natural resource usage (M. Yeheyis et al., 2012). The construction sector is also a key contributor to fossil fuel consumption through carbon energy.
Responsible for approximately 40% of energy consumption, the building sector is one of the main drivers of environmental impacts and accounts for roughly 36% of the CO_2 emission in Europe. This significant influence is due to direct and indirect energy demand and the natural resource consumption used in materials production. Buildings significantly impact the environment, and the construction of buildings consumes approximately 50% of raw materials and products, 71% of electricity, and 16% of the water used, while also producing 40% of the waste disposed in landfills (Oduyemi et al., 2017).
From 2013 to 2035, 168,900 houses are expected to be built on Reunion. More than 60% of this demand is related to the expected increase in the number of households, (DEAL, 2018). Moreover, the Ministry of Ecology has developed specific regulations called the RTAA and adapted to the DROM, which have been in effect since 2010 for new housing, (RTAA, 2016). These regulations were revised in 2016. No specific recommendations are given to address the question of environmental sustainability. Thus, the development of specific tools to evaluate the environmental performance of buildings or houses under different climates with the objective of building or regenerating more sustainable urban environments under insular and tropical conditions is fundamental.
The main focus of this paper is to implement a Life Cycle Assessment (LCA) of a typical residential house under two different geographical contexts. The first assessment occurs in France, which is a continental situation. The second assessment takes place on Reunion, which represents an insular context under a subtropical climate. Our study first focused on a global review of the application of LCA in building construction. Then, the methodology used for this paper is described in detail. The overview highlights that no previous works have investigated the specific situation of construction impact under an insular context. Hence, the present study focuses on this specific point to identify the effect in the construction sector and to define its drivers. These first results provide the first elements for defining new guidelines for policymakers who wish to develop a decarbonized roadmap for urban development in an insular situation and a subtropical climate.
This study focuses on the environmental assessment of a building in an island environment. To date, the report reports numerous studies for the Asian and Western zones. Very few cases deal with islands. Our work fills this gap in the literature by proposing a comparative study of contruction in sub-tropical and continental Europe. The objective is thus to evaluate the parameters and decisive steps in the extra environmental cost induced by insularity.

2. OVERVIEW AND THEORETICAL BACKGROUND

To try to reduce environmental impacts, several tools and methods exist for decision support, particularly for the implementation of the sustainable development of a building (H.J Kang 2015; S. Azhar et al. 2011; Z. Alwan et al., 2016).
Life Cycle Assessment is a widely used tool for quantifying the environmental impacts of the construction sector. More than 90% of LCA case studies focus on assessing environmental impacts in the building sector (Ortiz et al., 2009). LCA has been used in the building sector since the early 1990s and is an important tool for assessing the environmental performance of buildings. The reasons for the development of LCA were the problems with rising waste accumulation and the acknowledgment of limited resources and energy supply issues (Klopffer and Grahl, 2014). LCA is considered a comprehensive method for assessing the sustainability of a building throughout its life cycle (see Figure 1) (F. Asdrubali et al., 2013). LCA has evolved considerably over the years and is now a useful decision-making tool for assessing the environmental impacts of building materials

and facilitates the optimization of selecting among alternatives (Finndeven et al., 2009; Jeswani et al., 2010; Ding, 2014).
LCA can be broken down into four standardized steps as shown in Figure 2. The standardized methodology for LCA studies was first published by the International Standards Organization (ISO) as part of the ISO 14040 series in 1990s. The ISO 14040 series provides a standardized method of tracking; reporting; compiling; and evaluating the inputs and outputs, as well as the potential environmental impacts of a product, process or system throughout the life cycle. In accordance with ISO 14 040: 2006, which specifies the principles and framework applicable to conducting life cycle assessments, the definition of the LCA objectives and scope, the life cycle inventory phase, life cycle impact assessment phase, life cycle interpretation phase, life cycle analysis limitations, the relationship between life cycle analysis phases and conditions of use of the choice of values and elements are included. In a four-phase LCA study, the first step consists of the definition of the objectives and the scope of the study (which includes the system to be studied, the functions of the system, the functional unit, the boundaries, and the categories of impacts taken into account). Then, the second phase is the inventory of incoming material and energy flows (including raw materials, materials) and outflows (byproducts, liquid and solid waste). The third phase is the assessment of potential impacts from identified material and energy flows that are related to potential impacts due to uncertainties. Finally, the interpretation of the results obtained, according to the established objectives, is the last phase of the LCA. Interpretation is done at each step to verify that the objectives are met as they arise. This interpretation phase summarizes and analyzes the results of the study to draw useful conclusions for decision-making within the framework of the objectives initially set (Russel et al., 2005).

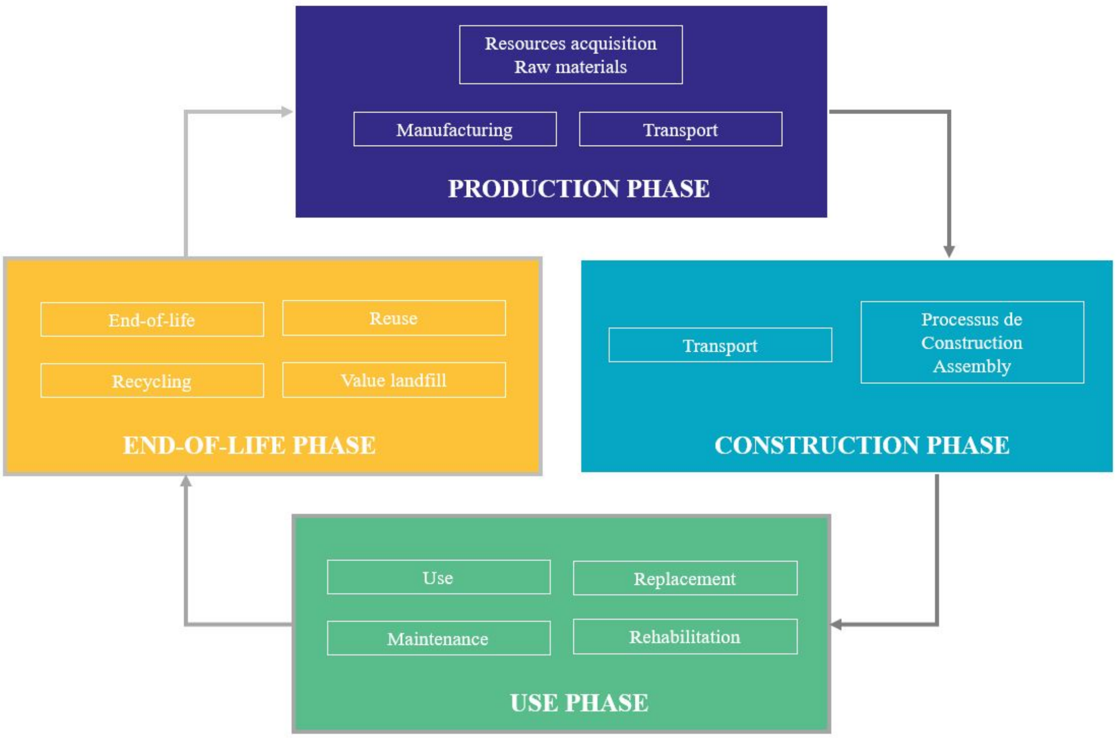


Figure 1 Life Cycle Assessment (LCA) of material, products, and system

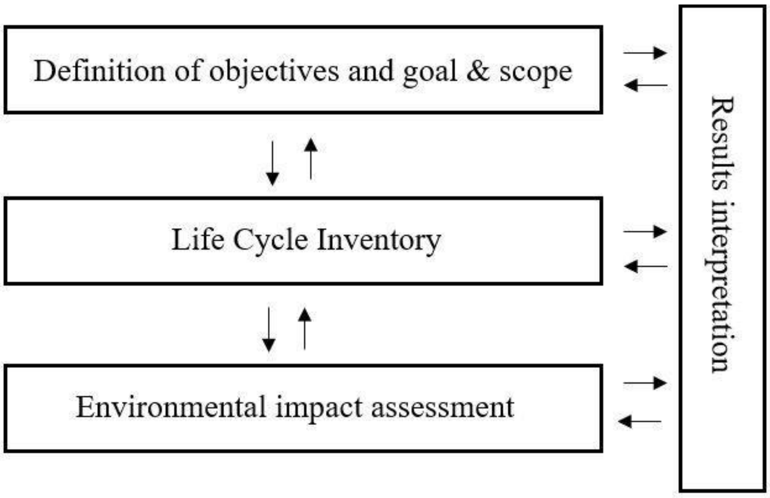


Figure 2 Four normalized steps of LCA

According to Anne Ventura, LCA is a "systemic methodology analyzing assessing which allows the assessment of anthropic impact. It aims to implement a rational approach to address the issues of sustainable development" (Anne Ventura, 2012). Other publications also define LCA as an analytical method, a multicriteria approach that evaluates the environmental impact of a product, service or system (Baumann et al., 2014; Bruno Peuportier et al., 2011; CSTB, 2018).
At the scale of the product or construction material, LCA can be conducted from the extraction phase to the end of life phase, with the possibility of taking into account material reuse and the recycling of landfills. The life cycle analysis of building products or materials corresponds in France to the Environmental and Sanitary Declarations Sheets. These sheets make it possible to evaluate the environmental characteristics of different sectors of products or building materials such as wood or concrete. Because of the relatively long life of building materials and because they often suffer significant damage and changes, an LCA was originally developed for the design of low-environmental-impact products, then it was expanded and used in the construction sector because materials and construction products have a specific data definition based on the following:

- they have several functions;
- they contain many components;
- they are produced in different parts of the Earth, which explains their complexities and their specificities.

LCA studies not only allow assessment of the impact of products and materials so that environmentally friendly materials can be produced and used in the design and construction of building but also, they allow the study of the environmental quality of materials or building systems. That is important because the results can provide significant information on the way low-impact materials are processed or the way processes are optimized for manufacturing, as well as showing the associated impacts throughout the life cycle of a product.
However, the application of LCA remains complex to use because data are limited. Deficiencies remain in data with respect to environmental indicators and how to present the results of LCA to users but also in how to simplify and adapt LCA for various purposes. Studies also indicate that existing studies in LCA are difficult to compare because of their specific properties, such as building type, climate, comfort requirements, and boundaries (Ortiz et al., 2009; Buyle et al., 2012). The

factors impacting the sustainability performance of a building may vary according to the project type, scale, location and process.
However, thanks to the standardization of the LCA methodology, the ISO has presented it as a clear framework that stakeholders can follow during their LCA study (Finkbeiner, 2014). LCA is being used more and more today at the scale of buildings because new buildings can cause environmental consequences that can compromise the ability of future generations to meet their needs (depletion of resources, eutrophication of rivers, acidification of rainfall, and production of radioactive waste). In France, with respect to these environmental consequences, several tools have been developed (Peuportier et al., 2004) that aim at minimizing the environmental costs induced by the construction of a building. Each building is unique and has a strong interaction with the site and the occupants. The lifespan of buildings is generally longer than that of current industrial products. However, buildings include a large number of materials and components, and their design processes appears to be complex, involving many actors. The LCA of buildings is a scientific methodology that is clearly accepted for the environmental assessment of buildings over their lifetime, taking into account impacts upstream (Anderson et al., 2015).
This paper proposes an approach to measure the effect of insularity in the case of the LCA of a single-family house, aiming to assess its environmental impact in continental and tropical environments and to define the representative part of insularity through this impact. Given the current context—the increase in energy prices, the reinforcement of the climate threat and the environmental impacts associated with energy consumption, the development of "more sustainable" cities from the social, environmental and social points of view—beginning with the construction of sustainable buildings, is necessary.

3. MATERIALS AND METHOD

The life cycle of a system has a significant effect on its total environmental performance. Consequently, the energy and materials that are consumed for the extraction of raw materials, transportation, maintenance and disposal stages of the life cycle are some of the indicative key factors that affect the total environmental performance of a system (Gaidajis and Angelakoglou, 2012).
This study proposes to analyze the environmental performance of a single-family house in production phase in two different environments: continental and tropical. Consideration of both the structural aspects and the joinery work is important. In Reunion, the joinery is assembled locally in Reunion; therefore, in this case, joinery is considered as part of the construction phase.

3.1. Methodology

This work is considered in two stages: a first stage, in which the raw emission factors are defined, and a second stage, during the production, when the emission factors are quantified by impact categories.
As indicated in the article, our approach is based on the LCA approach. We have built the database of materials and processes in order to be able to refine the impacts to the specific context of France and Reunion Island. The energy and process mix data are those of 2017 for France and 2018 for Reunion Island.
Various LCA tools have been developed and made available for use in environmental assessment. These tools have been classified according to the following three levels:

- LEVEL 1: Product comparison tools
- LEVEL 2: Whole building design decision or decision support tools
- LEVEL 3: Whole building assessment framework or systems

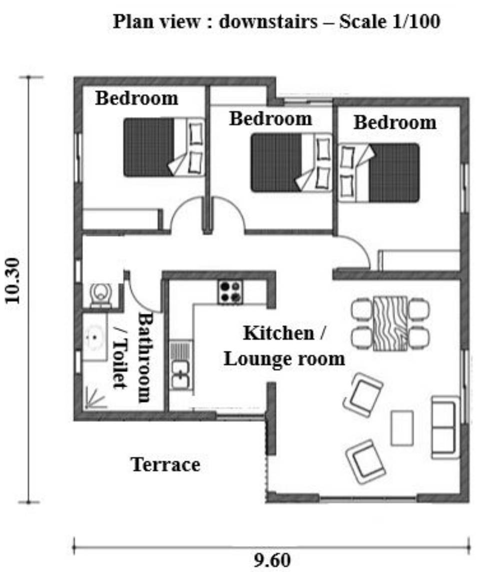
This study takes into account level 3.

Many databases are currently used for environmental evaluation: CML, DEAM TM, Ecoinvent Data, IINAS, Gabi 4 professional, IO-Database, Simapro Database, and the U.S. Life Cycle Inventory Database (Centre for Design at RMIT, 2001; Erlandsson M et al., 2003; Forsberg A et al. 2004; Larsson N, 2006). In France, an official reference database, INIES, is also available.

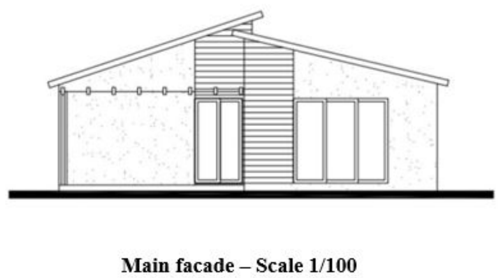
In this paper, a quantitative budget and database availability for calculating emission factors by impact category were necessary. The software used to calculate the emission factors was the **G**lobal **E**missions **M**odel for **I**ntegrated **S**ystems (Part **3.4.1;** GEMIS).

3.2 Case study

The selected case study is a single-family house, with an 88 m^2 net floor area. Figure 3 shows a 1/100 scale ground plane and a front facade plan of the studied house. It is a single-story house, comprising 3 bedrooms, a kitchen/lounge room, a bathroom and toilet, exclusive of the terrace.



(a) Ground plane



(b) Front façade

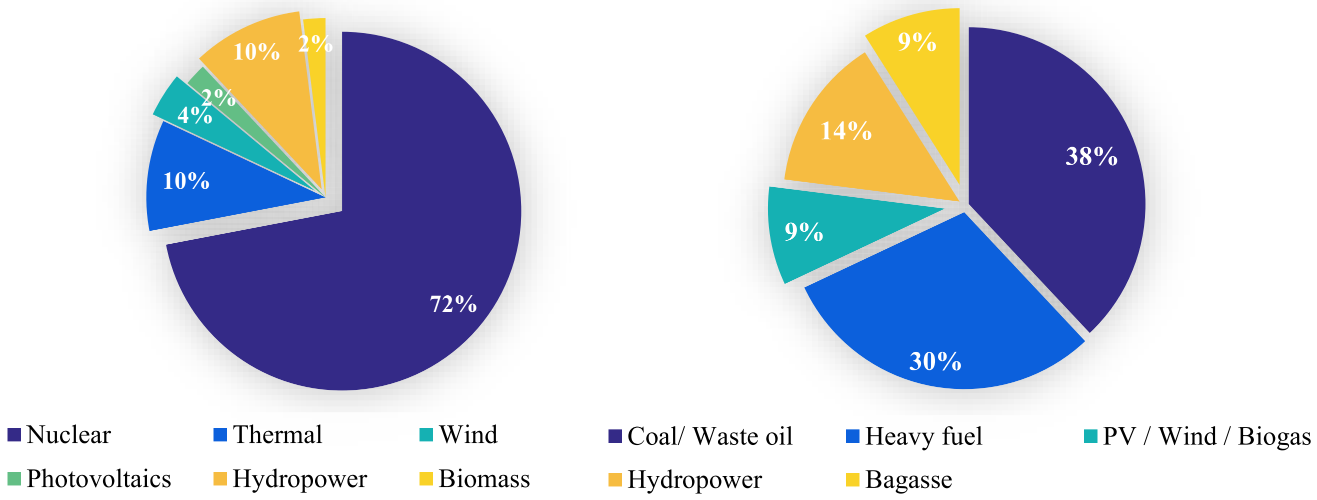
Figure 3 Single-family house

A house was used in each of the two different locations:

- The first house is in a continental environment: France.
- The second one is under a tropical insular context: Reunion island.

A comparative study identified effects based on those two locations.

As a French ultramarine region, Reunion Island has characteristics specific to its insularity. The economy of the island is highly dependent on France. Its geographical characteristics (remoteness, relief, climates...), socioeconomics and politics shape a territory largely dependent on the outside. The trade balance is in deficit, and few materials are produced locally (IEDOM). Reunion is a noninterconnected territory. This means that all electricity must be produced locally. However, electricity production is highly dependent on fossil imports (BER, 2018). The energy dependency on fossils resources was 87% in 2017 (BER, 2018). Diesel and coal are the main contributors to the electricity mix, with a contribution of 68% in total production (BER, 2018). As shown in Figure 4, in France, the local electricity mix is mainly dependent on nuclear energy. With this feature, the electricity mix has an environmental impact of 83.02 kg CO_2 eq, while the electricity mix of Reunion Island has an environmental impact of 662.63 kg CO_2eq. The environmental impact of Reunion's electricity mix is therefore much higher than that of France. This is due to the importance of coal in the Reunion electricity mix.



(a) France (b) Reunion

Figure 4 Electricity mix in France and Reunion

Reunion Island has an area of 2512 km^2, with a population concentrated mainly in the littoral zone. This is partly due to the highly rugged terrain in the center of the island (Fiona Bénard-Sora, Jean Philippe Praene, 2018). The Reunion Island area has multiple constraints and is strongly marked by social, economic and environmental inequalities (Thierry Simon, 2008). Reunion Island has always had constraints imposed by the very strong climatic context: however, it is exposed to multiple hazards such as eruptive volcano, heavy rainfall, rising water during cyclones, instability of slopes, and land movements (Thierry Simon, 2008). Despite these constraints, the island has been pursuing urban development projects for the last 30 years and is responding to the needs of the Reunion population for the construction or rehabilitation of sustainable buildings and neighborhoods (Thierry Simon, 2008).

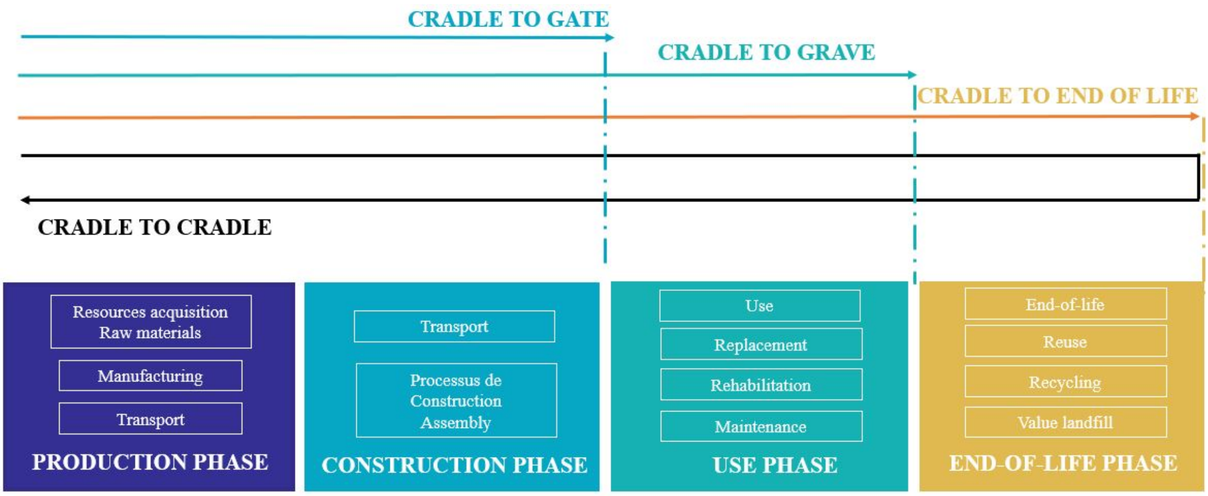
3.3 Assumptions of the study

The scope of the study and the functional unit are defined in this section. The categories of impacts and indicators selected for the case study are presented. The life cycle inventory and modeling software are listed. Finally, the validation of methodology is also established.

3.3.1 System boundary

The ISO standard defines four different levels of life cycle: cradle to gate, cradle to use, cradle to the end-of-life and cradle to cradle. These four levels and their joints are represented in the Figure 5. In this work, the “cradle to gate” level is considered. Energy and mass flows and environmental impacts have been assessed from the production of raw materials to the manufacture of the end-product, following the cradle-to-gate approach (Figure 5).

Figure 5 LCA boundary conditions – based on ISO 14040



3.3.2 Functional unit and calculation methodology

According to the ISO 14040 standard, the functional unit (f.u) is defined as the reference unit through which a system performance is quantified in an LCA. In this paper, the square meters of total built-up area of the building per year is the functional unit.

The aim of the study was to determine the total emissions E_T and the total and product impact ratios (respectively R_T and R_i), as follows:

$$E_T = \sum_{i=1}^{n} e_i$$

with $e_i = q_i.FU_i.FE_i$

where

e_i is the emission for a product i,
q_i is quantity of a product i,

FU_i is a functional unit product i, and
FE_i the emission factor obtained in GEMIS software for a product i.

$$R_T = \frac{E_T}{S}$$

$$R_i = \frac{e_i}{S}$$

where S is the net floor area.

3.3.3 Impact category

The working environment chosen for the emission factors calculation is the GEMIS software. It defines emission factors for four categories of impacts in its results. For each category, impact indicators represent a part of the environmental impact. This study focuses on three specific categories of impacts, represented by six indicators as specified in Table 1.

Table 1 Indicators considered in this case study

IMPACT CATEGORIES	INDICATORS	UNIT
GREENHOUSE GAS EMISSION INDICATORS	Global Warming Potential (GWP)	kg CO_2 eq
AIR EMISSION INDICATORS	Pollution of nutrients due to pollution (ACIDIFICATION)	kg SO_2 eq
	Tropospheric Ozone Pollution Project (TOPP)	kg
	Non Methanic Volatile Organic Compounds (NMVOC)	kg
OPERATING INDICATOR RESOURCES	Cumulative Renewable Energy Consumption (CEC - R)	GWh
	Cumulative Nonrenewable Energy Consumption (CEC- NR)	GWh

The choice of indicators was made according to the most frequently used indicators in the scientific literature. Among all the indicators used in the literature, GWP is the most widely used, especially in the construction sector.

As presented in the calculation methodology (see section 3.3.2), the indicators were then used for the calculation of ratios in MATLAB software.

3.4 Life Cycle Inventory and database

A life cycle inventory (LCI) phase is an inventory of the input and output data in the investigated study (United States Environmental Protection Agency, 1993). The inputs of an LCA study include the required energy and the raw materials, whereas the outputs are fundamentally solid, liquid, and gas waste materials that are released into the natural environment as consequence of the process (ISO 14040,2006). This phase involves the collection of all necessary data for the calculation of the environmental impact; these data can be retrieved from relevant studies, industrial, governmental and public databases, and scientific publications, as well as from established local and global databases of the employed LCA tool. The main limitation in conducting LCA studies of buildings is having access to up-to-date data. Around the world, many gaps in data exist because no accurate life cycle inventory data are available for all materials in buildings. In this paper, the inventory phase started from the analysis of the production process of extraction of raw materials: data were retrieved from the INIES database, and emissions factors had been calculated by different organizations.

3.4.1 Modeling software

Many design software packages are available and have been used in the Life Cycle Analysis of materials, products, systems or at the building scale to assess the environmental quality of buildings. The Table 2 lists all available software.

Table 2 Summary table of software used in LCA

SOFTWARE	USE	DESCRIPTION
ALCYONE	Geometric description of the building	2D-3D modeler: transfer of architectural data to the COMFIE thermal simulation tool
COMFIE	Thermal simulation (energy)	Model imported from ALCYONE supplemented by data on the use of the buildings, then the simulation is carried out using hourly meteorological data
EQUER	Life Cycle Analysis (LCA) of buildings (buildings impacts)	Model imported from COMFIE, supplemented by data on waste, water consumption, commuting
ARIADNE	Complete all the previous tools at the building level (neighborhood impacts)	EQUER results are imported for each type of building
ELODIE	Calculation of the environmental impact (building impacts)	Quantifies the environmental impacts over the entire life cycle of the building
GEMIS	Analyzes the energy part in decision-making processes	An energy planning tool, help to impose the analysis of environmental impacts as an integral part of decision-making processes in the field of energy savings at the municipal level

GABI	Models and traces the life cycle of materials	Models the life cycle for more than a thousand different industrial processes, draws up life cycle assessments
BEES	Assisting in the selection of the choice of construction products	A tool for measuring different performances, measuring the environmental performance of the production of buildings using the LCA approach
SIMAPRO	Analyzes environmental performance and calculation of uncertainties	Analyzes the results, compares the products with each other, models and analyzes the environmental performances, calculation of uncertainties by means of "Monte Carlo" type analyses
OPEN LCA	Life cycle assessment, sustainability	Calculation on sustainability, identification of key drivers throughout the life cycle by process category, flow or impact
CARBON FOOTPRINT	Diagnosis of greenhouse gas emissions	Assesses and reduces GHG emissions generated by a company's activities directly or indirectly, measures the carbon footprint
TEAM BÂTIMENT	Database Design, ACV realization	Builds and manages large databases, models all systems representing different operations related to a company's products, processes and activities

In this case study, the calculation of emission factors of the single-family home in France and on Reunion were calculated using German software. The GEMIS database contains the basic information for the model and consists of approximately 10,000 processes in more than 30 countries for the following groups:

- **energy carriers**: fossil, renewables, grass, Jatropha, and oil […] as well as hydrogen and uranium.
- **electricity and heat supply:** cogeneration and power plants for many sizes and fuels, district and local heating, and boilers […] including upstream processes and materials for construction.
- **materials:** base chemicals, construction materials, plastics, and metals […].
- **transport:** car (for biofuels, CNG, diesel, electricity, and gasoline), public transport, and airplanes, as well as freight transport (train, truck, pipelines and ships, including upstream processes and materials for construction).

In the GEMIS software, many databases are available, including IINAS, which are Open Sources.

GEMIS has been chosen for this work, as it is an open source software. Thus, the possibility exists to modify generic existing processes in the database without constraints.

Once the emission factors are retrieved under GEMIS, MATLAB software was used to analyze data, develop algorithms, and create models.

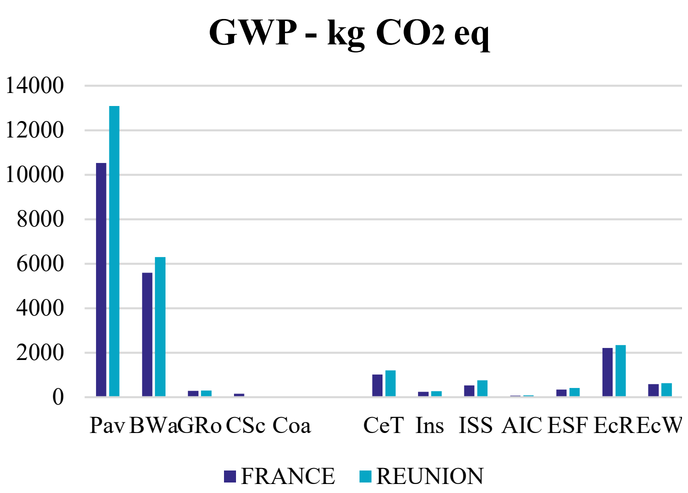
3.4.3 Element of validation

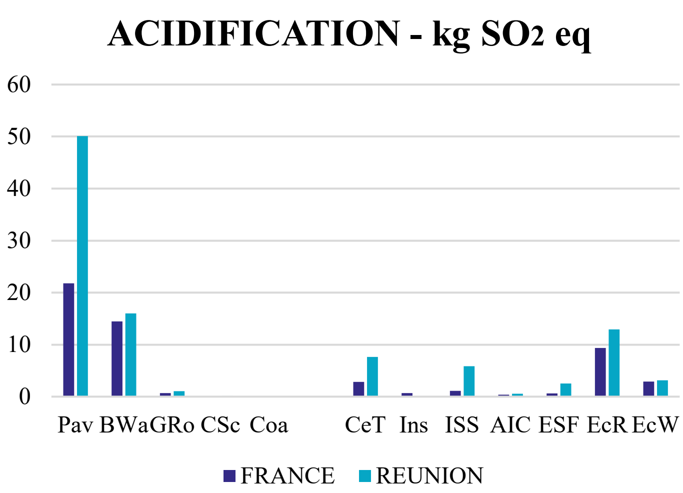
The INIES database was used to validate the method. Indeed, INIES provides the reference emission factors for France. For Reunion Island, no reference database is currently available. Consequently, the comparison between INIES and the results obtained in the study for France is used to validate the method. For each product on INIES, several emission factors depend on the source institution. An interval based on the minimum and maximum emission factors for all organisms is therefore used for validation.

4. RESULTS AND DISCUSSION

4.1 Overall results

To evaluate the environmental impact, the first element to be analyzed was the total emissions. Figure 6 shows the total emissions by indicator, by location, by selected structural parts, and by joinery work. For more readability of the results, the names of the materials are specified in abbreviated form. The nomenclature used is available in Annex 1.





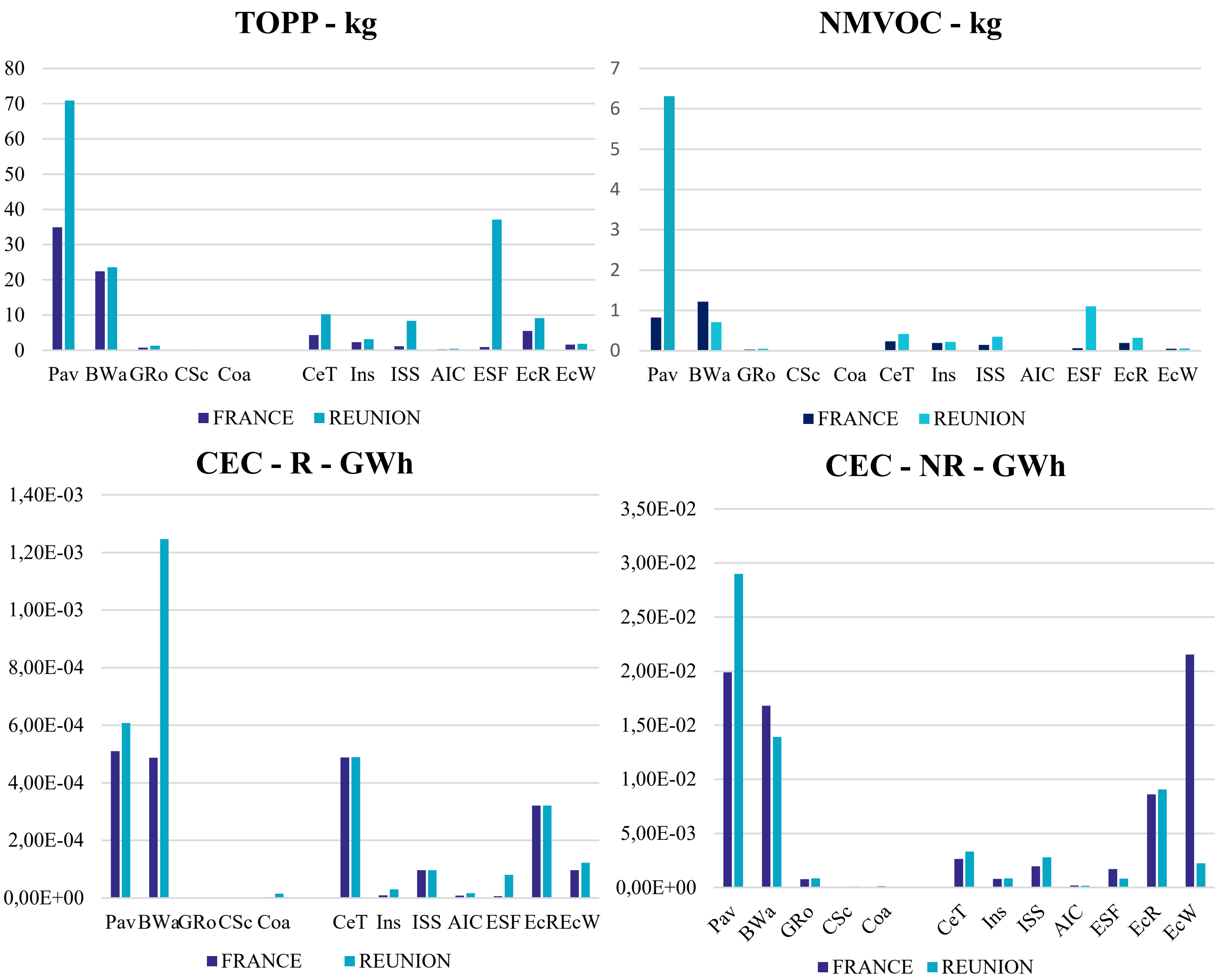


Figure 6: Total emissions by indicators for France and Reunion - structural part and joinery work

The total emissions in Figure 6 clearly show that the GWP indicator is mostly more emissive than the other indicators studied. In France, the GWP indicator is greater than 15,000 kg CO_2 eq for the structural part and just over 4,900 kg CO_2 eq for the joinery work. In Reunion, this indicator represents more than 20,000 kg CO_2 eq for the structural part and just over 5,600 kg CO_2 eq for the joinery work. A better understanding of the impact of the GWP is important, which is achieved by breaking it down by product to identify the most impacting products and materials. On the whole, the Pav, BWa, ExC and CeT are the most emissive materials wherever the location site (see Figure 7).

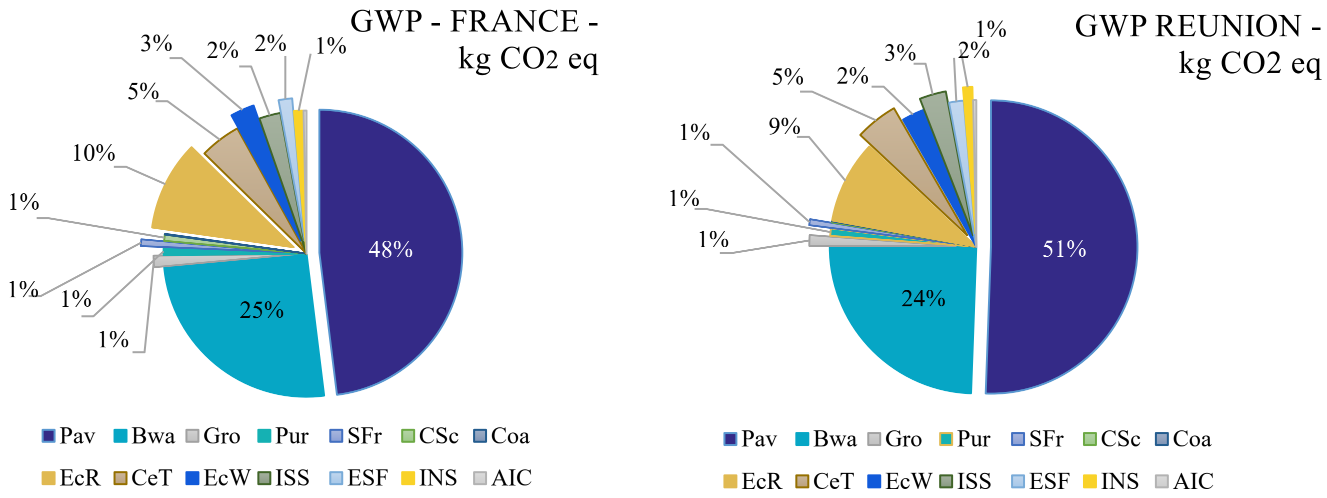


Figure 7: Ratio by indicators for France and Reunion - structural part and joinery work

Among the four most emissive materials, three scenarios are possible. For Pav and BWa, the elements are entirely extracted and produced locally. For CeT, the product is imported by sea and sold directly on the island without transformation. For aluminum joinery, maritime transport and assembly on the island are required, which introduces an additional impact due to the use of electricity. As shown in Figure 8, these four materials show high rates at the GWP indicator for France and Reunion. The results for Reunion are even higher than for France, with an average difference of +15.40% for Reunion rates. This difference can logically be explained by the composition of the electricity mix of Reunion Island and by the required maritime transport, which the island cannot avoid.

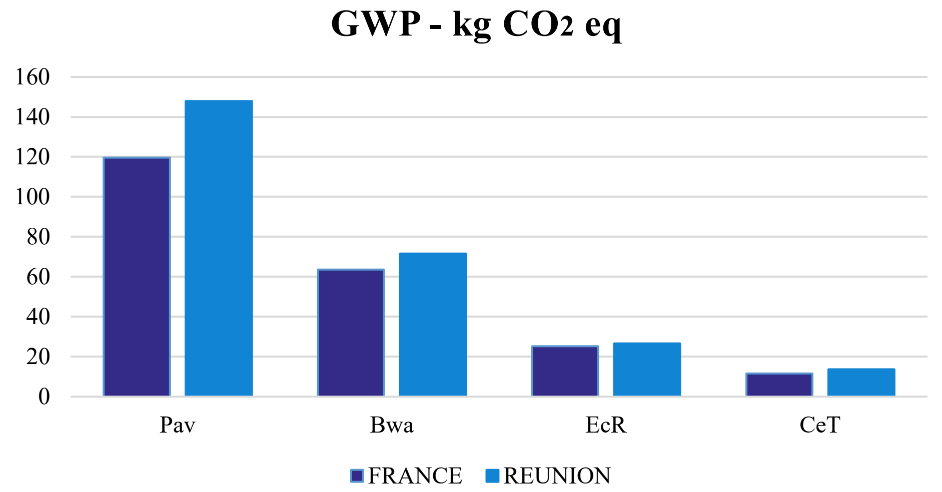


Figure 8: GWP by products in France and Reunion

Figures 7 and 8 show the impact of these four building materials. Therefore, one can question the choice of these materials: their use occurs because their environmental impacts are poorly known or because no better substitute currently exists for these materials. The choice of products and construction materials can vary as well depending on their technicality (material resistance, lifespan, etc.), their price (best value for money), their availability (available immediately locally or need to import), their location (proximity, etc.). When materials to be used are chosen, consideration of the local labor market is important, especially as the construction sector is an important sector of the island (Bilan Économique de La Réunion en 2017, 2018).

4.2 Breakdown per building element

The study shows a much greater environmental impact in Reunion than in France, with a difference of more than 17.78% between the two results. Indeed, the environmental impact of the house is 293.4 kg CO_2 eq/m^2/years in Reunion for only 249.1 kg CO_2 eq/m^2/years in France (Figure 10). The distinction between the structural part and joinery work similarly shows higher results for Reunion than for France. The 228.65 kg CO_2 eq impact of the structural part on Reunion Island, 18.87% more than in metropolitan France, is due to construction products and materials, with higher emission factors for the environment. Those materials are Pav and BWa. The highly-carbonated electricity mix of the island greatly impact both materials, which are produced locally. Although, for France, these materials are also the most emissive because of the local transport (long distances to travel by train or truck), the significant share of coal in the electrical mix of Reunion explains these important results (see Figure 4). In France, slightly more than 56.78 kg of CO_2 eq is required for the joinery work, whereas Reunion has more than 64.77 kg of CO_2 eq.

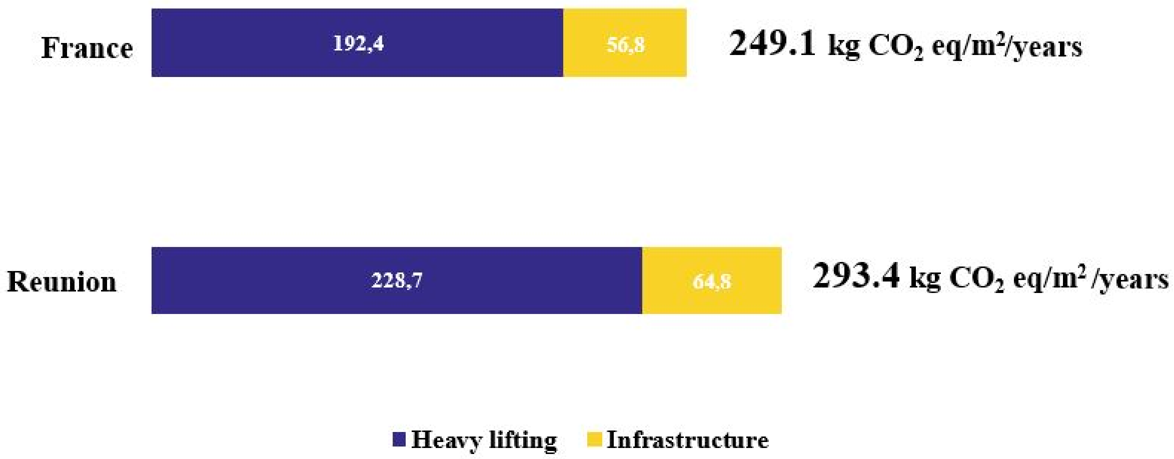
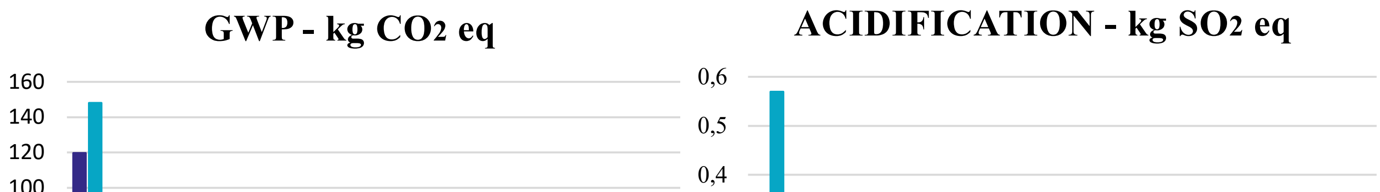


Figure 10: Ratios for France and Reunion - structural part and joinery work

As shown in Figure 10, regardless of the product and material analyzed, the ratio for Reunion is always larger. By observing the structural products more specifically, the analysis of the different impact indicators shows, in the same way as for the previous results, that the GWP indicator is predominant (see Figure 11). Similarly, Pav and BWa are the most impacting. A closer analysis of the joinery work shows the two most impacting materials are ExC and CeT.



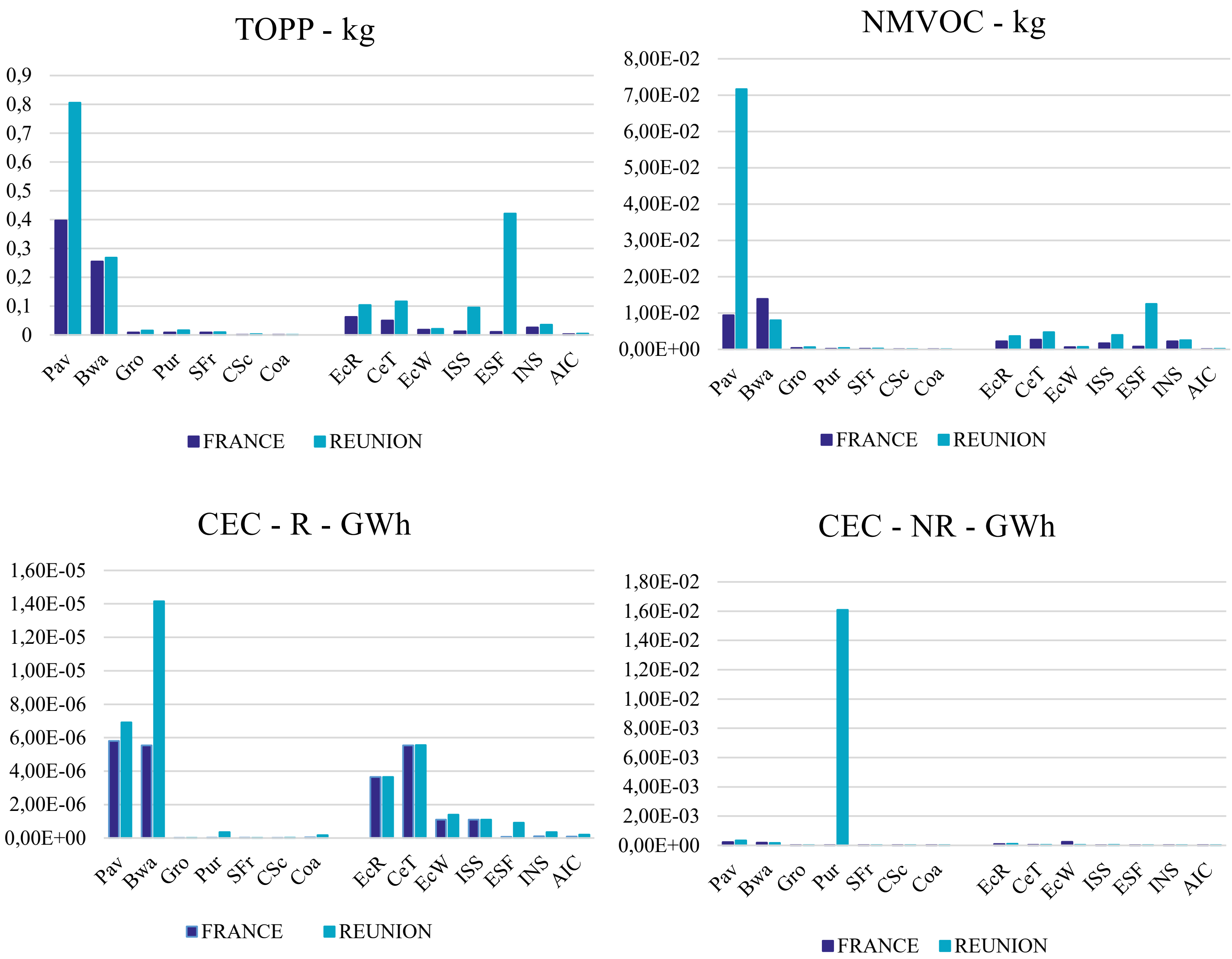


Figure 11: Ratio by indicators for France and Reunion - structural part and joinery work

4.3 The other impact categories

The results presented so far emphasize the predominance of the GWP indicator. Nevertheless, the other indicators should not be discounted. Table 4 shows that the ratios are always higher for Reunion than for France. Thus, regardless of the impact category or indicator analyzed, Reunion always shows higher results. This observation truly makes it possible to question the impact of insularity in these results.

The indicators with more impacting emissions are mainly acidification, TOPP and the NMVOC. The air emissions indicators are also more impacting than the resource exploitation indicators.

Table 4: Ratio of the products and materials of the structural part and joinery work in France and Reunion

PRODUCTS	ACIDIFICATION	TOPP	NMVOC	CEC - R	CEC - NR
STRUCTURAL PART					
Pav	0.25	0.397	9.37E-03	5.80E-06	2.26E-04
Bwa	0.16	0.255	1.39E-02	5.53E-06	1.91E-04
Gro	0.01	0.009	3.91E-04	6.21E-10	8.76E-06
Pur	0.01	0.009	1.97E-04	2.91E-08	6.72E-06
SFr	0.01	0.008	1.79E-04	2.77E-08	6.05E-06
CSc	4.13E-04	0.001	1.93E-05	6.47E-09	3.03E-07
Coa	3.76E-04	3.59E-04	4.10E-05	3.28E-08	1.16E-06
JOINERY WORK					
EcR	0.11	0.063	2.26E-03	3.64E-06	9.79E-05
CeT	0.03	0.050	2.66E-03	5.54E-06	2.99E-05
EcW	0.03	0.018	6.10E-04	1.10E-06	2.45E-04
ISS	0.01	0.013	1.67E-03	1.10E-06	2.22E-05
ESF	0.01	0.010	7.79E-04	7.07E-08	1.95E-05
INS	0.01	0.026	2.22E-03	1.09E-07	9.05E-06
AIC	4.47E-03	0.003	7.89E-05	9.16E-08	2.09E-06

4.3 Effect of insularity

To refer to insularity is to emphasize isolation and specificity and sometimes even singularity. An island territory presents an original spatial organization; having its own geophysical limits, insularity refers to the finitude of an island, to a limited stock of resources and to the fragility of endemic species being subjected to very localized anthropic pressure (Thierry Simon, 2008). Since the 1950s, Reunion has embarked on a process of economic catch up with France. At the same time, it has not yet completed its demographic transition, which has created a need on the island for housing and buildings (Fiona Bénard-Sora, Jean Philippe Praene, 2016). The construction of these buildings (single-family houses, collective housing dwellings, office spaces, and commercial buildings) on Reunion Island often encounter constraints related to the unavailability of immediate resources, i.e., to the time related to maritime transport. This is one of the main constraints of insularity that we can highlight here: the import of materials. However, this is not the only constraint. When the material is produced entirely or simply assembled on the island, the environmental impact will also be influenced the environmental quality of the electricity generation. Because of its insularity, fossil fuels are still dominant in the electricity mix. As the electricity is highly carbonized (share of renewable sources < 35%), its use consequently impacts the environmental balance of the construction sector when electricity is used for the processes.

In this case study, we now focus on the elements for an explanation of the differences in the obtained results: the single-family house located in France (continental context) had a higher environmental impact when it is installed on Reunion Island (insular context). Figure 12 shows the representative part of the effect of insularity when the environmental impact of a building was assessed. The effect of insularity is visible in the share of the electricity mix and the share of maritime transport.

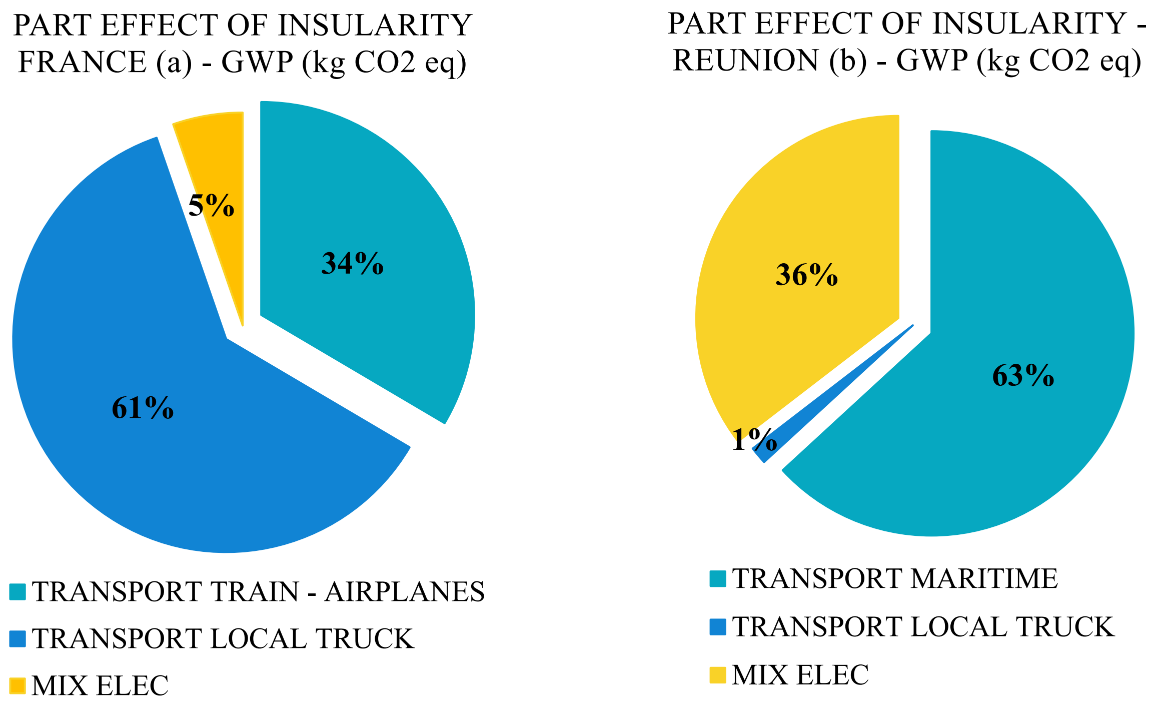


Figure 12: Global representation of the effect of insularity through the single-family house studied (GWP) in France (a) and on Reunion (b)

The choice of the origin of products or building materials that were used to build this single-family house in France and on Reunion allowed an initial explanation that, depending on the location of the house, the type and the transport distance is “specific,” depending on the layout of the house. In the continental hemisphere, the choice of products, construction materials and import choices are not the same as those of the tropical environment, which automatically includes maritime transport as one of the only means of transporting construction. The share of local transport is greater in France (61%), whereas the share of maritime transport is most important for the insular environment (63%). The transportation of materials to the construction site has inherent environmental impacts to the energy consumption and GHG emissions associated with the mode of transport, such as trucks, ships or aircraft. As discussed by John and al, 2009, in the case of their study in the USA, road transport was considered because of high distance in the country. However, in our case, due the small size of the island (63 km long and 45 km wide), we have made the assumption that road transport is negligible.
The impact of maritime transport is more marked for Reunion, which exhibits a geographical constraint and an unavailability of the majority of raw material resources. A large part of the construction products and materials are imported from China, Europa, Italy, Indonesia, etc. In addition, the local electricity mix, which has a minimal impact for France, is a major impact on Reunion. The large share of nuclear energy in the French electricity mix and the large share of fossil fuels in the Reunion electricity mix explain these results (see Figure 4).

5. CONCLUSION

The requirements for a sustainable building, a sustainable neighborhood, or a sustainable city are numerous in the construction sector. Since 2015, among the existing labels, a new label has appeared, indicating not only the “energy performance” but also the “environmental performance” of buildings. This “Positive Energy and Carbon Reduction” or “E+C-” label, which has allowed the evolution of the regulations and the improvement of the energy performance of buildings, should contribute to the generalization of low-carbon buildings. With a strong environmental impact, the construction sector is experiencing environmental crises such as resource consumption, greenhouse gas emissions, water use, and energy consumption […].
development of the LCA approach according to the ISO 14 040 standard makes it possible, in a clear framework, to analyze each phase of the life cycle of a material, product or system, thus making it possible to obtain the emission factors of each phase. The LCA approach was conducted to assess the environmental impact of a single-family house to compare and highlight the share of effect that insularity has in the total impact of the construction of the individual house. Located in the continental environment, the construction of the single-family home is based on the sourcing of building products and materials from Europe and other continental countries. On the other hand, the origin of the materials or construction products for Reunion come from India, China, and Italy […].
This paper allows to defining a ratio to the m^2 built of a single house located in two distinct places (in a continental and tropical environment). It allows a comparison of the environmental impact that construction ca generate depending on its location. The results highlight through this case study that Reunion is double sanctioned 228.65 kg CO_2 eq/m^2 against 192.35 for France. This environmental cost more consequent for the island is mainly induced on the one hand by its many imports, but also by electric mix.
The Island has almost no resources of raw materials, and taking into account its small size, the importation of products and building materials from several continents (near and far, depending on the needs of raw materials) is imperative. However, possibly, in the short-to-medium term, the local carbon-based electricity mix can be modified by favoring more renewable energies, such as wind

turbines, photovoltaic panels or maritime energies, for the purpose of have a deduction in pollution emissions and a less significant environmental impact in the medium term.

However, another alternative that might be favored so that the construction sector will have less environmental impact would be to directly import the finished products to the island for distribution, without permanent use of the local mix of electricity. However, this alternative is not without consequence because, although it lowers the environmental impact, it would have a greater impact on the Reunion economy because a greater need would exist for local labor to work on the semifinished products before their distribution.

The final scope of this study was to initiate a first approach to discuss environmental impact in an insular and subtropical context. This research aims to share the results and tools in order to influence the decision-making of the various stakeholders for the integration in the near future of environmental impact regulation for France in the overseas energy and environmental regulation RTAA.

This paper, therefore, contributes to highlight the weight of insularity in the implementation of a building during its construction in a tropical environment. However, we should try to reduce this environmental impact for Reunion by integrating more renewable energies in its high carbon electricity mix.

The island should also consider importing its products and building materials from nearest countries to mitigate a significant additional environmental cost due to shipping.

The discussion on environmental impact is closely linked to economical concern. Indeed, the strategy for materials import is a difficult balance to achieve between economy and environment. On the one hand, as Reunion has an electricity mix mainly based on fossil fuels it currently looks interesting to focus on finished products imports. On the other hand, in the Reunion construction sector is the most employment-intensive in the private sector. It is therefore important to maintain the development of the economic activity of the building sector.

Acknowledgments: This project has received funding from the National Association for Research and Technology and Fibres Industries Bois under grant agreement **N° 2017/1242**.

6. References

- Asdrubali. F., Baldassarri C., Fthenakis V., 2013. Life cycle analysis in the construction sector: Guiding the optimization of conventional Italian buildings. *Journal of Energy and Buildings*.
- Anderson J.E., Wulfhost, G & Lang, W., 2015. Energy analysis of the built environment - A review and outlook *Renewable and Sustainable Energy Review*, 44
- Anne Ventura. 2012. Approche systémiques et éco-conception. Une réflexion sur les fondements conceptuels et les applications de l'Analyse de Cycle de Vie. Génie Civil. Université de Nantes
- Baumann, H., Tillman, A., 2004. The Hitch Hiker's Guide to LCA. Lund : Studentlitteratur AB.
- Bilan économique de La Réunion en 2017. 2018 https://habiter-la-reunion.re/economie-a-la-reunion/
- BER 2018. Bilan Energétique de La Réunion. Edition 2017. http://energies-reunion.com/wp-content/uploads/2015/01/BER-Technique-2018-very-BD.pdf
- Bruno P., Morgane C., Cédissia de C., Youssef D., Christophe G., Grégory H., Thibaut J., Charlotte T., Maxime T. 2011 : Analyse de Cycle de Vie à l'échelle du quartier : un outil d'aide à la décision

- Buyle, M., Braet, J. & Audenaert, A., 2012. LCA in the construction industry : a review. *International Journal of Energy and Environment*, 6 (4)
- Carmine Cavalliere, Guido Raffaele Dell'Osso, Alessandra Pierucci, Francesco Iannone, 2018. Life cycle assessment data structure for building information modelling, *Journal of Cleaner Production,* Volume 199, Pages 193-204, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2018.07.149.
- Centre for Design at RMIT. 2001. Background report LCA Tools, data and application in the building and construction industry. http://buildlca.rmit.edu.au§menu8.html
- CSTB Editions. 2018 Bâtir le développement durable – L'Analyse du cycle de vie dans le bâtiment .
- DEAL, 2018, Les besoins en logements à La Réunion à l'horizon 2035.
- Dimoudi, A., Tompa, C., 2008. Energy and environmental indicators related to construction of office buildings. *Resour. Conserv. Recycl.* 53, 86e95. https://doi. org/10.1016/j.resconrec.2008.09.008.
- Ding, G.K.C., 2014. Life cycle assessment (LCA) of sustainable building materials : An overview. In : Pacheco-Torgal, F., Cabeza, L.F., Labrincha, J., de Magalhaes, A (Eds) Eco-Efficient Construction and Building Materials, Life Cycle Assessment (LCA), Eco-Labelling and Case Studies. Oxford : Woodhead Publishing, pp. 38-62
- Erlandsson M, Borg M. 2003. Generic LCA- methodology applicable for buildings, constructions and operation services – today practice and development needs. *Build Environ.* 38 (7) : 919-38.
- European Commission, Eurostat, Greenhouse gas emission statistics. June 2017. Available online: http://ec.eurpa.eu/eurostat/statistics-explained/index.php/greenhouse_gas_emission_statistics (Retrieved 14 October 2017)
- European Commission, "Energy Roadmap 2050", European Union, 2012
- Fiona Bénard-Sora., Jean Philippe Praene 2018. Sustainable urban planning for a successful energy transition on Reunion Island: From policy intentions to practical achievement *Utilities Policy*, Vol 55, P: 1-13
- Fiona Bénard-Sora., Jean Philippe Praene 2016. Territorial analysis of energy consumption of a small remote island: Proposal for classification and highlighting consumption profiles *Renewable and Sustainable Energy Reviews,* Vol 59, P: 636-648
- Finkbeiner, M., 2014. Product environmental footprint - Breakthrough or breakdown for policy implementation of life cycle assessment ? *International Journal of Life Cycle Assessment* 19, 266-271
- Finndeven , G., Hauschild, M, Z., Ekvall, T., et al, 2009. Recent developments in life cycle assessment. *Journal of Environmental MAnagement* 91 (1), 1-21
- Forsberg A, von Malmborg F. 2004. Tools for environmental assessment of the built environment. *Build Environ*. 39 : 223-8
- Gaidajis, G., & Angelakoglou, K. 2012. Environmental performance of renewable energy systems with the application of life- cycle assessment : a multi-Si photovoltaic module case study. *Civil Engineering and Environmental Systems* 29(4), 231-238
- H.J Kang 2015. Development of a systematic model for an assessment tool for sustainable buildings based on a structural framework, *Energy Building* 104. 287-301
- ISO 14040. 2006 Environment Management – Life cycle assessment – Principles and framework.
- IEDOM, 2018. Rapport 2017. https://www.iedom.fr/IMG/pdf/ra2017_la_re_union.pdf
- Jeswani, H.K., Azapagic, A., Schepelman, P., Ritthoff, M, 2010. Options for broadening and deepening the LCA approaches. *Journal of Cleaner Production* 18 (2), 120-127

- John, S., Nebel, B., Perez, N., Buchanan, A., 2009. Environmental impacts over the life cycle of residential building using different exterior wall systems. *Journal of Infrastructure Systems* 15 (3)
- Klöpffer W., Grahl B., 2014. Life Cycle Assessment (LCA): A Guide to Best Practice. ISBN: 978 -3 – 527 – 32986 - 1
- Larsson N. 2006. Sustainable building information systems (SBIS). http://www.sbis.info/about.jsp
- Markovska N., Duic N., Mathiesen B.V., Guzovic Z., Piacentino A., Schlör H., Lund H., 2016. Addressing the main challenges of energy security in the twenty-first century _ Contributions of the conferences on Sustainable Development of Energy, Water and Environment Systems. Energy, 115 (3): p. 1504 – 1512. DOI: 10.1016/j.energy.2016.10.086
- M. Yeheyis, K. Hewage, M.S Alam, C. Eskicioglu, R. Sadiq 2012. An overview of construction and demolition waste management in Canada : a life cycle analysis approach to sustainability, Clean Technol. Environmental Policy 81-91. doi : 10.1007/s10098-012-0481-6
- Ortiz O, Castells F, Sonnemann G. 2009. Sustainability in the construction industry : a review of recent developments based on LCA. *Construction and Building Materials* 1 : 28-39
- Oyudemi, O., Okoroh, M.I., Fajana, O.S., 2017. The application and barriers of BIM in sustainable building design. *Journal of Facilities Management* 15 (1), 15-34
- Peuportier B., Kellenberger D., Anink D., Mötzl H., Anderson A., Vares S., Chevalier J., and König H., 2004. Inter-comparison and benchmarking of LCA-based environmental assessment and design tools, *Sustainable Building*, Conference, Waesaw, paper N°75
- RTAA, 2016, RTAA 2016 – Arrêté du 11 janvier 2016 modifiant les arrêtés du 17 avril 2009.
- Russel, A., Ekvall, T., Baumann, H., 2005. Life cycle assessment – introduction and overview. *Journal of Cleaner Production*. (13) 1207 - 1210
- S. Azhar, W.A Carlton, D. Olsen, I. Ahmad 2011. Building information modeling for sustainable design and LEED 217-224.
- United State Environmental Protection Agency. 1993. Office of Research and Development, Life Cycle Assessment : Inventory Guidelines and Principles, EPA/600/R-92/245, US.
- Z. Alwan, P. Jones, P. Holgate 2016. Strategic sustainable development in the UK construction industry, through the framework for strategic sustainable development, using Building Information Modeling, *Journal Clean Prod.*

ANNEX 1: NOMENCLATURE

ABBREVIATIONS	NAMES OF PRODUCTS
AIC	Aluminum interior carpentry
BWa	Block wall
CeT	Ceramic tiling
Coa	Coating
CSr	Concrete screed
EcR	External carpentry works type roller shutter
EcW	External carpentry works
ESF	Exterior siding facade
Gro	Galvanized roofing
INS	Insulation
ISS	Interior separation and suspended ceiling
Pav	Paving in ferroconcrete
Pur	Purlin
SFr	Steel framing